PAPER

Two-Way Release Message Transmission and Its Wavelength Selection Rules for Preemption in OBS Networks*

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SUMMARY In this paper, we propose a new preemptive scheme with release message in optical burst switching (OBS) networks. In the proposed scheme, when a low priority burst is preempted at some intermediate node, two RELEASE messages are sent immediately from the intermediate node to both source and destination nodes (two-way release message transmission), and the RELEASE messages release the corresponding wavelengths for the preempted burst. We consider six wavelength selection rules for the preemption and evaluate the performances of the selection rules by simulations. Numerical examples show that our scheme utilizes wavelengths effectively and, with the optimal selection rule, can decrease the burst loss probability in a large-scale DWDM network.

key words: *optical burst switching, preemptive scheme, release message, immediate reservation, wavelength selection rule*

1. Introduction

Optical burst switching (OBS) has been considered as one of the promising technologies for the next-generation optical Internet. In OBS networks, a burst is assembled with multiple IP packets and is transmitted from its source to destination, and a signaling protocol plays a crucial role in the burst transmission. As for the signaling protocol, delayed reservation such as JET protocol and immediate reservation such as JIT protocol have been proposed [1], [2].

In the delayed reservation, an output wavelength is reserved with a SETUP message just before the arrival of the burst [1]. The wavelength is released just after the burst transmission with a timer. When there are no available wavelengths at the arrival time of the corresponding burst, the SETUP message is rejected and the burst is lost. Moreover, in the delayed reservation, the void between two bursts in a wavelength can be utilized and wavelengths are utilized effectively.

On the other hand, in the immediate reservation, an output wavelength is reserved after the arrival of a SETUP message [2]. When there are no available wavelengths at the arrival time of the SETUP message, the SETUP message is rejected and the corresponding burst is lost. When a RELEASE message is used in the immediate reservation, the reserved wavelength is released after the arrival of the corresponding RELEASE message. When a RELEASE message is not used, the reserved wavelength is released just after the burst transmission with a timer. Because a wavelength is reserved immediately after the arrival of the SETUP message, the void between two bursts in a wavelength cannot be utilized in the immediate reservation.

In the OBS networks, service differentiation has to be supported for multimedia applications such as Voice over IP, video conference, and video-on-demand. Because high priority traffic requires a small burst loss probability, the burst loss probability is an important QoS measure. To support the service differentiation in terms of the burst loss probability, several schemes have been proposed in the literature.

In the delayed reservation, the service differentiation scheme based on extra offset time [3], segmentation [4], prioritized routing [5], intentional dropping [6], and preemption [7] have been proposed. For example, in the extra offset time scheme, the high priority burst has a large offset time and the SETUP message can reserve a wavelength for the burst prior to the low priority burst. As a result, the small loss probability is provided for the high priority burst.

As for the immediate reservation, a probabilistic preemptive scheme has been studied [7]–[9]. In the probabilistic preemptive scheme, when a new SETUP message for a high priority burst arrives at a congested node, it can preempt a low priority burst transmission with a given preemption probability. Hence, the small burst loss probability is provided for the high priority class. However, in the OBS networks, the SETUP message of the preempted priority burst cannot recognize the event that the corresponding burst is preempted. This is because the SETUP message is transmitted in advance before the burst transmission. The SETUP message continues to reserve wavelengths for the preempted burst at the subsequent nodes. As a result, the reservation for the preempted burst wastes wavelengths between the node where the preemption occurs and the destination node. This inefficient use of wavelengths causes a large burst loss probability.

In this paper, we propose a new preemptive scheme for the immediate reservation with release message. In the proposed scheme, when a low priority burst is preempted at an intermediate node, two RELEASE messages are sent immediately from the intermediate node to both source and destination. The RELEASE messages release the corresponding wavelengths for the preempted burst. We consider six wavelength selection rules for the preemption and evaluate

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the performances of the selection rules with simulation.

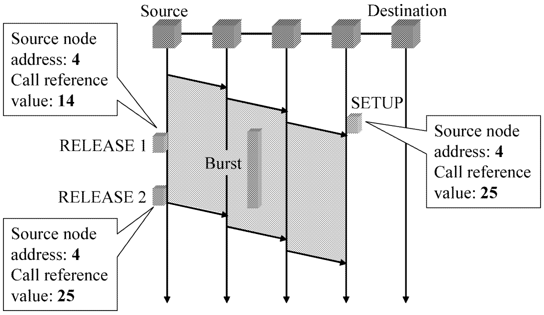
The rest of the paper is organized as follows. Section 2 summarizes the immediate reservation with and without release message. Section 3 describes a preemptive scheme with one-way release message transmission for the immediate reservation with release message. In Sect. 4, we present the preemptive scheme with two-way release message transmission and its wavelength selection rules, and numerical examples are shown in Sect. 5. We discuss the effectiveness of wavelength selection rules for the proposed scheme in Sect. 6. Finally, conclusions are presented in Sect. 7.

2. Immediate Reservation with and without Release Message

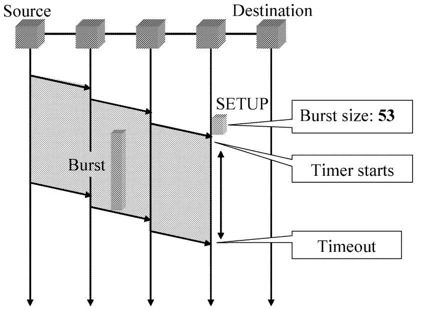
In this section, we summarize the immediate reservation with and without release message.

In the immediate reservation with release message, a bursts is transmitted from its source to destination with two control packets; SETUP message and RELEASE message. The SETUP message is transmitted before the burst transmission, and it configures resources inside the OBS switch at each node (see Fig. 1(a)). After the configuration, the SETUP message is forwarded to the next node. If there exist no available resources at a node, the SETUP message fails in the configuration and the corresponding burst is lost at the node. The RELEASE message is transmitted from the source node just after the burst transmission in order to release the configured resources.

Here, both the SETUP and RELEASE messages have a field for *call reference value*, and a unique call reference value is allocated for each burst transmission [2]. When a SETUP message configures the resources at some node, the node stores information about the configured resources with its unique value and the address of its source node. When a RELEASE message arrives at the node, the RELEASE message releases the resources associated with the same call reference value and with the same source node address. In Fig. 1(a), the first RELEASE message (RELEASE 1) cannot release the configured resources but the second RELEASE message (RELEASE 2) can release it.



(a) Immediate reservation with release message.



(b) Immediate reservation without release message.

Fig. 1 Immediate reservation with and without release message.

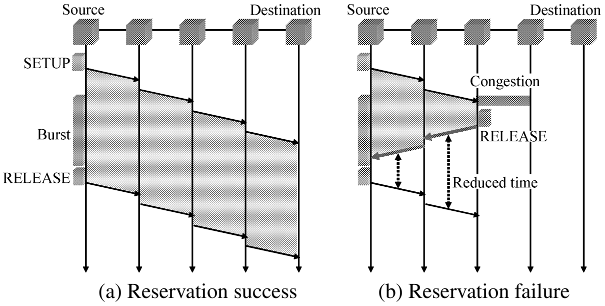
On the other hand, in the immediate reservation without release message, a burst is transmitted with only a SETUP message. When the SETUP message configures the resources inside the OBS switch at a node, a timer for the configured resources starts (see Fig. 1(b)). Here, the SETUP message has information about the burst size and a timeout value of the time is set to the end time of the burst transmission. When the timer reaches the timeout value, the configured resources are released.

The immediate reservation with release message cannot use wavelengths more effectively than that without release message and results in a larger burst loss probability. However, burst scheduling for the immediate reservation with release message is easier than that without release message because timers are not required in order to release the configured resources. Therefore, the switch hardware for the immediate reservation with release message is not complex.

3. Preemptive Scheme in Immediate Reservation with Release Message

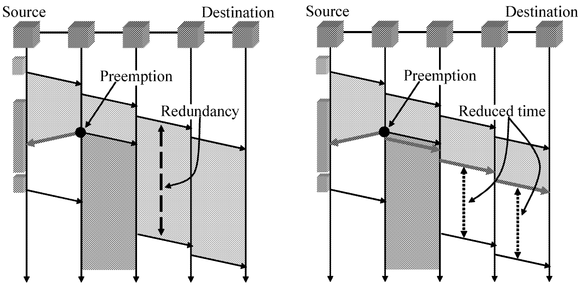
As shown in the previous section, in the immediate reservation with release message, a burst is transmitted with SETUP and RELEASE messages. When the SETUP message succeeds in reserving wavelengths between its source and destination nodes, the burst is transmitted to the destination node. Then the RELEASE message releases the wavelengths with the call reference value and the address of the source node (see Fig. 2(a)).

If the SETUP message fails in reserving a wavelength at an intermediate node due to congestion, the SETUP message is rejected and the burst is lost at the node. Just after the rejection of the SETUP message, a RELEASE message



(a) Reservation success (b) Reservation failure

Fig. 2 Burst transmission in Immediate reservation with release message.



(a) One-way transmission (b) Two-way transmission

Fig. 3 Preemptive scheme with two-way release message transmission.

is sent from the intermediate node to the source one (see Fig. 2(b)). This release message transmission results in the early release of wavelengths used for the lost burst. If the source node receives the RELEASE message from the intermediate node before the transmission of RELEASE message, the source node does not send the RELEASE message to the destination node. Otherwise, the source node may send the RELEASE message to the destination node [2].

In this paper, we focus on the preemptive scheme for the service differentiation in terms of the burst loss probability. In the preemptive scheme, the SETUP message of a high priority burst can preempt some wavelength reservation for a low priority burst at a congested node, and hence a small loss probability is provided for the high priority class.

As is the case with the reservation failure in Fig. 2(b), if the RELEASE message for the low priority burst is sent to the source node just after the preemption, the wavelengths for the preempted burst are early released (see Fig. 3(a)). In the following, we call this release message transmission to the source node *one-way release message transmission*. In the one-way release message transmission, the wavelengths between the congested node and the destination one are still reserved until the timer for wavelength reservation expires or the RELEASE message from the source node arrives at those nodes. This causes the inefficient use of wavelengths and the resulting burst loss probability is not considerably improved.

4. Preemptive Scheme with Two-Way Release Message Transmission

In this section, we propose a preemptive scheme with two-way release message transmission. In the following, we assume that the number of QoS classes is two; high and low priority classes.

In the proposed scheme, two RELEASE messages are utilized when the low priority burst is preempted. The congestion node sends the one RELEASE message to the source node and the other RELEASE message to the destination one (see Fig. 3(b)). The wavelengths reserved for the preempted burst are early released and those are likely to be used by newly arriving bursts. That is, the proposed scheme saves the wavelength reservation time of preempted bursts and decreases the overall burst loss probability.

Note that the burst loss probability is greatly affected by the length of the residual reservation time for the preempted burst, and hence it significantly depends on wavelength selection rules.

In this paper, we consider the following six wavelength selection rules in the case of preemption; (1) random (RA), (2) the smallest elapsed time (SE), (3) the largest elapsed time (LE), (4) the smallest residual time (SR), (5) the largest residual time (LR), and (6) n-last arrival (n-LA). The details are as follows:

1) Random (RA) rule
Among all the wavelengths used by low priority bursts, a wavelength for preemption is selected at random.

2) the Smallest Elapsed time (SE) rule
Among all the wavelengths for low priority bursts, the wavelength with the smallest elapsed reservation time is selected. In this rule, a timer is required for each wavelength in order to count the elapsed time.

3) the Largest Elapsed time (LE) rule
Among all the wavelengths for low priority bursts, the wavelength with the largest elapsed reservation time is selected. In this rule, a timer is required for each wavelength in order to count the elapsed time.

4) the Smallest Residual time (SR) rule
Among all the wavelengths for low priority bursts, the wavelength with the smallest residual reservation time is selected. In this rule, a timer and the information of total wavelength reservation time (from the arrival epoch of the SETUP message to that of the RELEASE message) are required for each wavelength. The residual time is derived from the total wavelength reservation time minus the elapsed time which is counted with the timer.

5) the Largest Residual time (LR) rule
Among all the wavelengths for low priority bursts, the wavelength with the largest residual reservation time is selected. In this rule, a timer and the information of total wavelength reservation time are required for each wavelength.

6) n-Last Arrival (n-LA) rule
In this rule, each node has a memory space where wavelength index information of low-priority bursts is stored. The memory holds the indices of the wavelengths used by low-priority bursts, not by high-priority bursts. Here, the maximum number of indices stored in the memory is n. When a wavelength, say w_i, is reserved for a newly arriving low-priority burst at a node, the node stores the index i in the memory space. Figure 4 shows an example in the case of $n = 3$. The stored information is updated so that the index of the oldest arriving low-priority burst is replaced with the index of the latest one. In Figs. 4(a) and (b), the oldest index 4 is deleted from the memory and the latest index 5 is stored in the memory when a newly arriving low-priority burst reserves wavelength w_5. When the wavelength whose index is stored is released, the stored index information is not updated. In Figs. 4(b) and (c), index 5 is not deleted from

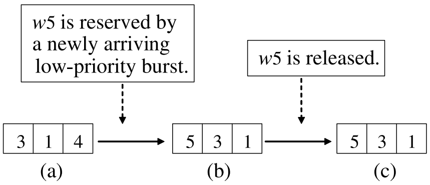


Fig. 4 Wavelength indices in the memory for 3-LA rule.

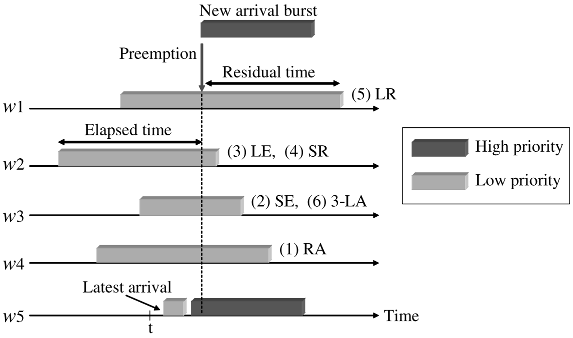


Fig. 5 Wavelength selection rules for the Preemptive scheme with two-way release message transmission.

the memory although wavelength w_5 is released. Based on the stored index information, the node selects a wavelength which has been used by a later arriving low-priority burst for preemption. If all the n wavelengths have already been released, one of the other wavelengths used for low-priority bursts is selected at random. In the cases of Figs. 4(a) and (b), the wavelengths w_3 and w_5 are selected for the preemption due to the latest index, respectively. On the other hand, in the case of Fig. 4(c), the wavelength w_3 is selected because w_5 has been already released. The performance of the n-LA rule approaches that of the SE rule as n increases while the performance of the n-LA rule with small n approaches that of the RA rule.

Figure 5 shows how the preempted wavelengths are selected according to the six selection rules. In this figure, all the five wavelengths w_1 to w_5 have been already utilized. When a new high priority burst arrives at the congested node, according to the RA rule, a wavelength w_4 is randomly selected among the four wavelengths reserved for low-priority bursts. On the other hand, according to the SE (LE) rule, w_3 (w_2) is selected, and w_2 (w_1) is selected according to the SR (LR) rule. In the 3-LA rule, the wavelength indices (5,3,1) are stored (see Fig. 4(c)). Although w_5 was previously used for the latest-arriving low-priority burst, w_5 is utilized by a high priority class, and therefore w_3 is selected.

Here, we consider the implementation cost for each rule. In the SE and LE rules, a timer is required for each wavelength in order to count the elapsed reservation time. In the SR and LR rules, wavelength reservation time is required for each wavelength in addition to the timer. Therefore, the implementation of the SR and LR rules is more complex than that of the SE and LE rules. As the number of wavelengths becomes large, the implementation of these four rules becomes more complex. On the other hand, in the n-LA rule, memory space is required in order to store n wavelength indices. Note that memory space does not depend on the number of wavelengths, but only the number of wavelength indices n.

5. Numerical Examples

In this paper, we consider an uni-directional ring network and NSFNET with 14 nodes. In these networks, we assume that the number of QoS classes is two; high priority class and low priority one. We also assume that high priority bursts can preempt low priority bursts with probability 1.0. We evaluate by simulation the overall burst loss probability of the wavelength selection rules for the proposed scheme in these networks.

5.1 Ring Network

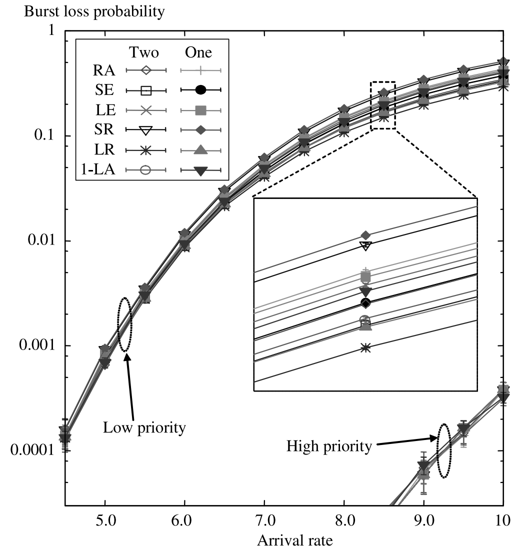
In the uni-directional ring network, we assume that the number of nodes is L and that all nodes have the capability of full-range wavelength conversion. The distance between adjacent nodes is 200 km. Moreover, we assume that the number of wavelengths is W and that the transmission speed of each wavelength is 1.0 Gbps.

We assume that a burst of each priority class arrives at the ring network according to a Poisson process with rate $\lambda/2$ [number/ms]. That is, the total arrival rate is λ [number/ms]. The pair of source and destination nodes of an arriving burst is distributed uniformly, i.e., any pair is selected with the same probability. Moreover, we assume that the burst size is exponentially distributed with the mean $D = 2.0$ Mbits, i.e., the mean transmission time of a burst is $D = 2.0$ ms. Here, the processing time of a control packet (SETUP or RELEASE message) at each node is δ ms.

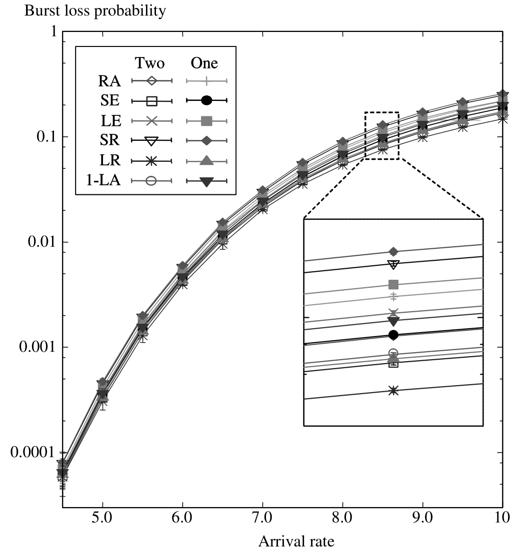
5.1.1 Impact of Burst Arrival Rate

First, we consider how the burst arrival rate λ affects the performances of wavelength selection rules. Here, we set $L = 7$, $W = 32$, and $\delta = 1.0$.

Figures 6(a) and (b) show the the burst loss probability of each priority class and the overall burst loss probability, respectively, against the burst arrival rate. In the figures, we set $n = 1$ for the n-LA rule. Moreover, the burst loss probabilities for the one-way transmission are plotted. From Fig. 6(a), we find that the burst loss probabilities of the high priority class for the two-way release message transmission are almost the same as those for the one-way release message transmission, regardless of the wavelength selection rules. On the other hand, in terms of the low priority class, the burst loss probability for the two-way release message transmission is smaller than that for the one-way release message transmission for each selection rule. As shown in Figs. 6(a) and (b), the decrease of the blocking probability for the low priority class results in that of the overall burst



(a) Burst loss probability of each priority class.

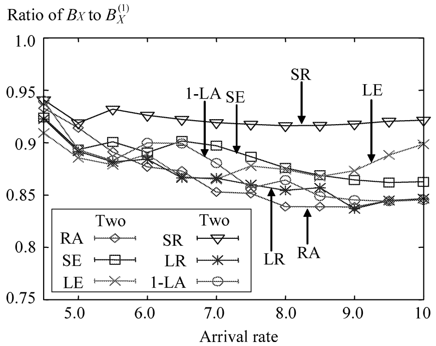


(b) Overall burst loss probability.

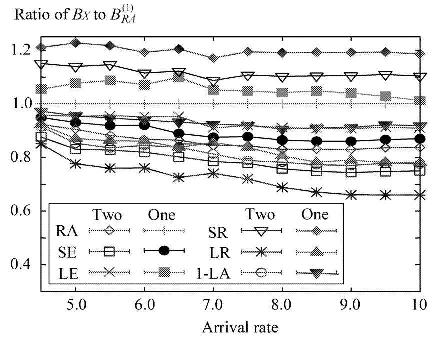
Fig. 6 Burst loss probability vs. burst arrival rate in a ring network (L = 7, W = 32, and δ = 1.0).

loss probability. This is because the two-way release message transmission aggressively releases wavelengths which are reserved redundantly, and this method never degrades the effectiveness of the preemption. Therefore, the two-way release message transmission is more effective for the service differentiation than the one-way release message transmission [7]–[9].

The effectiveness of the two-way release message transmission in the case of Fig. 6 is shown in Fig. 7(a). Let B_X denote the burst loss probability of the two-way release message transmission with rule X (=RA, SE, LE, SR, LR, and 1-LA). We also define $B_X^{(1)}$ as the burst loss probability of the one-way transmission with rule X.



(a) Ratio of B_X to $B_X^{(1)}$ for rule X.



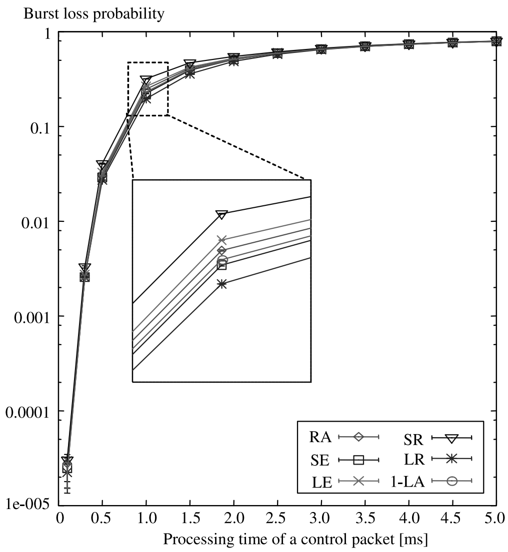
(b) Ratios of B_X and $B_X^{(1)}$ to $B_{RA}^{(1)}$ for rule X.

Fig. 7 Impact of burst arrival rate in a ring network (L = 7, W = 32, and δ = 1.0).

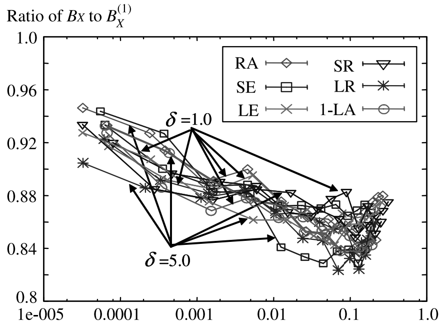
Figure 7(a) shows the ratio of B_X to $B_X^{(1)}$ for selection rule X, i.e., $B_X/B_X^{(1)}$. When the ratio is smaller (larger) than one, the two-way release message transmission is more (less) effective than the one-way transmission for the rule X. From this figure, we find that $B_X/B_X^{(1)}$'s for all rules are smaller than one. This implies that the two-way release message transmission is more effective than the one-way transmission regardless of the wavelength selection rules. In this case, the two-way release message transmission can decrease the overall burst loss probability by about 7 to 15%.

We investigate how the wavelength selection rules affect the overall burst loss probabilities. Figure 7(b) shows the ratio of B_X ($B_X^{(1)}$) for rule X to $B_{RA}^{(1)}$ for the one-way transmission with the rule RA, i.e., $B_X/B_{RA}^{(1)}$ ($B_X^{(1)}/B_{RA}^{(1)}$). If $B_X/B_{RA}^{(1)}$ ($B_X^{(1)}/B_{RA}^{(1)}$) for rule X is smaller than $B_Y/B_{RA}^{(1)}$ ($B_Y^{(1)}/B_{RA}^{(1)}$) for rule Y, the rule X is more effective than the rule Y for the two-way release message transmission (the one-way transmission). From this figure, for both the two-way and one-way transmissions, we observe that among the six wavelength selection rules, the LR rule provides the smallest burst loss probability, while the SR rule provides the largest burst loss probability, as expected. With the LR rule, the burst loss probability of the RA rule decreases by about 10%.

We also find that the burst loss probability of the 1-LA rule is smaller than that of the RA rule and is larger than that of the SE rule. If the latest reserved wavelength for low priority class is frequently preempted, the performance of the 1-LA rule is almost the same as that of the SE rule. Otherwise, the performance of the 1-LA rule is similar to that of the RA rule. As a result, the burst loss probability for the 1-LA rule is in the range between the burst loss probability



(a) Overall burst loss probability vs. processing time of control packet in the case of $\lambda = 11.0$.



(b) $B_X/B_X^{(1)}$ for rule X in the cases of $\delta = 1.0$ and 5.0 ms.

Fig. 8 Impact of processing time of a control packet in a ring network ($L = 7$ and $W = 32$).

for the SE rule and that for the RA rule.

From the above observations, we have the following inequalities in terms of the burst loss probability.

$$B_{LR} < B_{SE} < B_{1\text{-}LA} < B_{RA} < B_{LE} < B_{SR}, \tag{1}$$

$$B^{(1)}_{LR} < B^{(1)}_{SE} < B^{(1)}_{1\text{-}LA} < B^{(1)}_{RA} < B^{(1)}_{LE} < B^{(1)}_{SR}. \tag{2}$$

5.1.2 Impact of Processing Time of Control Packet

In this subsection, we investigate how the processing time of a control packet δ affects the performance of each wavelength selection rule.

Figure 8(a) shows the overall burst loss probability against the processing time of a control packet. Here, we set $L = 7$, $W = 32$, and $\lambda = 11.0$. In this figure, the burst loss probabilities of the six selection rules for the two-way release message transmission are plotted. We also set $n = 1$ for the n-LA rule.

From this figure, we observe that all the burst loss probabilities become large as the processing time increases. This is because the large processing time causes the large wavelength reservation time in the immediate reservation. This figure also shows that the burst loss probability of each wavelength selection rule satisfies the inequalities (1) regardless of the processing time of a control packet.

Figure 8(b) shows ratios of B_X for the two-way release message transmission with the rule X to $B_X^{(1)}$ for the corresponding one-way release transmission, $B_X/B_X^{(1)}$, against $B_X^{(1)}$ in the cases of $\delta = 1.0$ and 5.0. From this figure, we find that all ratios are smaller than one. This implies that the two-way release message transmission is more effective than the one-way transmission regardless of wavelength selection rules and δ.

Moreover, we observe that the ratio of each rule in the case of $\delta = 5.0$ is almost the same as that for $\delta = 1.0$. When the processing time of a control packet is large, the wavelength reservation time is large. Therefore, the two-way release message transmission with all rules in the case of $\delta = 5.0$ can reduce larger wavelength reservation time than that in the case of $\delta = 1.0$. However, the one-way release message transmission in the case of $\delta = 5.0$ can also reduce larger reservation time than that in the case of $\delta = 1.0$. As a result, the effectiveness of the two-way release message transmission is insensitive to the processing time of a control packet. Nevertheless, the two-way release message transmission is still more effective than the one-way transmission in WDM networks where the processing time of a control packet is large.

In the immediate reservation, the wavelength reservation time comprises of the burst size and the processing time of a control packet δ. The impact of the burst size on the wavelength reservation time is almost the same as that of δ. Hence, the effectiveness of the two-way release message transmission is also insensitive to the burst size.

5.1.3 Impact of Number of Wavelengths

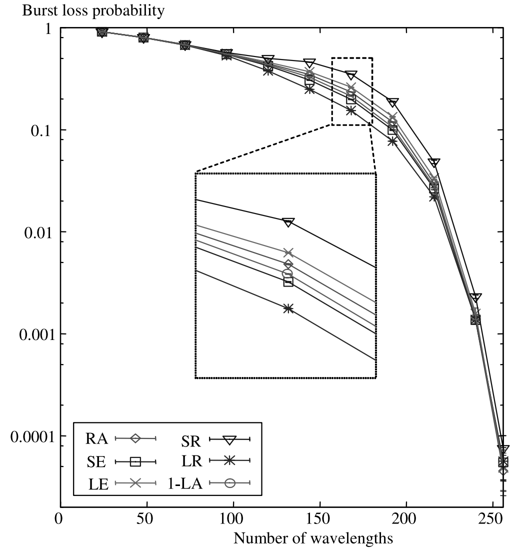
Next we consider how the number of wavelengths W affects the performance of each wavelength selection rule. Here, we set $L = 7$, $\delta = 1.0$, and $n = 1$.

Figure 9(a) shows the overall burst loss probabilities of the six selection rules for the two-way release message transmission. This figure shows that the burst loss probabilities of wavelength selection rules satisfy the inequalities (1) regardless of the number of wavelengths.

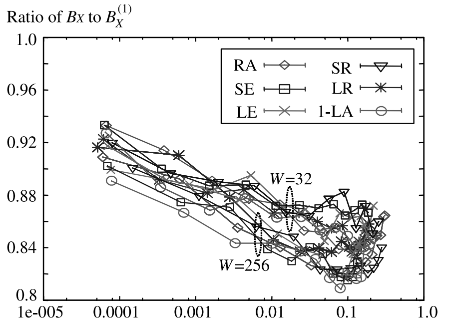
Figure 9(b) shows $B_X/B_X^{(1)}$ against $B_X^{(1)}$ in the cases of $W = 32$ and $W = 256$. From this figure, we observe that the ratio of each rule for $W = 256$ is almost the same as that for $W = 32$. This implies that the two-way release message transmission is effective regardless of the number of wavelengths. Hence, even in a network with a large number of wavelengths such as a DWDM network, the two-way release message transmission is effective.

5.1.4 Impact of Number of Nodes

We investigate how the number of nodes L affects the performance of each wavelength selection rule. Figure 10(a)



(a) Burst loss probability vs. number of wavelengths in the case of $\lambda = 120$.

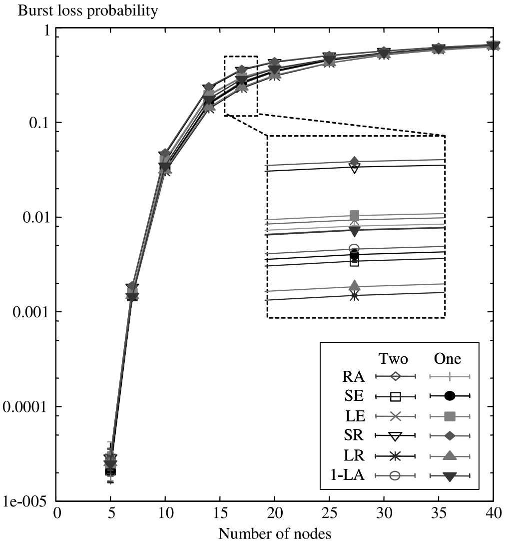


(b) $B_X/B_X^{(1)}$ for rule X in the cases of $W = 32$ and 256.

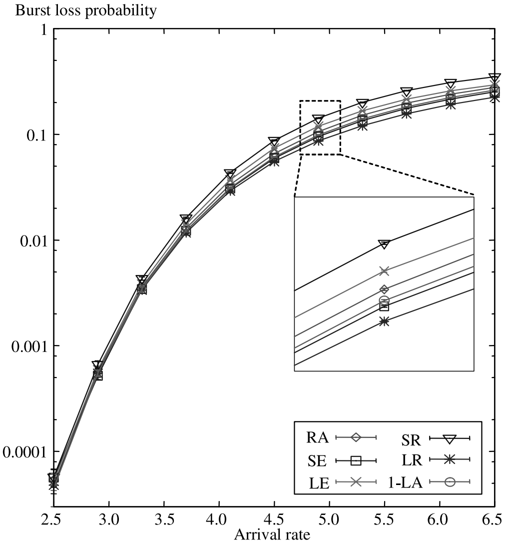
Fig. 9 Impact of number of wavelengths in a ring network ($L = 7$ and $\delta = 1.0$).

shows the overall burst loss probability against the number of nodes L in the case of $W = 32$, $\delta = 1.0$, and $n = 1$. In Fig. 10(a), the overall burst loss probability increases as the number of nodes L increases. This is because the transmission of bursts with a large number of hops is likely to fail, resulting in a large overall burst loss probability. In addition, for the case of $L = 14$, Fig. 10(b) shows the overall burst loss probability against the burst arrival rate. From these figures, we find that the burst loss probabilities of wavelength selection rules satisfy the inequalities (1) and (2) regardless of the number of nodes and burst arrival rate†.

Figure 11 shows $B_X/B_X^{(1)}$ against $B_X^{(1)}$ in the cases of $L = 7$ and 14. From this figure, we find that the ratio of each rule for $L = 14$ is smaller than that for $L = 7$. This is because the two-way release message transmission can decrease redundant wavelength reservation time at a large number of nodes. This result implies that the two-way release message transmission is significantly effective in a large scale WDM network with a large number of nodes.



(a) Overall burst loss probability vs. number of nodes.



(b) Overall burst loss probability vs. burst arrival rate in the case of $L = 14$.

Fig. 10 Impact of number of nodes in a ring network ($W = 32$ and $\delta = 1.0$).

5.1.5 Impact of n-Last Arrival (n-LA) Rule

In this subsection, we investigate how the number of wavelength indices n affects the burst loss probability of the n-LA rule.

Figure 12 shows the burst loss probability against the number of wavelength indices. Here, we set $L = 7$, $W = 32$, $\delta = 1.0$, and $\lambda = 8.0$. In this figure, the burst loss probabilities of the RA, SE, and n-LA rules are plotted. Note that the blocking probabilities of the RA and SE rules are independent of the number of wavelength indices n and this

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† We found that the inequalities (1) and (2) are satisfied for all pairs of $L = 5, 10, 15, 20, 30, 40$ and $W = 8, 16, 32, 64, 128$, but these results are omitted from this paper.

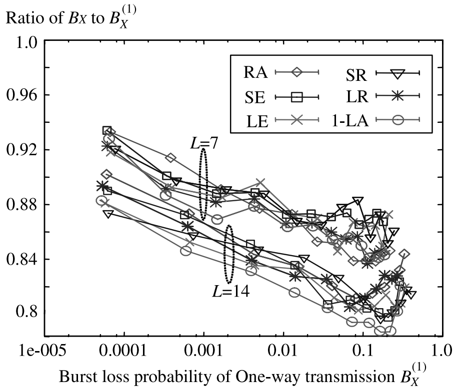


Fig. 11 Impact of number of nodes in a ring network ($W = 32$ and $\delta = 1.0$).

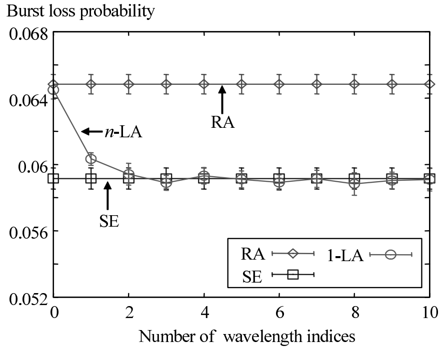


Fig. 12 Burst loss probability vs. the number of wavelength indices ($L = 7$, $W = 32$, $\delta = 1.0$, and $\lambda = 8.0$).

results in the constant burst loss probabilities against n.

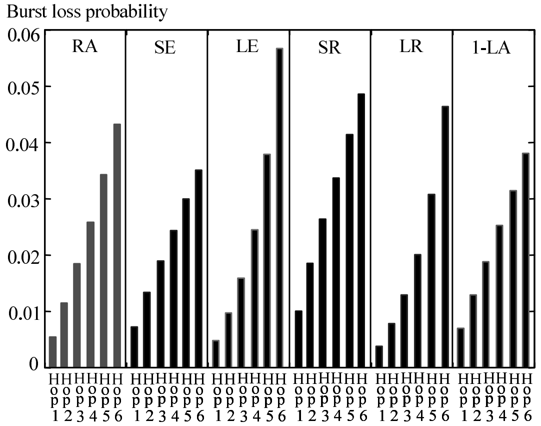
From this figure, we observe that the burst loss probability of the n-LA rule is the same as that of the RA rule in the case of $n = 0$ and that it approaches the burst loss probability of the SE rule as n increases. When the number of wavelength indices is two, the performance of n-LA is almost the same as that of the SE rule. This implies that the performance of the 1-LA rule can be improved even with a small n.

With the optimal n which achieves the minimum of the burst loss probability in the n-LA rule, the burst loss probabilities for six wavelength selection rules satisfy the following inequalities[†].

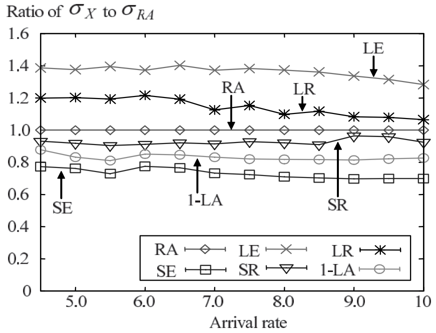
$$B_{LR} < B_{SE} = B_{n-LA} < B_{RA} < B_{LE} < B_{SR}. \tag{3}$$

5.1.6 Fairness of Burst Loss Probability in Terms of Number of Hops

In the OBS network, a burst is transmitted from its source node to its destination node using reserved wavelengths without receiving ACK message. Therefore, the burst loss probability increases as the burst traverses intermediate OBS nodes, and this causes unfairness in terms of the burst loss probability among the bursts with different numbers of hops [10]–[12].



(a) Overall loss probability of bursts with different number of hops in the case of $\lambda = 7.0$.



(b) Standard deviation of burst loss probabilities in terms of the number of hops.

Fig. 13 Fairness of burst loss probability in terms of the number of hops in a ring network ($L = 7$, $W = 32$, and $\delta = 1.0$).

Figure 13(a) shows the overall loss probabilities of bursts whose number of hops is 1 to 6 in the ring network with $L = 7$ nodes. Here, we set $W = 32$, $\delta = 1.0$, $n = 1$, and $\lambda = 7.0$. From this figure, we observe that the loss probability of bursts with a large number of hops is larger than that of bursts with a small number of hops for all selection rules, as expected. We also find that the loss probability of bursts with five hops is significantly large in the case of the LE rule. In the OBS network, the wavelength reservation time for the burst with a large number of hops is larger than that for the burst with a small number of hops. This causes a large elapsed reservation time for the burst with five hops. Therefore, in the LE rule, the burst with a large number of hops tends to be preempted.

Let σ_X denote the standard deviation of burst loss probabilities in terms of the number of hops for wavelength selection rule X. Figure 13(b) shows the ratio of σ_X for rule X to σ_{RA} for the RA rule, given by σ_X/σ_{RA}. When this ratio for the rule X is smaller (larger) than one, the X rule provides better fairness (worse unfairness) than the RA rule.

From this figure, we find that the ratios of the SE and 1-LA rules are much smaller than one. Because the small-

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[†] We investigated several cases for n from zero to 120 and found that the inequalities (3) are satisfied for all pairs of $L = 5, 10, 15, 20, 30, 40$ and $W = 8, 16, 32, 64, 128$.

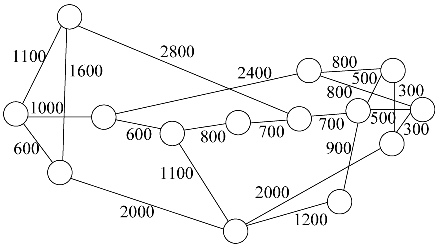


Fig. 14 NSFNET with 14 nodes.

est elapsed time does not depend on the number of hops so much, bursts are preempted regardless of the number of hops in the SE and 1-LA rule. On the other hand, in the RA rule, bursts with a large number of hops are likely to be preempted although a preempted wavelength is selected at random. This is because bursts with a large number of hops use a larger number of wavelengths. Therefore, the SE and 1-LA rules are effective than the RA rule in terms of fairness.

From the above observations, we have the following inequalities in terms of the standard deviation of burst loss probability[†].

$$\sigma_{SE} < \sigma_{1-LA} < \sigma_{SR} < \sigma_{RA} < \sigma_{LR} < \sigma_{LE}. \tag{4}$$

5.2 NSFNET

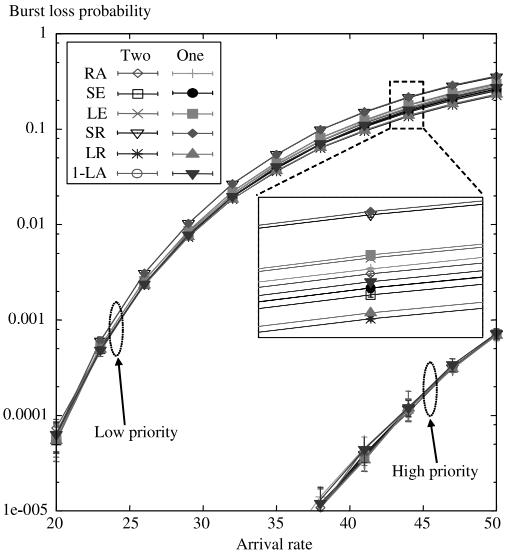
Next, we show the simulation results for NSFNET. Figure 14 shows the NSFNET with 14 nodes. In this network, all nodes have the capability of full-range wavelength conversion and distances between adjacent nodes are shown in this figure. Here, the number of wavelengths is $W = 32$, and the transmission speed of each wavelength is 1.0 Gbps.

We assume that a burst of each priority class arrives at the NSFNET according to a Poisson process with rate $\lambda/2$ and that the pair of source and destination nodes of an arriving burst is distributed uniformly. Moreover, we assume that the transmission time of a burst is exponentially distributed with the mean $D = 2.0$ ms. Here, the processing time of a control packet (SETUP or RELEASE message) at each node is $\delta = 1.0$ ms.

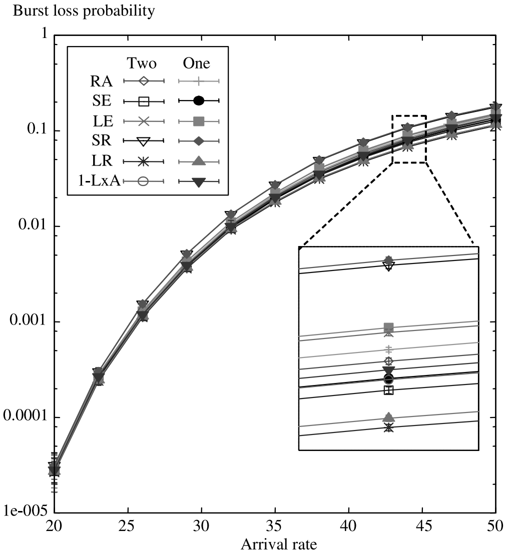
5.2.1 Impact of Burst Arrival Rate

In the NSFNET with 14 node, we consider how the burst arrival rate λ affects the performances of wavelength selection rules. Here, we set $n = 1$ for the n-LA rule.

Figures 15(a) and (b) show the burst loss probability of each priority class and the overall burst loss probability, respectively, against the burst arrival rate. As is the case with a uni-directional ring network, we find from these two figures that the two-way release message transmission is more effective than the one-way release message transmission. Therefore, the two-way release message transmission is effective for the service differentiation, regardless of the network topology.



(a) Burst loss probability of each priority class.



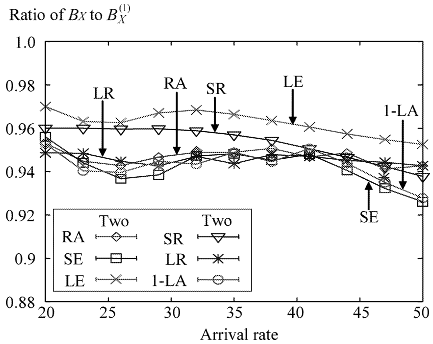
(b) Overall burst loss probability.

Fig. 15 Burst loss probability vs. burst arrival rate in NSFNET ($W = 32$ and $\delta = 1.0$).

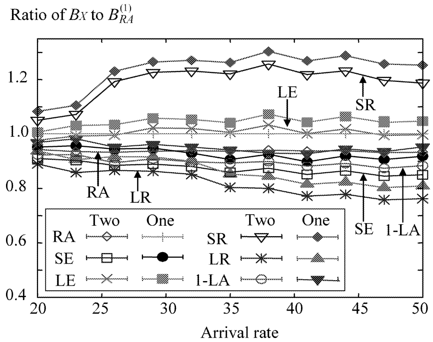
Moreover, Fig. 16(a) shows the ratio of the burst loss probability for the two-way release message transmission with rule X, B_X, to the burst loss probability for the corresponding one-way transmission $B_X^{(1)}$. Note that B_X is smaller (larger) than $B_X^{(1)}$ if the ratio $B_X/B_X^{(1)}$ is smaller (larger) than one.

From Fig. 16(a), we observe that $B_X/B_X^{(1)}$'s for all rules are smaller than one. This implies that the two-way release message transmission is more effective than the one-way transmission regardless of the wavelength selection rules. In this case, the two-way release message transmission can decrease the burst loss probability by about 3 to 7%.

[†] The inequalities (4) are satisfied for all pairs of $L = 5, 10, 15, 20, 30, 40$ and $W = 8, 16, 32, 64, 128$.

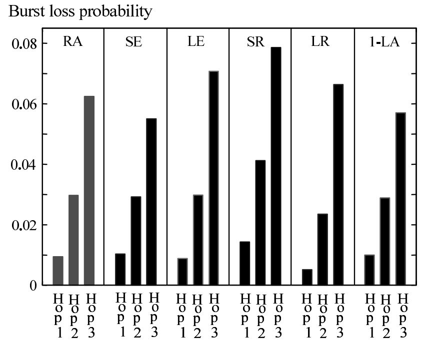


(a) Ratio of B_X to $B_X^{(1)}$ for rule X.

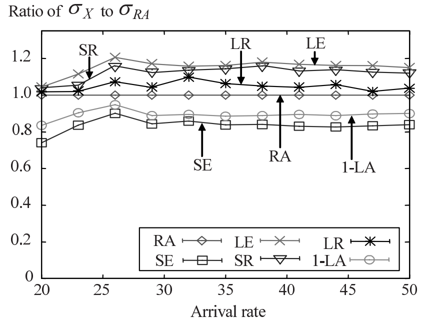


(b) Ratios of B_X and $B_X^{(1)}$ to $B_{RA}^{(1)}$ for rule X.

Fig. 16 Impact of burst arrival rate in NSFNET (W = 32 and δ = 1.0).



(a) Overall loss probability of bursts with different number of hops in the case of λ = 38.



(b) Standard deviation of burst loss probabilities in terms of the number of hops.

Fig. 17 Unfairness of burst loss probability in terms of the number of hops in NSFNET (W = 32 and δ = 1.0).

Comparing Fig. 16(a) with Fig. 7(a), the effectiveness of the two-way release message transmission in the NSFNET is smaller than that in the ring network. This is because the maximum number of hops in the NSFNET, which is three, is smaller than that in the ring network with 7 nodes. Nevertheless, the two-way release message transmission is still effective in the NSFNET.

Figure 16(b) shows the ratio of B_X ($B_X^{(1)}$) for rule X to $B_{RA}^{(1)}$ for the one-way transmission with the rule *RA*, i.e., $B_X/B_{RA}^{(1)}$ ($B_X^{(1)}/B_{RA}^{(1)}$). From this figure, we find that even in the NSFNET, the burst loss probability of each wavelength selection rule also satisfies the inequalities (1)[†]. Hence, the performance of the six rules are insensitive to network topology.

5.2.2 Fairness of Burst Loss Probability in Terms of Number of Hops

Figure 17(a) shows the overall loss probabilities of bursts whose number of hops is 1 to 3 in the same condition as Fig. 15, except that λ is equal to 38. Moreover, Fig. 17(b) shows the ratio of σ_X for rule X to σ_{RA} for the RA rule.

From these figures, we have the following inequalities in terms of the standard deviation of burst loss probability[††].

$$\sigma_{SE} < \sigma_{1-LA} < \sigma_{RA} < \sigma_{LR} < \sigma_{SR} < \sigma_{LE}. \tag{5}$$

Note that these inequalities are different from (4) in terms of SR rule. In the NSFNET, wavelength reservation time is not sensitive to the number of hops so much because the maximum number of hops is small. Therefore, in the SR rule, bursts with larger number of hops tends to be preempted. This results in the unfairness in terms of the burst loss probability. Nevertheless, the SE and 1-LA rule can improve the unfairness of the burst loss probability in terms of the number of hops.

6. Discussion

From the numerical examples, we found that the two-way release message transmission is more effective than the one-way transmission. In a large-scale DWDM network, the two-way release message transmission is significantly effective. We also found that the burst loss probabilities of wavelength selection rules satisfy (1) or (3). Moreover, the standard deviations of the burst loss probabilities in terms of the number of hops satisfy (4) or (5) depending on network topology.

From the above relationships among the six wavelength selection rules, the LR rule is the most effective in order to decrease the overall burst loss probability. On the other hand, the SE rule is the most effective in order to decrease the overall burst loss probability and to improve the unfairness in terms of the number of hops. In order to satisfy the above two requirements with a small implementation cost,

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[†] We found that the inequalities (1) are satisfied in the cases of W = 8, 16, 64, and 128.

[††] We found that the inequalities (5) are satisfied in the cases of W =8, 16, 64, and 128.

the n-LA rule is the most effective in a large scale DWDM network. If the two-way release message transmission is performed with the smallest cost, the RA rule should be used.

7. Conclusions

In this paper, we proposed the preemptive scheme with two-way release message transmission for the immediate reservation and considered the six wavelength selection rules. We evaluated the performance of the proposed scheme with simulation, and numerical examples showed that our scheme is effective in a large scale DWDM network. We also observed that the burst loss probabilities of the selection rules satisfy (1) to (5). From these inequalities, the n-LA rule is the most effective in order both to decrease the overall burst loss probability and to improve the unfairness in terms of the number of hops with small cost.

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