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Dynamic Routing and Wavelength Assignment with Backward Reservation in Wavelength-routed Multifiber WDM Networks

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***Abstract*— In wavelength-routed WDM networks, blocking probability of lightpath establishments is generally high due to coarse granularity and wavelength continuity constraint. Therefore, blocking of lightpath establishments is one of crucial issues which must be resolved. Multifiber environments reduce blocking probability of lightpath establishments because each link consists of multiple fibers and multifiber links can be viewed as limited-range wavelength conversion. Blocking probability can be further reduced by an appropriate routing and wavelength assignment (RWA) scheme. This paper proposes a dynamic RWA scheme using signaling of backward reservation for wavelength-routed multifiber WDM networks. In the proposed scheme, information on link state is collected by signaling of backward reservation along multiple routes between a sender node and a receiver node whenever a new lightpath-setup request arrives. Then the proposed scheme selects a combination of a route and a wavelength at the receiver node based on the collected information in such a way that it avoids the generation of bottleneck links and the depletion of a specific wavelength. Through simulation experiments, we show that the proposed scheme efficiently reduces blocking probability of lightpath establishments in multifiber WDM networks.**

***Index Terms*— multifiber WDM networks, routing and wavelength assignment, dynamic lightpath establishment, backward reservation**

I. INTRODUCTION

With the growth of the Internet, optical networks have gained much attention due to their large transmission bandwidth. The wavelength division multiplexing (WDM) technology increases the capacity of a fiber optic link by simultaneously transmitting multiple signals with different wavelengths over a single fiber [3]. In WDM networks, a lightpath is established between a sender node and a receiver node to transmit data stream. This paper focuses on WDM networks with dynamic lightpath establishments in which lightpaths are dynamically established as lightpath-setup requests arrive [14]. The performance metric in such networks is typically blocking probability of lightpath establishments. In WDM networks, blocking probability of lightpath establishments is generally high because a lightpath occupies a wavelength in all links along an end-to-end route. Therefore, multiple same-wavelength lightpaths cannot be established in a fiber on the same link. Furthermore, without wavelength conversion technology [10], a lightpath must use a common wavelength in all links along the route (i.e., wavelength continuity constraint). As a result, lightpath establishments are often blocked. Therefore, blocking of lightpath establishments is one of crucial issues which must be resolved in WDM networks.

Multifiber environments enhance the performance of WDM networks [2], [5], [8], [9]. In multifiber WDM networks, a link consists of multiple fibers and multiple same-wavelength lightpaths can be established in the link. Thus, blocking probability of lightpath establishments is reduced. Blocking probability can be further reduced by an appropriate dynamic routing and wavelength assignment (RWA) scheme which selects a route and a wavelength for lightpaths [7], [13].

In the past, several dynamic RWA schemes have been proposed for multifiber WDM networks without wavelength conversion [4], [11]. In [4], the authors proposed three dynamic RWA schemes named MCR, LSNLR, and $F(w, l)$. These schemes first select a route among the pre-determined routes and then they selects a wavelength based on wavelength availability. In [11], the authors proposed two RWA schemes named PACK and SPREAD. They select a combination of a route and a wavelength based on some metric associated with each combination. Although the authors showed that these RWA schemes reduce blocking probability of lightpath establishments, they need link state information such as wavelength availability in each link in advance. Therefore, each node has to exchange link state information periodically with a given time interval or every time the link state changes [1], [6], [15], and blocking probability of lightpath establishments depends on how to exchange the link state information. Because network status changes continuously, they may not work well due to lack of precise link state information. Moreover, they do not consider wavelength reservation protocols such as backward reservation [12]. The wavelength reservation protocols

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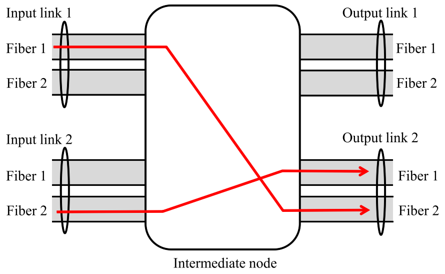

Figure 1. Intermediate node in multifiber WDM networks.

reserve a wavelength along a route for a lightpath by means of signaling. We should take into account the impact of delay of signaling such as propagation delay and processing time of signaling at intermediate nodes on blocking probability of lightpath establishments.

This paper proposes a dynamic RWA scheme using signaling of backward reservation in multifiber WDM networks. In the proposed scheme, information on link state is collected by signaling of backward reservation along multiple routes between a sender node and a receiver node whenever a new lightpath-setup request arrives. Then the receiver node selects a combination of a route and a wavelength using the collected information, and thus the proposed scheme does not need to exchange link state information. The proposed scheme aims at reducing blocking probability of lightpath establishments by selecting a combination of a route and a wavelength based on wavelength availability. Specifically, the proposed scheme tends to select a combination whose route has many available wavelengths in order to avoid the generation of bottleneck links. Also, the proposed scheme tends to select a combination whose wavelength is least used along the route in order to avoid the depletion of a specific wavelength. As a result, the proposed scheme is expected to reduce blocking probability of lightpath establishments in multifiber WDM networks efficiently.

The rest of this paper is organized as follows. In Section II, we explain multifiber WDM networks and backward reservation. Section III discusses our proposed scheme. In Section IV, the performance of the proposed scheme is discussed with the results of simulation experiments. Finally, we conclude the paper in Section V.

II. MULTIFIBER WDM NETWORKS

In single fiber WDM networks, multiple lightpaths with the same wavelength cannot be simultaneously established in the same link because each link has a single fiber. On the other hand, in multifiber WDM networks, multiple lightpaths can be established with the same wavelength in the same link as shown in Fig. 1. In this figure, we assume that a lightpath from input link 1 to output link 2 has already been established at an intermediate node. If the number of fibers in output link 2 is 1, i.e., single fiber link, a new lightpath for output link 2 cannot be established with the same wavelength. In multifiber networks, a new lightpath from input link 2 with the same wavelength can be established through a different fiber in the output link 2 as long as there are same wavelengths available in other fibers. In particular, multifiber links can be viewed as limited-range wavelength conversion [7], and thus multifiber environments reduce blocking probability of lightpath establishments.

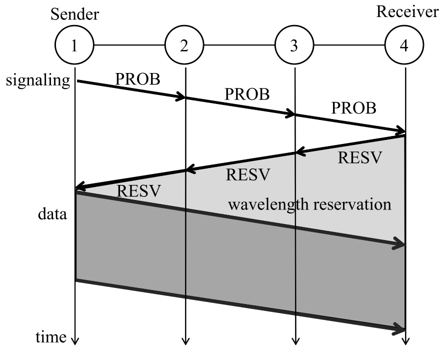

Figure 2. Backward reservation.

In networks with dynamic lightpath establishments, a lightpath is dynamically established by reserving a wavelength in all links along a route from a sender node to a receiver node whenever the lightpath-setup request arrives. In establishing lightpaths, this paper uses signaling of a wavelength reservation protocol known as backward reservation [12]. In the backward reservation, a sender node selects a route and a receiver node selects a wavelength for a new lightpath. Fig. 2 illustrates the procedure of the backward reservation. At first, the sender node selects a route according to a routing algorithm (e.g., shortest path routing). Then the sender node sends a PROB message to a receiver node without reservation of wavelength resources along the selected route. The PROB message collects information on available wavelengths along the route. After the PROB message arrives at the receiver node, the receiver node selects a wavelength based on a wavelength selection algorithm (e.g., first-fit selection and random selection). Then the receiver node sends a RESV message which reserves the selected wavelength on a fiber at each link along the route in order to establish a lightpath. After the sender node receives the RESV message, it sends data to the receiver node via the established lightpath. When data transmission finishes, then the wavelength reservation is released.

Fig. 3 illustrates an example of backward reservation in multifiber WDM networks, where $\mathcal{W}_i$ $(i = 1, 2)$ in each link denotes a set of available wavelengths in fiber i on the link and each fiber supports three wavelengths w_1, w_2, and w_3. First, the sender node sends a PROB message. In this example, wavelengths $\{w_1, w_2, w_3\}$ and wavelength $\{w_1\}$ are available in fiber 1 and fiber 2 on the first link, respectively. Similarly, wavelengths available in fiber 1 and fiber 2 on the second link are $\{w_2, w_3\}$ and $\{w_2\}$, respectively. The PROB message collects information on such wavelength availability. After receiving the PROB message, the receiver node knows that w_2 and w_3 are available along the entire route because w_1 is already used

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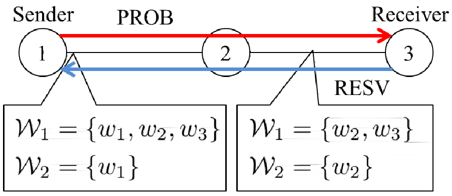

Figure 3. Example of backward reservation in multifiber WDM networks.

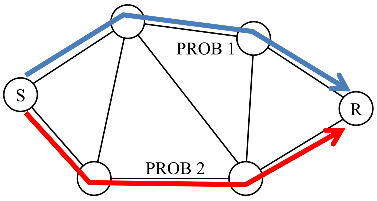

Figure 4. Collecting information along routes by signaling of backward reservation.

in all fibers on the second link. The receiver node selects a wavelength from w_2 and w_3. Then, the receiver node sends a RESV message to the sender node in order to reserve the selected wavelength.

Note that in multifiber WDM networks, a new lightpath establishment is blocked when there are no available wavelengths along a selected route. Specifically, in the case where a PROB message detects that all wavelengths in all fibers on a link along the selected route are already used by other lightpaths, the new lightpath cannot be established. Moreover, the new lightpath establishment is blocked when a RESV message detects that lightpaths with the same wavelength are already established in all fibers on an output link at an intermediate node.

III. PROPOSED SCHEME

A. Overview

The proposed scheme provides an RWA approach in multifiber WDM networks. In the conventional backward reservation, a route is selected by a sender node. On the other hand, in the proposed scheme, a receiver node selects a route from pre-defined routes which are link-disjoint paths, i.e., paths which do not share a link. Specifically, the receiver node selects a combination of a route and a wavelength based on information collected by PROB messages along those pre-defined routes whenever a new lightpath-setup request arrives. Thus the proposed scheme does not need to know link state information in advance.

The proposed scheme aims at reducing blocking probability of lightpath establishments by selecting a combination of a route and a wavelength in such a way that it avoids the generation of bottleneck links and the depletion of a specific wavelength. A bottleneck link is generated when traffic concentrates in a certain link and all wavelengths in the link are in simultaneous use. In this case, further lightpaths cannot be established in the link. Therefore, we expect to reduce blocking probability by avoiding the generation of bottleneck links. In order to distribute loads and avoid the generation of bottleneck links, the proposed scheme tends to select a combination whose route has many available wavelengths.

Moreover, it is not preferable that a specific wavelength is used in all fibers on a link. A lightpath must use a common wavelength along the entire route due to wavelength continuity constraint. Therefore, a wavelength cannot be used in cases where the wavelength is already used in all fibers on a certain link along the route even if the wavelength is available in other links. Thus, in order to avoid this situation, the proposed scheme selects a combination of a route and a wavelength for each lightpath establishment based on usage of each wavelength in links along routes. In particular, the proposed scheme tends to select a combination whose wavelength is least used along the route.

B. The procedure of the proposed scheme

In what follows, we explain the detail of the proposed scheme. We assume that wavelength conversion is not available at any intermediate node.

1) Construction of pre-defined paths: The proposed scheme constructs lightpaths via pre-defined link-disjoint paths. In this paper, we adopt the following simple algorithm to construct those paths for each pair of a sender node and a receiver node. Let $G = (\mathcal{V}, \mathcal{E})$ denote a directed graph, where $\mathcal{V}$ and $\mathcal{E}$ denote sets of nodes and links, respectively. At first, we find the shortest path from a sender node to a receiver node on G, using Dijkstra's algorithm, and adopt the path as a link-disjoint path. Then the links along the path are removed from G. We find the new shortest path on the resulting graph and the path is adopted as a new link-disjoint path. The procedure is repeated until no routes from the sender node to the receiver node remain.

2) Collecting information by signaling: The proposed scheme collects information on wavelength availability on links along multiple routes from a sender node to a receiver node with signaling of backward reservation whenever a new lightpath-setup request arrives. The procedure is as follows. When a new lightpath-setup request arrives, a sender node sends PROB messages to a receiver node along pre-defined link-disjoint paths in parallel as shown in Fig. 4. The PROB messages do not reserve wavelength resources. They collect information on wavelength availability in links along the paths. The receiver node waits until it receives all PROB messages from the sender node. After receiving them, the receiver node selects a route and a wavelength based on information collected by PROB messages as we will see in Section III-B.3. Then the receiver node sends a RESV message to the sender node along the selected route to establish a lightpath with the selected wavelength. Note that the proposed scheme efficiently uses wavelength resources because it reserves the selected wavelength only in links along the selected route.

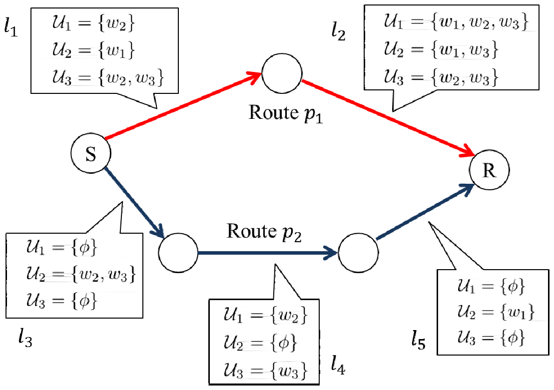

Figure 5. An example of the proposed scheme.

3) Route and wavelength selection: After receiving all PROB messages, a receiver node selects a combination of a route and a wavelength based on information collected by signaling as described in Section III-B.2. Specifically, the proposed scheme assigns cost $C_{w,p}$, which is defined later, to a combination of route p and wavelength w. The receiver node selects a combination with the smallest cost $C_{w,p}$. If $C_{w,p}$ is infinity for all combinations, a new lightpath establishment is blocked. Note that if there are two or more combinations with the minimum cost, the proposed scheme selects a combination with shorter hops. If the numbers of hops among them are the same, the proposed scheme selects one randomly. In the proposed scheme, $C_{w,p}$ is defined as follows:

$$C_{w,p} = \frac{\sum_{l \in \mathcal{E}_p} c_{w,l}}{|\mathcal{A}_p|}, \tag{1}$$

where $\mathcal{E}_p$ denotes the set of links along route p from the sender node to the receiver node, $c_{w,l}$ denotes the cost of wavelength w in link l, and $\mathcal{A}_p$ denotes the set of available wavelengths along route p. We define $c_{w,l}$ as follows:

$$c_{w,l} = \begin{cases} n_{w,l} \times \dfrac{\sum_{f \in \mathcal{F}_l} u_{l,f}}{\sum_{f \in \mathcal{F}_l} W_{l,f}}, & \text{if } n_{w,l} < |\mathcal{F}_l|, \\ \infty, & \text{otherwise,} \end{cases} \tag{2}$$

where $n_{w,l}$ denotes the number of link l's fibers in which wavelength w is already used, $\mathcal{F}_l$ denotes the set of fibers in link l, $u_{l,f}$ denotes the number of used wavelengths in fiber f on link l, and $W_{l,f}$ denotes the number of wavelengths supported by fiber f on link l. As it can be seen from (1) and (2), the proposed scheme tends to select a combination whose route has many available wavelengths as mentioned in Section III-A. Specifically, the cost increases with the sum $\sum_{f \in \mathcal{F}_l} u_{l,f}$ of numbers of wavelengths used in link l. Also, the cost decreases with the increase in the number $|\mathcal{A}_p|$ of available wavelengths along route p. Moreover, the proposed scheme tends to select a combination whose wavelength is least used along the route because the cost increases with the number $n_{w,l}$ of link l's fibers in which wavelength w is used.

We show an example of the proposed scheme in Fig. 5, where $\mathcal{U}_i$ $(i = 1, 2, 3)$ in each link denotes the set of used wavelengths in fiber i. In this figure, we assume that there are two pre-defined routes between the sender node and the receiver node. Route p_1 includes links l_1 and l_2. Route p_2 includes links l_3, l_4, and l_5. Each link consists of three fibers and each fiber supports three wavelengths w_1, w_2, and w_3. As we can see from this figure, the cost c_{w_1,l_1} of w_1 in the link l_1 is $1 \times 4/9 = 4/9$ because $n_{w_1,l_1} = 1$, $\sum_{f \in \mathcal{F}_{l_1}} u_{l_1,f} = 4$, and $\sum_{f \in \mathcal{F}_{l_1}} W_{l_1,f} = 9$ in (2). Also, the cost c_{w_1,l_2} of w_1 in link l_2 is $2 \times 7/9 = 14/9$ because $n_{w_1,l_2} = 2$, $\sum_{f \in \mathcal{F}_{l_2}} u_{l_2,f} = 7$, and $\sum_{f \in \mathcal{F}_{l_2}} W_{l_2,f} = 9$. Furthermore, $|\mathcal{A}_{p_1}|$ is 2 because w_3 is not available along route p_1 (i.e., $\mathcal{A}_{p_1} = \{w_1, w_2\}$). Thus the cost C_{w_1,p_1} of the combination of route p_1 and wavelength w_1 is $(4/9+14/9)/2 = 1$, which is calculated by (1). Similarly, we can calculate the cost of each combination as shown in Table I. In this case, C_{w_1,p_2} is the smallest. Thus, the receiver node selects the combination of route p_2 and wavelength w_1.

TABLE I.
COST OF THE EXAMPLE.

Combination	Cost
C_{w_1,p_1}	$(4/9 + 14/9)/2 = 1$
C_{w_2,p_1}	$(8/9 + 14/9)/2 = 11/9$
C_{w_3,p_1}	$(4/9 + \infty)/2 = \infty$
C_{w_1,p_2}	$(0 + 0 + 1/9)/3 = 1/27$
C_{w_2,p_2}	$(2/9 + 2/9 + 0)/3 = 4/27$
C_{w_3,p_2}	$(2/9 + 2/9 + 0)/3 = 4/27$

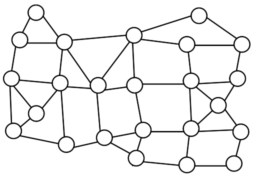

Figure 6. Network model.

IV. PERFORMANCE EVALUATION

A. Model

To evaluate performance of the proposed scheme, we conduct simulation experiments with the network topology shown in Fig. 6. We assume that there are no wavelength converters at any node. System parameters are listed in Table II. For simplicity, we assume that the propagation delay of each link is equal to 1 [msec], and processing time of signaling at each node is 0.1 [msec]. The number W of wavelengths supported by each fiber is set to be 4 and the number F of fibers in each link is set to be 8, unless stated otherwise. Holding time of each lightpath follows an exponential distribution with mean L = 10 [sec], unless stated otherwise. At each node, lightpath-setup requests are generated according to a Poisson process with rate λ. The destination of each request is independently chosen equally likely among all possible nodes. We define ρ as the offered load per wavelength on a fiber:

$$\rho = \frac{\lambda L}{FW}.$$

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TABLE II.
PARAMETERS IN SIMULATION EXPERIMENTS.

Parameter	Value
Propagation delay of each link	1 [msec]
Processing time of signaling at each node	0.1 [msec]
Number W of wavelengths in each fiber	4
Number F of fibers in each link	8
Average holding time L of lightpaths	10 [sec]

We collect 30 independent samples from simulation experiments, and 95% confidence intervals are shown (even though most of them are invisible).

For the sake of comparison, we use the following two schemes. The procedure of these schemes is the same as that of the proposed scheme except that they behave in different manner when a receiver node selects a route and a wavelength (see Section III-B.3). The first scheme uses different cost functions instead of (1) and (2). In particular, it selects a combination of wavelength w and route p with the smallest cost $C'_{w,p}$. We define $C'_{w,p}$ as

$$C'_{w,p} = \sum_{l \in \mathcal{E}_p} c'_{w,l},$$

where

$$c'_{w,l} = \begin{cases} 1, & \text{if } n_{w,l} < |\mathcal{F}_l|, \\ \infty, & \text{otherwise.} \end{cases}$$

In this scheme, the receiver node randomly selects one from combinations with the shortest route in terms of the number of hops.

The second scheme is based on the $F(w, l)$ method [4], which first selects a route and then selects a wavelength along the selected route. In particular, this scheme first calculates the cost C''_p for each route p as follows:

$$C''_p = \frac{\displaystyle\sum_{w \in \mathcal{A}_p} \sum_{l \in \mathcal{E}_p} n_{w,l}/|\mathcal{F}_l|}{|\mathcal{A}_p|^2 \displaystyle\sum_{w \in \mathcal{A}_p} \min_{l \in \mathcal{E}_p} m_{w,l}},$$

where $m_{w,l}$ denotes the number of link l's fibers in which wavelength w is available (i.e., $m_{w,l} = |\mathcal{F}_l| - n_{w,l}$), and it selects route p with the smallest C''_p. Then, wavelength w with largest C''_w along the selected route p_s is selected, where C''_w is given as

$$C''_w = \min_{l \in \mathcal{E}_{p_s}} m_{w,l}.$$

We call the first and second schemes SR and $F(w, l)$ hereafter, respectively.

B. Simulation results

Fig. 7 shows blocking probability of lightpath establishments as a function of the offered load ρ. Note that blocking probability of lightpath establishments is defined as

$$\text{blocking probability of lightpath establishments} = \frac{\text{the number of blocked lightpath-setup requests}}{\text{the total number of lightpath-setup requests}}.$$

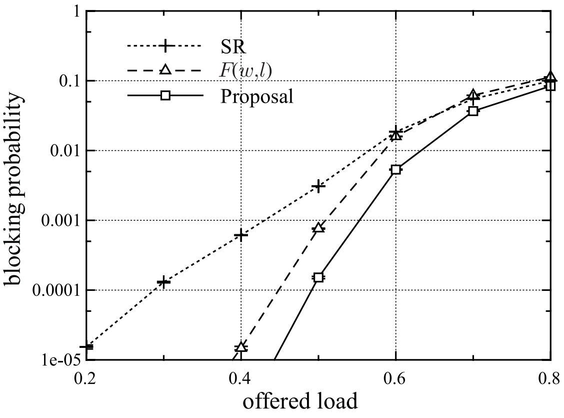

Figure 7. Blocking probability ($F = 8$, $W = 4$, $L = 10$).

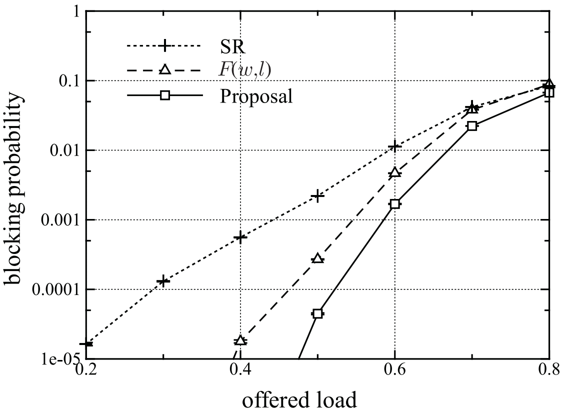

Figure 8. Blocking probability ($F = 8$, $W = 8$, $L = 10$).

As it can be seen from Fig. 7, the blocking probability of SR is very high because it does not consider wavelength availability in the network and frequently generates bottleneck links. On the other hand, $F(w, l)$ and the proposed scheme reduce the blocking probability of lightpath establishments because they effectively utilize wavelength resources. We also observe that the proposed scheme reduces blocking probability more efficiently than $F(w, l)$. In $F(w, l)$, a receiver node first selects a route and then selects a wavelength. On the other hand, the proposed scheme selects a combination of a route and a wavelength simultaneously. The proposed scheme can select a combination from more candidates than $F(w, l)$, and wavelength resources in the network are efficiently utilized by the proposed cost function defined by (1). As a result, the proposed scheme exhibits an excellent performance.

We then demonstrate the robustness of the superior performance of the proposed scheme against system parameter values such as the number W of wavelengths supported by each fiber, the number F of fibers in each link, and the average holding time L of lightpaths.

First, we examine the performance of the proposed scheme against the number W of wavelengths supported by each fiber. Figs. 8-10 show the blocking probability of lightpath establishments as a function of the offered load ρ, where $W = 8$, $W = 12$, and $W = 16$, respectively.

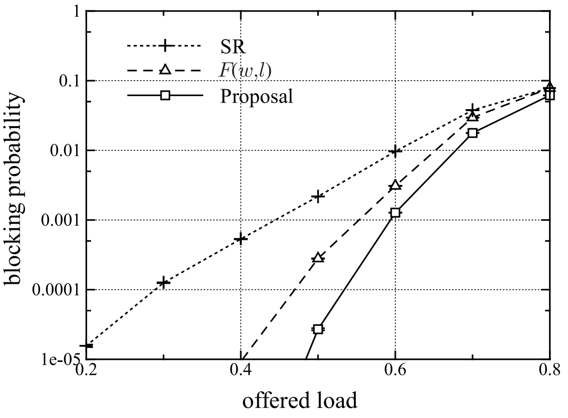

Figure 9. Blocking probability ($F = 4$, $W = 12$, $L = 10$).

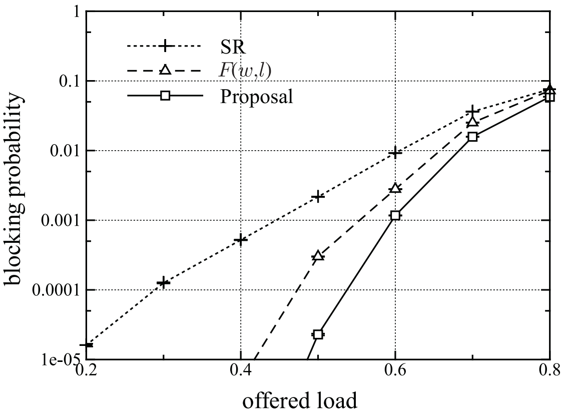

Figure 10. Blocking probability ($F = 8$, $W = 16$, $L = 10$).

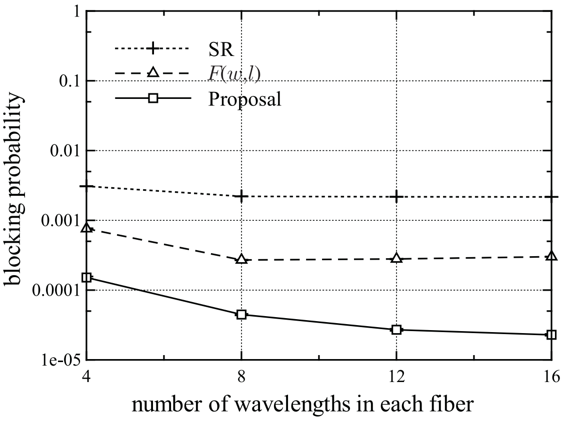

Figure 11. Blocking probability ($F = 8$, $L = 10$, $\rho = 0.5$).

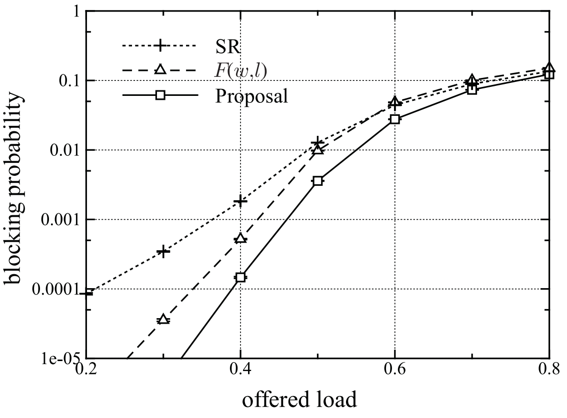

Figure 12. Blocking probability ($F = 4$, $W = 4$, $L = 10$).

As we can see from these figures, SR has high blocking probability. We also observe that the proposed scheme reduces the blocking probability more efficiently than $F(w, l)$. These results are similar to the result with $W = 4$ shown in Fig. 7. Fig. 11 shows the blocking probability of lightpath establishments as a function of W, where $\rho = 0.5$. We observe that the blocking probability of each scheme decreases with the increase in W because of the large-scale effect. We also observe that the proposed scheme reduces the blocking probability more efficiently than other schemes. We conclude that the proposed scheme efficiently reduces the blocking probability of lightpath establishments regardless of the number W of wavelengths supported by each fiber.

Next, we examine the performance of the proposed scheme against the number F of fibers in each link. Figs. 12-14 show the blocking probability of lightpath establishments as a function of the offered load ρ, where $F = 4$, $F = 12$, and $F = 16$, respectively. As we can see from these figures, the proposed scheme exhibits an excellent performance like the result with $F = 8$ shown in Fig. 7. Fig. 15 shows the blocking probability of lightpath establishments as a function of F, where $\rho = 0.5$. As shown in this figure, the blocking probability of each scheme decreases with the increase in F because multifiber links fill the role of limited-range wavelength conversion. We also observe that the proposed scheme efficiently reduces the blocking probability, regardless of the number F of fibers in each link.

Finally, we examine the performance of the proposed scheme against the average holding time L of lightpaths. Figs. 16-18 show the blocking probability of lightpath establishments as a function of the offered load ρ, where $L = 1$, $L = 100$, and $L = 1000$, respectively. As shown in these figures, the proposed scheme reduces the blocking probability more efficiently than $F(w, l)$, regardless of the average holding time. Fig. 19 shows the blocking probability of lightpath establishments as a function of L, where $\rho = 0.5$. We observe that the blocking probability of each scheme decreases with the increase in the average holding time L. When L is small, the network status changes frequently. Therefore, there are many cases where a RESV message cannot reserve a selected wavelength in a link due to depletion of the wavelength even if the corresponding PROB message detects the wavelength is available. Thus, the blocking probability is large for small L. When L is large, cases where a RESV message cannot reserve a selected wavelength are rare, and thus the blocking probability of each scheme decreases. We also observe that the proposed scheme exhibits an excellent performance.

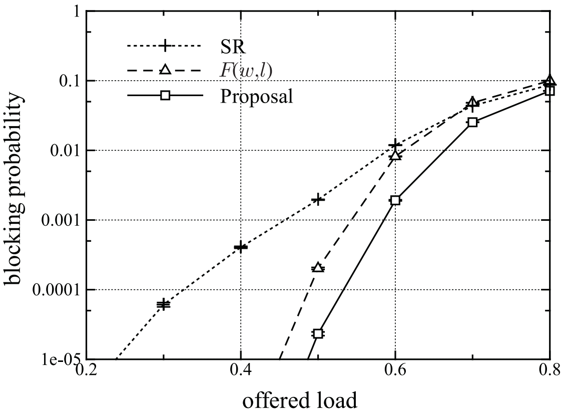

Figure 13. Blocking probability ($F = 12$, $W = 4$, $L = 10$).

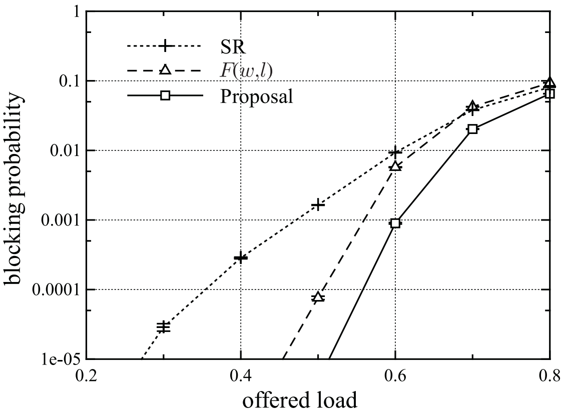

Figure 14. Blocking probability ($F = 16$, $W = 4$, $L = 10$).

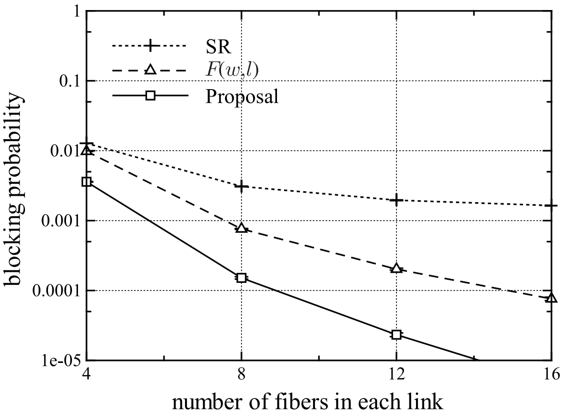

Figure 15. Blocking probability ($W = 4$, $L = 10$, $\rho = 0.5$).

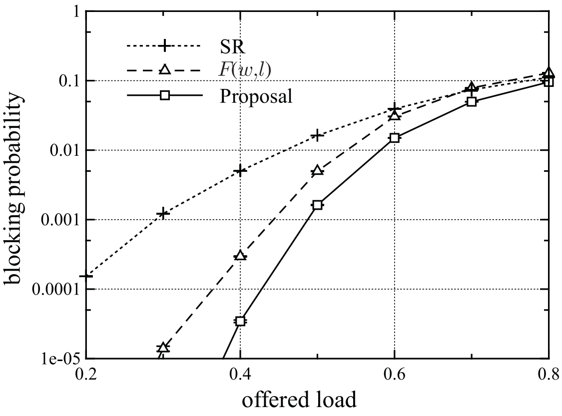

Figure 16. Blocking probability ($F = 8$, $W = 4$, $L = 1$).

V. CONCLUSION

This paper proposed a dynamic RWA scheme using signaling of backward reservation in multifiber WDM networks. In the proposed scheme, a route and a wavelength are selected based on information about wavelength availability which is collected by signaling of backward reservation along routes between a sender and a receiver. The proposed scheme avoids the generation of bottleneck links and the depletion of a specific wavelength. Through simulation experiments, we showed that the proposed scheme efficiently reduces blocking probability of lightpath establishments in multifiber WDM networks.

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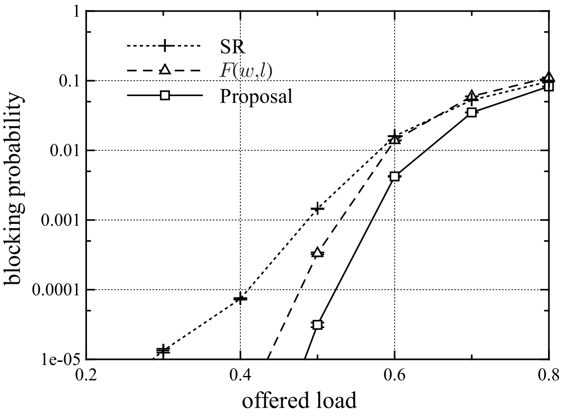

Figure 17. Blocking probability $(F = 8,\ W = 4,\ L = 100)$.

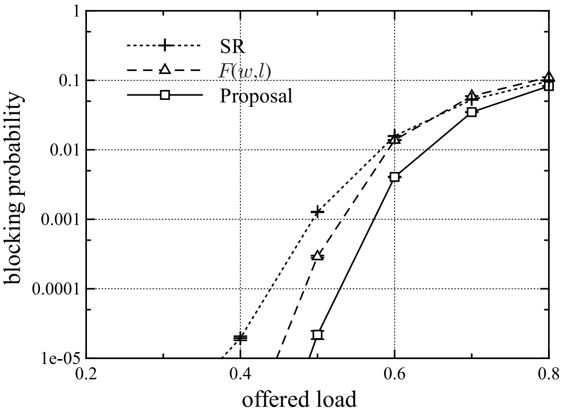

Figure 18. Blocking probability $(F = 8,\ W = 4,\ L = 1000)$.

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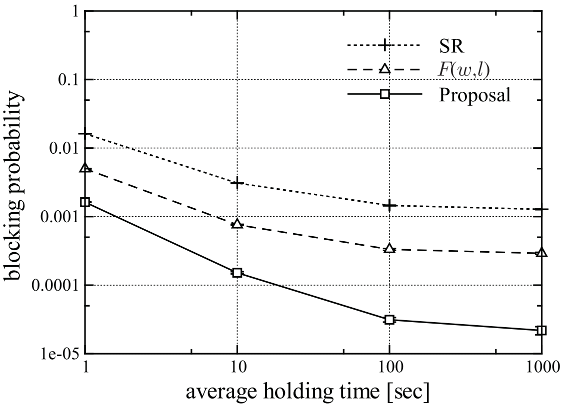

Figure 19. Blocking probability $(F = 8,\ W = 4,\ \rho = 0.5)$.

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