IEICE TRANS. COMMUN., VOL.E91–B, NO.3 MARCH 2008

PAPER

Intermediate-Hop Preemption to Improve Fairness in Optical Burst Switching Networks

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SUMMARY In optical burst switching (OBS) networks, burst with different numbers of hops experience unfairness in terms of the burst loss probability. In this paper, we propose a preemptive scheme based on the number of transit hops in OBS networks. In our proposed scheme, preemption is performed with two thresholds; one is for the total number of hops of a burst and the other is for the number of transit hops the burst has passed through. We evaluate the performance of the scheme by simulation, and numerical examples show that the proposed scheme improves the fairness among the bursts with different numbers of hops, keeping the overall burst loss probability the same as that for the conventional OBS transmission without preemption.

key words: *optical burst switching, preemption, fairness, immediate reservation, burst loss probability, number of hops*

1. Introduction

Optical burst switching (OBS) has been considered as one of the promising technologies for the next-generation optical Internet based on wavelength division multiplexing (WDM). In OBS networks, a burst consisting of multiple IP packets is transmitted with wavelengths from its source to destination nodes. The wavelengths are reserved by the corresponding control packet. In one-way reservation, a burst is transmitted to its destination node by its source node without receiving ACK message, while in two-way reservation, it is transmitted after receiving ACK message. In this paper, we focus on OBS networks based on one-way reservation due to its lower end-to-end latency.

For the one-way reservation, there are two types of wavelength reservation protocols; delayed reservation protocol and immediate reservation protocol. In the delayed reservation protocol such as JET [1], [2], a control packet has information about the burst arrival time for each transit node. Based on the information, a wavelength can be reserved so as to utilize the wavelength from the burst arrival epoch. On the other hand, in the immediate reservation protocol such as JIT [3], [4], a control packet has no information about the burst arrival time. Therefore, the control packet has to reserve a wavelength immediately when it arrives at each node. As a result, in the immediate reservation, wavelengths are utilized less effectively than those in the delayed reservation. However, the immediate reservation can be implemented more easily than the delayed reservation due to a simple wavelength reservation process.

In OBS networks, regardless of whether delayed reservation or immediate reservation is used, the burst transmission succeeds only when the corresponding control packet can reserve a wavelength at every intermediate node. 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 [5]. To improve the fairness, several schemes have been proposed in the literature.

For the delayed reservation protocol, a hop-by-hop priority-increasing scheme was proposed so as to improve the fairness [6]. This method gives an extra offset time to the burst with a small number of remaining hops using fiber delay lines (FDLs). With this method, the loss probability of a burst with a small number of remaining hops decreases. As a result, the fairness in terms of the burst loss probability is improved.

In addition, in the optical composite burst switching (OCBS) that discards the initial part of a burst until a wavelength becomes free on the output fiber (head-dropping), a burst dropping technique based on the number of hops was proposed [7]. In this method, a burst in transmission can perform head-dropping at a congested node if the estimated length of the remaining part of the burst after preemption is greater than or equal to a pre-specified threshold for each number of hops. This method decreases (increases) the loss probability of packets with a large (small) number of hops, improving the unfairness of the loss probability on packet level.

On the other hand, for the immediate reservation, a balanced just-in-time scheme (BJIT) and a prioritized random-early-discard (PRED) scheme were proposed to improve the fairness [8]. In BJIT, as a burst is transmitted from one hop to the next, the number of wavelengths available for the burst gradually increases. The burst with a larger number of transit hops can use more wavelengths than that with a smaller number of transit hops. Because the loss probability of burst with a large number of transit hops becomes small, this method can improve the fairness of the burst loss probability. However, even if there are idle wavelengths at a node, the burst with a small number of transit hops may not use the idle wavelengths. Therefore, the BJIT increases the overall burst loss probability. PRED is based on proactive

Manuscript received February 23, 2007.
Manuscript revised July 6, 2007.

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DOI: 10.1093/ietcom/e91–b.3.710

burst dropping with a discarding probability that decreases as the burst hop-number increases. This scheme discards a newly incoming burst according to probabilistic parameters at the source network access station, improving the fairness of the burst loss probability. Nevertheless, it is difficult to determine the optimal parameters a priori.

In [9], [10], we proposed the last-hop preemption based on the number of hops. In the last-hop preemption, if a burst whose number of hops between its source and destination nodes is larger than or equal to a pre-specified value fails in reserving a wavelength at its last hop, the burst can preempt the other burst transmission. In the method, the number of preemptions through a burst transmission is limited to one at its last hop. Because multiple preemptions make the overall burst-loss probability large [11], the last-hop preemption does not increase the overall burst loss probability so much. However, it does not work well for the OBS network with a large number of transmission hops because a burst can only preempt a burst transmission at its last hop.

In this paper, in order to improve the fairness for the immediate reservation, we propose the intermediate-hop preemption based on the number of transit hops. In the intermediate-hop preemption, a burst in transmission can preempt the other burst transmission at an intermediate hop in congestion based on the number of transit hops. It is expected that the intermediate-hop preemption can provide better fairness performance than the last-hop preemption for the OBS network with a large number of transmission hops. Here, the proposed method is available not only for the immediate reservation but also for the delayed reservation. However, in this paper, we focus only on the immediate reservation. This is because as far as the authors know, fairness improving methods for the immediate reservation have not been proposed except for the methods in [8]–[10], and the proposed method is more effective for the immediate reservation than the delayed reservation. We evaluate by simulation the loss performance of the intermediate-hop preemption for a uni-directional ring network and an ARPA2 network.

The rest of the paper is organized as follows. Section 2 summarizes the last-hop preemption and Sect. 3 describes the intermediate-hop preemption based on the number of transit hops. Some numerical examples are shown in Sect. 4. Finally, conclusions are presented in Sect. 5.

2. Last-Hop Preemption

In this section, we summarize the last-hop preemption based on the number of hops between source and destination nodes [9], [10]. In the following, we assume the immediate reservation with estimated release [3] for signaling protocol.

In the last-hop preemption, a burst whose number of transmission hops is larger than or equal to α can preempt a burst transmission at its last hop in congestion. If α is set to a small value, the number of bursts which can preempt a burst transmission increases. On the other hand, if α is set to a large value, the number of bursts which can preempt a burst transmission decreases.

When the control packet eventually arrives at the last-hop node and finds that all wavelengths are already used, the wavelength reserved by the burst whose transit-hop number is smaller than that of the newly arriving burst is preempted. If there exist some bursts which satisfy this condition, the burst with the smallest-hop number is chosen for preemption. If there exists no wavelength reserved for the burst whose hop-number is smaller than that of the arriving burst, the control packet fails in reserving a wavelength and this arriving burst is lost.

Let h denote the number of hops of the burst just generated at its ingress edge node. There are three cases of preemption in terms of h. Figure 1 shows the three cases when α is equal to 4.

(i) $h < \alpha$ (Fig. 1(i)).
The burst is not allowed to preempt other burst transmission at its last-hop node. Therefore, this burst is lost similarly to the conventional immediate reservation when congestion occurs at an intermediate node.

(ii) $h \geq \alpha$ and congestion occurs at an intermediate node, not the last-hop node (Fig. 1 (ii)).
The burst is allowed to preempt a burst transmission at its last-hop node, however, it cannot preempt any burst transmission at any intermediate node in congestion. The burst is lost at the congested node due to the failure of wavelength reservation.

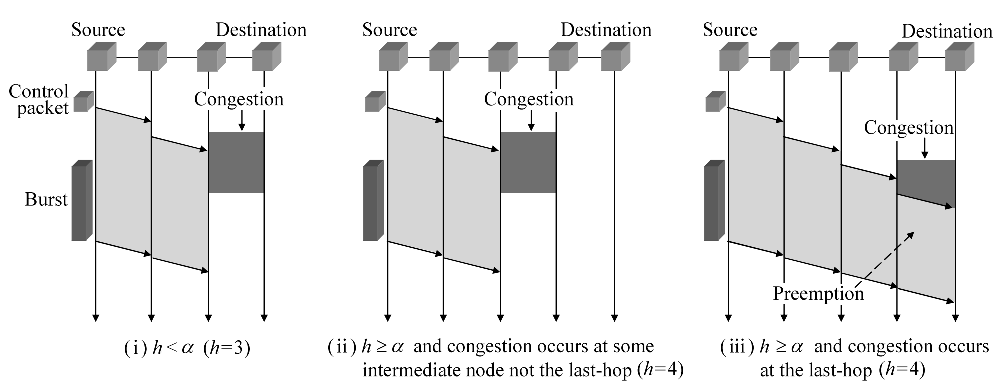


Fig. 1 Last-hop preemption based on the number of hops (α = 4).

(iii) $h \geq \alpha$ and congestion occurs at the last-hop node (Fig. 1 (iii)).
The burst can preempt a burst transmission at the last-hop node. When congestion occurs only at the last-hop node and there exist some wavelengths reserved by the bursts whose hop-numbers are smaller than h, the newly arriving burst succeeds in preemption and is eventually transmitted to its destination.

The last-hop preemption, however, does not work well for the OBS network with a large number of transmission hops. To overcome the drawback of the last-hop preemption, we consider the intermediate-hop preemption in the following.

3. Intermediate-Hop Preemption Based on the Number of Hops

The intermediate-hop preemption works with two thresholds: α and β. α is the threshold for the total hop-number of a burst, while β is for the transit hop-number of the burst at an intermediate node in congestion. The transit hop-number is defined as the sum of one and the number of hops between the source and congested nodes. Figure 2 illustrates the case where the burst is in transmission at the first intermediate node in congestion. In this case, the total hop-number of the burst is three and its transit-hop number is two.

A burst whose total-hop number is greater than or equal to α is allowed to preempt a burst transmission at a congested node if the transit-hop number is greater than or equal to β. Note that $\alpha \geq \beta$. Here, the number of preemptions through a burst transmission is limited to one. Therefore, it is expected that the intermediate-hop preemption does not increase the overall burst loss probability so much, as well as the last-hop preemption.

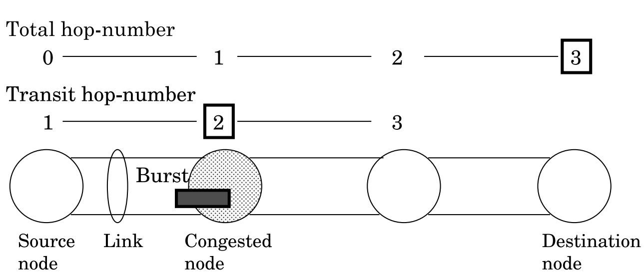


Fig. 2 Total and transit hop-numbers.

If α is set to a small value, the number of bursts which can preempt a burst transmission in congested node increases, however, frequent preemption may degrade the throughput performance. On the other hand, if β is set to one, the burst can preempt a burst transmission at the first hop. When β becomes large, the number of nodes at which the burst can preempt a burst transmission decreases. We will discuss the efficient setting of α and β in Section 4.

When a new burst is generated at its ingress edge node, the burst is allowed to preempt a burst transmission if the total hop-number of the burst is greater than or equal to α. This step is performed at the ingress edge node when the burst's offset time is calculated, and the resulting information is included in the associated control packet.

When the control packet arrives at an intermediate node and there exist available wavelengths, one of the wavelengths is reserved and then the control packet is transmitted to the next OBS node. If the control packet finds that all wavelengths are already used, the control packet can preempt the wavelength reserved by the burst whose total hop-number is smaller than that of the newly arriving burst. If there exist some bursts which satisfy this condition, the wavelength reserved by the burst with the smallest-hop number is chosen for preemption. If the preempted burst has also reserved wavelengths at other nodes, the wavelengths are released with a timer or another control packet. Here, the intermediate-hop preemption requires that the OBS node keeps the hop-number information associated with the reserved wavelength. Note that the amount of information stored in the OBS node is slightly larger than that of the last-hop preemption.

If there exists no wavelength reserved for the burst whose total hop-number is smaller than that of the arriving burst, its control packet fails in reserving a wavelength and this arriving burst is lost. It is expected that the transmission of bursts with a large number of hops is more likely to succeed than the conventional immediate reservation.

Let h denote the number of hops of the burst just generated at its ingress edge node. We define n as the number of transit hops of the burst at an intermediate node in con-

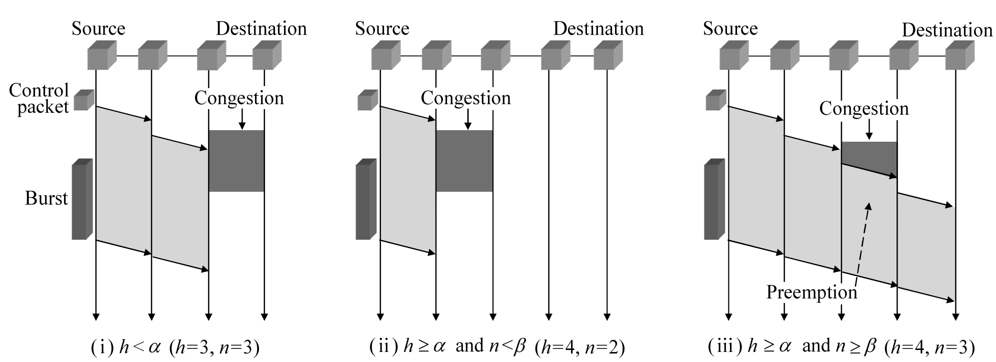


Fig. 3 Intermediate-hop preemption based on the number of transit hops ($\alpha = 4, \beta = 3$).

gestion. There are three cases of the preemption in terms of h and n. Figure 3 shows the three cases when α is equal to 4 and β is equal to 3.

(i) $h < \alpha$ (Fig. 3(i)).
The burst is not allowed to preempt other burst transmission at any node. Therefore, this burst is lost at the node in congestion similarly to the conventional immediate reservation.

(ii) $h \geq \alpha$ and $n < \beta$ (Fig. 3 (ii)).
The burst is allowed to preempt a burst transmission, however, it cannot preempt any burst transmission at the node such that $n < \beta$. The burst is lost at the congested node due to the failure of wavelength reservation.

(iii) $h \geq \alpha$ and $n \geq \beta$ (Fig. 3 (iii)).
The burst is allowed to preempt a burst transmission at the node such that $n \geq \beta$. When congestion occurs at the node and there exist some wavelengths reserved by the bursts whose hop-numbers are smaller than h, the newly arriving burst succeeds in preemption and is transmitted to the next OBS node.

4. Numerical Examples

In this section, we investigate by simulation the performance of the intermediate-hop preemption. First, we consider a uni-directional ring network, and then we consider an ARPA2 network.

4.1 Ring Network

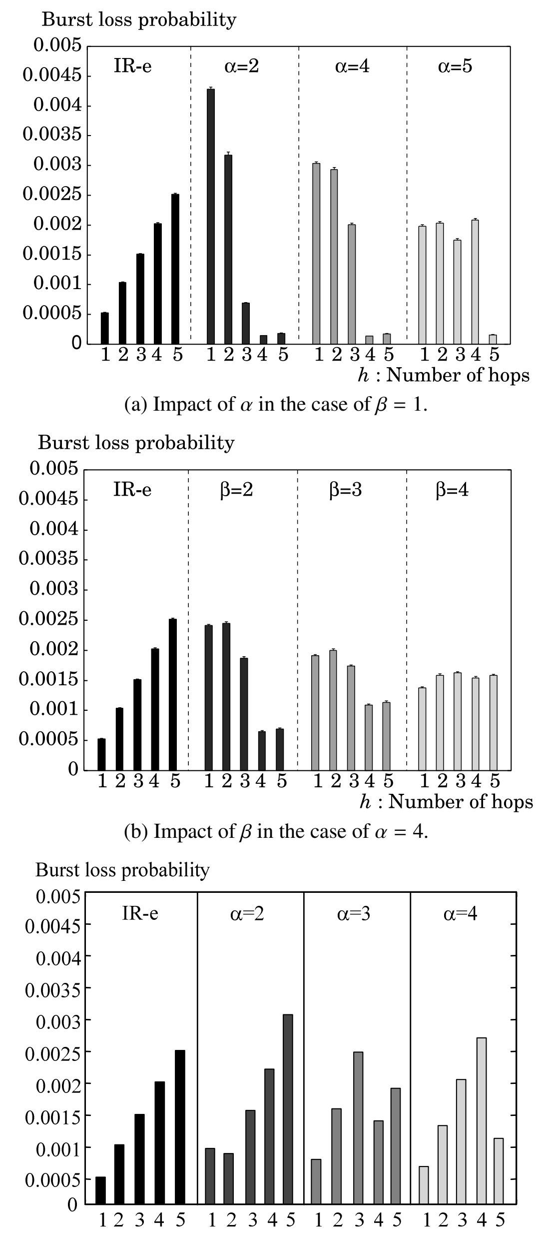
In this subsection, we evaluate the performance of the intermediate-hop preemption in the uni-directional ring network with N nodes. Here, each node has a full-range wavelength conversion capability and the distance between adjacent nodes is 200 km. In this network, we assume that the number of wavelengths is W and that the transmission speed of a wavelength is 10 Gbps. We also assume that a burst arrives at each node according to a Poisson process with rate λ and that the burst size is exponentially distributed with the mean 5 Mbytes. The destination node of a burst is chosen by equal probability 1/(N-1), and the arrival rate of burst of each hop-number transmission is equally set to $\frac{N}{N-1}\lambda$. The processing time of a control packet at each node is 1.0 ms.

At each node, an available wavelength is selected at random when a control packet arrives at a node. The intermediate-hop preemption can be performed only when all W wavelengths have been utilized. If there exist multiple bursts to be preempted, one of them is randomly selected for preemption. We also consider the immediate reservation with estimated release (IR-e), and show the simulation results for the IR-e with and without the intermediate-hop preemption.

4.1.1 Impacts of α and β on Fairness

We consider how α and β affect the loss probabilities of bursts with different numbers of hops. Figures 4 and 5 shows the impacts of α and β on the burst loss probability in the cases of $N = 6$ and 9, respectively. In Fig. 4, the number of wavelengths is $W = 16$ and λ is 1/3000. On the other hand, in Fig. 5, the number of wavelengths is $W = 16$ and λ is 1/6000.

Figure 4(a) shows the burst loss probability with $\beta = 1$ for the intermediate-hop preemption in the case of $N = 6$. In our proposed method, when β is equal to one, a burst whose

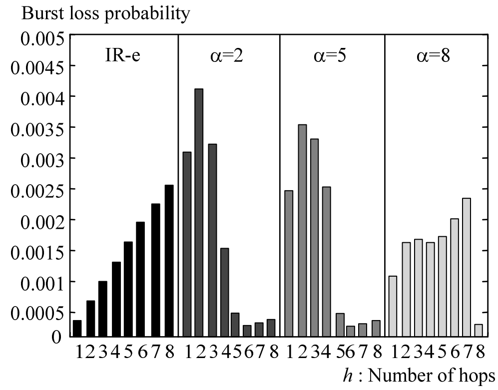


(a) Impact of α in the case of $\beta = 1$.

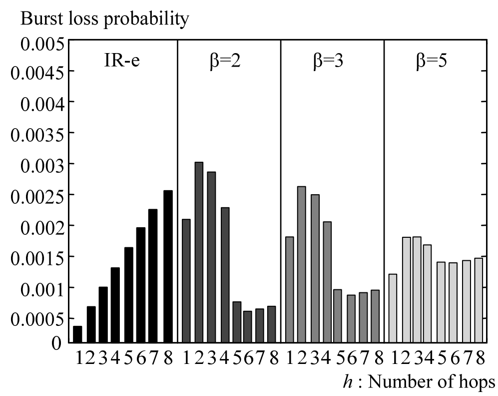
(b) Impact of β in the case of $\alpha = 4$.

(c) Effect of the first rule in the intermediate-hop preemption.

Fig. 4 Impacts of α and β on fairness in the case of $N = 6$.



(a) Impact of α in the case of $\beta = 1$.



(b) Impact of β in the case of $\alpha = 4$.

Fig. 5 Impacts of α and β on fairness in the case of $N = 9$.

number of transmission hops h is larger than or equal to α can preempt a burst transmission once at any intermediate node. The burst with a small number of hops h is likely to be preempted.

From the case of $\alpha = 2$ in this figure, we find that the burst loss probability for $h = 1$ is significantly larger than that for the IR-e. This is because the burst with $h = 1$ cannot preempt a burst transmission and is preempted freequently by bursts with $h \geq 2$. On the other hand, the burst with $h \geq 4$ can preempt a burst transmission at a congestion node and it is rarely preempted by other bursts. Therefore, the burst loss probability for $h \geq 4$ is significantly smaller than that for the IR-e. Please note that the bursts with $h = 4$ and 5 can preempt a burst transmission similarly. In this case, the loss probability of the bursts with $h = 4$ is likely to be smaller than that of the bursts with $h = 5$ due to a small number of transmission hops, as shown in the case of the IR-e.

We also find that the burst loss probability for $h = 2$ is larger than that for the IR-e even though the bursts with $h = 2$ can preempt a burst transmission. This is because the number of bursts with $h = 2$ which are preempted by other bursts is larger than the number of bursts which preempt a burst transmission. From the same reason, the burst loss probability for $h = 3$ is larger than that for $h \geq 4$.

As α becomes large, the number of bursts which can preempt a burst transmission at a congested node becomes small. When α is equal to five, only the burst loss probability for $h = 5$ is significantly small. This causes a small loss probability for burst with a small number of hops. Note that the burst loss probability for $h = 3$ is smaller than that for $h = 4$. When $\alpha = 5$, the bursts with $h = 3$ and 4 can not preempt a burst transmission at a congested node regardless of β. In addition, those bursts are less preempted than the bursts with a small number of hops. The loss probability of the bursts with $h = 3$ is likely to be smaller than that of the bursts with $h = 4$ due to a small number of transmission hops.

Figure 4(b) shows the burst loss probability for each β in the case of $\alpha = 4$. When $\alpha = 4$, only the bursts with $h =$ 4 and 5 can preempt a burst transmission at their congested node if the transit hop-number of the burst is greater than or equal to β. From this figure, we find that the burst loss probabilities for $h = 4$ and 5 (for $h = 1$, 2, and 3) become large (small) as β becomes large. This is because large β gives bursts with $h = 4$ and 5 a small number of preemptions.

From these two figures, we find that the unfairness among bursts with different hop-numbers is significantly improved when α and β is well tuned.

As shown in the previous Sect. 3, the intermediate-hop preemptions is comprised of two rules. According to the first rule, a burst preempts a burst transmission based on (α, β), and according to the second rule, a burst transmission with the smallest number of transmission hops is preempted.

Figure 4(c) shows the effect of the first rule in the intermediate-hop preemption for the case of Fig. 4(a). Note that we assume that the preempted burst is selected at random without the second rule. From this figure, we find that the burst loss probability for $h = 5$ is much large than that in Fig. 4(a). Even when α is five, i.e., only a burst whose number of hops is five can preempt a burst transmission, the intermediate-hop preemption can not decrease the burst loss probability for hop 5 significantly. This is because a burst whose number of hops is large can be preempted by other bursts. As β becomes large, a burst whose number of hops is large preempts a burst transmission less frequently, resulting in a large burst loss probability for $h = 5$ (See Fig. 4(b)). Therefore, the fairness of the burst loss probability is not sufficiently improved only with the first rule of the intermediate-hop preemption.

Figure 5 shows the impacts of α and β on fairness in the case of $N = 9$. From Fig. 5, we also find that the impacts of α and β in the case of $N = 9$ are almost the same as those of $N = 6$. Therefore, the impacts of α and β are not greatly sensitive to the number of nodes.

Let H denote the maximum number of hops in a network and $P^{(i)}_{loss}$ $(i = 1, \cdots, H)$ the loss probability of burst with $h = i$. We define $P_{overall}$ as the overall burst loss probability. We also define δ_{inter} (δ_{IR-e}) as the standard deviation of burst loss probabilities in terms of the number of hops for the intermediate-hop preemption (the IR-e). Here, δ_A ($A = inter, IR - e$) is given by

$$\delta_A = \sqrt{\sum_{i=1}^{H} (P^{(i)}_{loss} - P_{overall})^2 / H}. \tag{1}$$

Table 1 Standard deviation ratio (N = 6 and W = 16).

(α, β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
IR-e	1	1.5250×10^{-3}
(2, 1)	2.4495	1.6949×10^{-3}
(2, 2)	1.4842	1.6312×10^{-3}
(3, 1)	2.3846	1.6857×10^{-3}
(3, 2)	1.4686	1.6284×10^{-3}
(3, 3)	0.71333	1.5777×10^{-3}
(4, 1)	1.8319	1.6564×10^{-3}
(4, 2)	1.1426	1.6149×10^{-3}
(4, 3)	0.55565	1.5766×10^{-3}
(4, 4)	0.12502	1.5441×10^{-3}
(5, 1)	1.0487	1.6030×10^{-3}
(5, 2)	0.68347	1.5804×10^{-3}
(5, 3)	0.43734	1.5598×10^{-3}
(5, 4)	0.43156	1.5421×10^{-3}
(5, 5)	0.66581	1.5279×10^{-3}

When δ_{inter} is smaller (larger) than δ_{IR-e}, i.e., when $\delta_{inter}/\delta_{IR-e}$ is smaller (larger) than one, the intermediate-hop preemption provides better (less) fairness than the conventional method. On the other hand, when $\delta_{inter}/\delta_{IR-e} = 1$, both the performances are the same.

Table 1 shows $\delta_{inter}/\delta_{IR-e}$'s and $P_{overall}$'s for all (α, β)'s in the case of $N = 6$ and $W = 16$. We observe from Table 1 that $\delta_{inter}/\delta_{IR-e}$ greatly depends on (α, β). When (α, β) is (4, 4), the intermediate-hop preemption achieves the minimum of $\delta_{inter}/\delta_{IR-e}$. A remarkable point is that, even in the case of (4, 4), $P_{overall}$ does not increase so much. This is because the number of preemptions through a burst transmission is limited to one. Therefore, the intermediate-hop preemption can improve the fairness of burst loss probability. In addition, we investigated the case of $\lambda = 1/2400$ and observed that (α, β) = (4, 4) also achieves the minimum.

4.1.2 The Determination of (α, β)

In this subsection, we investigate which (α, β) provides the minimum of $\delta_{inter}/\delta_{IR-e}$.

First, we consider how the number of wavelengths in a fiber affects the improvement of the difference among the burst loss probabilities of different numbers of hops. We assume that the number of nodes is $N = 6$. We consider the two cases of W = 64 and 128, and, λ is set to 1/450 for W = 64, and 1/192 for W = 128. Note that with this setting, the overall burst loss probability for W = 64 is almost the same as that for W = 128. Table 2 shows the $\delta_{inter}/\delta_{IR-e}$ of the IR-e and the top three $\delta_{inter}/\delta_{IR-e}$'s in ascending order for the intermediate-hop preemption. The corresponding overall burst loss probability $P_{overall}$ is also presented.

From the table, we observe that (α, β) = (4, 4) achieves the minimum of $\delta_{inter}/\delta_{IR-e}$ for both W = 64 and 128 (We also confirmed that (α, β) = (4, 4) achieves the minimum for both cases with different λ.). Note that $P_{overall}$'s for the three cases are almost the same as that for the IR-e. This implies that the intermediate-hop preemption does not degrade the overall loss performance in comparison with the IR-e. We also observe from Table 2 that $\delta_{inter}/\delta_{IR-e}$ of (α, β) = (4, 4) for W = 128 is larger than that for W = 64. Note that the offered load in the case of W = 128 is larger than that of W = 64. When the offered load is large, the number of bursts with a small hop-number increases and those bursts are more likely to be preempted by the bursts with a large hop-number, resulting in large unfairness.

Table 2 Standard deviation ratio for IR-e and top three standard deviation ratios for the proposed method (N = 6 and W = 64, 128).

W	(α, β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
64	IR-e	1	1.4124×10^{-3}
	(4, 4)	0.35352	1.4301×10^{-3}
	(5, 4)	0.43284	1.4250×10^{-3}
	(5, 3)	0.57044	1.4458×10^{-3}
128	IR-e	1	1.8979×10^{-3}
	(4, 4)	0.44632	1.9353×10^{-3}
	(5, 4)	0.45353	1.9284×10^{-3}
	(5, 5)	0.63575	1.9056×10^{-3}

Table 3 Standard deviation for IR-e and top three standard deviation ratios for the proposed method (N = 9).

W	(α, β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
16	IR-e	1	1.4882×10^{-3}
	(6, 5)	0.27027	1.5290×10^{-3}
	(5, 5)	0.28043	1.5274×10^{-3}
	(6, 6)	0.35839	1.5068×10^{-3}
64	IR-e	1	1.7878×10^{-3}
	(6, 6)	0.30519	1.8196×10^{-3}
	(7, 5)	0.36884	1.8408×10^{-3}
	(6, 5)	0.38529	1.8509×10^{-3}
128	IR-e	1	1.2499×10^{-3}
	(6, 6)	0.47096	1.2742×10^{-3}
	(7, 6)	0.49226	1.2725×10^{-3}
	(7, 5)	0.57119	1.2895×10^{-3}

Next, we consider how the number of nodes affects the improvement of the difference among the burst loss probabilities of different numbers of hops. We assume that the number of nodes is $N = 9$. We consider three cases of W = 16, 64, and 128. λ is set to 1/5400 for W = 16, 1/774 for W = 64, and 1/342 for W = 128. Table 3 shows the $\delta_{inter}/\delta_{IR-e}$ of the IR-e and the top three $\delta_{inter}/\delta_{IR-e}$'s for the intermediate-hop preemption in cases of W = 16, 64 and 128.

From Table 3, we observe that (α, β) = (6, 5) achieves the minimum of $\delta_{inter}/\delta_{IR-e}$ when W = 16, and that $P_{overall}$'s for the intermediate-hop preemption are slightly larger than that for the IR-e. When W = 64 and 128, however, (α, β) = (6, 6) achieves the minimum of $\delta_{inter}/\delta_{IR-e}$, keeping $P_{overall}$ almost the same as the IR-e. Note that (6, 6) in W = 16 does not provide the minimum of $\delta_{inter}/\delta_{IR-e}$ but provide a better value than other (α, β)'s except for (6, 5) and (5, 5). Therefore, (6, 6) is one of recommended values for the ring network with N = 9 irrespective of W.

From the above results, we consider which (α, β) significantly improves unfairness. Let $\bar{h}$ denote the mean total

Table 4 Standard deviation for IR-e and top three standard deviation ratios for the proposed method (N = 12 and 15).

$N = 12$			
W	(α,β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
16	IR-e	1	1.3925×10^{-3}
	(7, 7)	0.31817	1.4290×10^{-3}
	(8, 7)	0.34160	1.4302×10^{-3}
	(8, 6)	0.34291	1.4490×10^{-3}
64	IR-e	1	1.3664×10^{-3}
	(8, 7)	0.25493	1.4083×10^{-3}
	(7, 7)	0.25577	1.4079×10^{-3}
	(8, 8)	0.35106	1.3917×10^{-3}
128	IR-e	1	1.7372×10^{-3}
	(8, 8)	0.41503	1.7744×10^{-3}
	(9, 7)	0.42830	1.7942×10^{-3}
	(7, 7)	0.46105	1.7998×10^{-3}

$N = 15$			
W	(α,β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
16	IR-e	1	1.4861×10^{-3}
	(8, 8)	0.35092	1.5415×10^{-3}
	(9, 8)	0.35849	1.5430×10^{-3}
	(9, 9)	0.41024	1.5265×10^{-3}
64	IR-e	1	2.2820×10^{-3}
	(9, 9)	0.26187	2.3465×10^{-3}
	(10, 8)	0.27482	2.3723×10^{-3}
	(10, 9)	0.28171	2.3481×10^{-3}
128	IR-e	1	1.1968×10^{-3}
	(9, 9)	0.37259	1.2310×10^{-3}
	(10, 9)	0.37658	1.2314×10^{-3}
	(10, 10)	0.43031	1.2205×10^{-3}

hop-number of a burst. Then we have $\bar{h} = 3$ for $N = 6$ and $\bar{h} = 4.5$ for $N = 9$. Note that the minimum of $\delta_{inter}/\delta_{IR-e}$ is achieved when (α, β) = (4, 4) for $N = 6$ with $\bar{h} = 3$, and when (α, β) = (6, 6) for $N = 9$ with $\bar{h} = 4.5$. Therefore we can conjecture that

$$\alpha = \beta = < \bar{h} + 1 >, \tag{2}$$

where $< x >$ denote the rounded number of x, provides the minimum of $\delta_{inter}/\delta_{IR-e}$ or a value close to the minimum.

Table 4 shows the $\delta_{inter}/\delta_{IR-e}$'s and $P_{overall}$'s for the ring networks with N = 12 and 15. As for the number of wavelengths in a fiber, W = 16, 64 and 128 are considered. For each (N, W), we compare the top-three values of $\delta_{inter}/\delta_{IR-e}$ for the intermediate-hop preemption with the IR-e, except for (N, W) = (12, 128) and (15, 16). In the cases of (N, W) = (12, 128) and (15, 16), the top-two values of $\delta_{inter}/\delta_{IR-e}$ and the one with the recommended (α, β) are compared. Note that the recommended (α,β)'s, which are obtained from (2), are (7, 7) for N = 12 and (9, 9) for N = 15. The value of λ for each (N, W) is also presented in Table 5.

First, we consider the cases for N = 12. Note that the recommended (α,β) for N = 12 is (7, 7) from (2). When (N, W) = (12, 16), the recommended (α, β) = (7, 7) achieves the minimum of $\delta_{inter}/\delta_{IR-e}$. When ($N$, W) = (12, 64), (α, β) = (7, 7) does not provide the minimum of $\delta_{inter}/\delta_{IR-e}$ but it provides the second smallest $\delta_{inter}/\delta_{IR-e}$, and the difference between the first and second smallest $\delta_{inter}/\delta_{IR-e}$'s is quite small. When (N, W) = (12, 128), (α, β) = (7, 7) does not also provide the minimum but the difference among the three $\delta_{inter}/\delta_{IR-e}$'s are significantly small.

Table 5 The values of λ for (N, W).

$N \setminus W$	16	64	128
12	1/8400	1/1200	1/516
15	1/10500	1/1650	1/735

Next, we focus on the cases for N = 15. Note that the recommended (α, β) for N = 15 is (9, 9) from (2). When (N, W) = (15, 16), the $\delta_{inter}/\delta_{IR-e}$ of (α, β) = (9, 9) is the largest among the three (α,β)'s, and the difference between the minimum value and that of (α, β) = (9, 9) is not small. However, (α,β) = (9, 9) achieves the minimum of $\delta_{inter}/\delta_{IR-e}$ in both (N, W) = (15, 64) and (15, 128). Note that $P_{overall}$'s are almost the same for any (N, W).

From the above results, the (α, β) obtained from (2) is quite useful for the ring network in which the number of nodes is large.

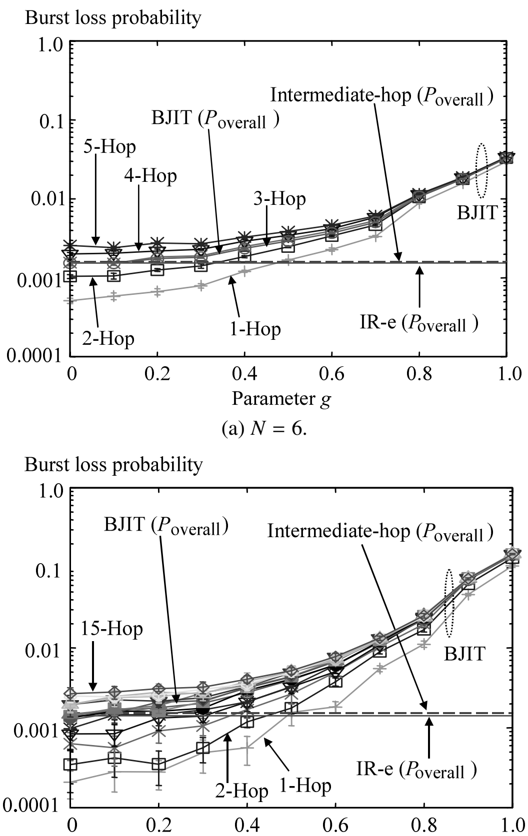
4.1.3 Comparison of the Intermediate-Hop Preemption and BJIT, PRED

In this subsection, we compare the intermediate-hop preemption with the BJIT and PRED. The readers are referred to [6] for details of the BJIT and PRED.

First, we compare the intermediate-hop preemption with the BJIT. In the BJIT, the parameter g significantly affects the performance of the BJIT. As g becomes large, the number of wavelengths which are available for bursts with a small number of transit hops becomes small. A large g increases (decreases) the loss probability of bursts with a small (large) number of transmission hops. As a result, this large g improves the unfairness of the burst loss probability in terms of the number of hops.

Figures 6(a) and (b) show the overall loss probabilities of the intermediate-hop preemption, BJIT, and IR-e against g in the cases of N = 6 and 15, respectively. Here, the number of wavelengths is W = 16 and λ is set to 1/3000 (1/5400) in the case of N = 6 (N = 15). In the case of N = 6 (N = 15), $P_{overall}$ of the intermediate-hop preemption is obtained with the recommended (α, β) = (4, 4) ((α, β) = (9, 9)). Note that $P_{overall}$'s of the intermediate-hop preemption and the IR-e are independent of g and this results in constant $P_{overall}$'s. Moreover, in these figures, the burst loss probability of the BJIT for each hop-number is illustrated.

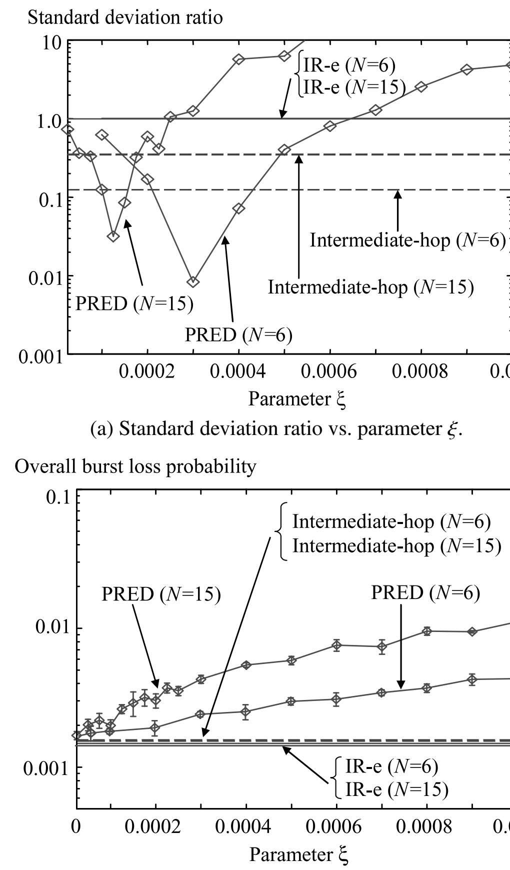
From Figs. 6(a) and (b), we observe that the burst loss probabilities of the BJIT converge as the parameter g becomes large. This implies that a large g can improve the unfairness of the burst loss probability, as it is expected. However, as g becomes large, the overall burst loss probability of the BJIT also becomes large. Comparing $P_{overall}$



(a) N = 6.

(b) N = 15.

Fig. 6 Burst loss probability vs. parameter g of the BJIT.



(a) Standard deviation ratio vs. parameter ξ.

(b) Burst loss probability vs. parameter ξ.

Fig. 7 Impact of the parameter ξ of the PRED.

of the BJIT with that of the intermediate-hop preemption, $P_{overall}$ of the BJIT method is much larger than that of the intermediate-hop preemption. Therefore, the intermediate-hop preemption is effective in order to improve the unfairness of the burst loss probability, keeping the overall burst loss probability unchanged.

Next, we compare the intermediate-hop preemption with the PRED. In the PRED, a burst whose number of transmission hops is i is discarded at its source node with probability p_i, while the burst is transmitted from the source node with probability $1 - p_i$. When p_i is larger than p_j for $i < j$, the loss probability of bursts with a small number of hops becomes large. If the probability p_i is well tuned for each i, the unfairness of the burst loss probability is improved.

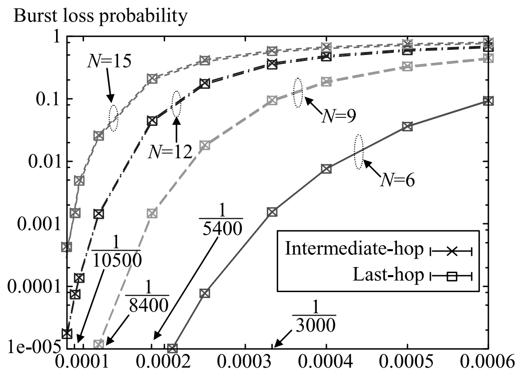
Let H denote the maximum number of hops. We set $p_i = (H - i)\xi$ $(0 \le \xi \le 1/(H - 1))$. Because p_i is larger than p_j for $i < j$, it is expected that the unfairness of the burst loss probability is improved.

Figure 7(a) shows the standard deviation ratio $\delta_{inter}/\delta_{IR-e}$ for the intermediate reservation and the standard deviation ratio for the PRED against the parameter ξ in the cases of $N = 6$ and 15. Moreover, Fig. 7(b) shows the overall loss probabilities of the intermediate-hop preemption, PRED, and IR-e against ξ in the cases of $N = 6$ and 15. In both the cases of $N = 6$ and 15, we use the same parameter settings of W, λ, and (α, β) as the case of the BJIT.

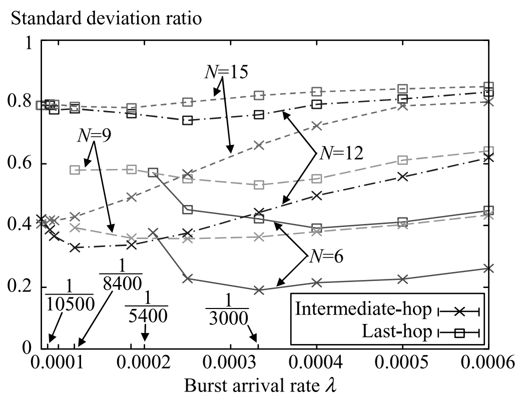
We find from Fig. 7(a) that the PRED can improve the fairness of the burst loss probability, and from Fig. 7(b) that the PRED does not increase the overall burst loss probability so much. In the case of $N = 6$, the PRED with $\xi = 0.0003$ significantly decreases the standard deviation ratio. However, in the case of $N = 15$, the PRED with $\xi = 0.0003$ provides a large standard deviation ratio and fails to improve the fairness of the burst loss probability. Note that in the case of $N = 15$, the most effective parameter is $\xi = 0.0001$. This implies that it is difficult for the PRED to find the p_i's with which the fairness of the burst loss probability is achieved. Please note that [8] didn't provide any information about how to determine the p_i's.

4.1.4 Comparison of the Intermediate-Hop Preemption and the Last-Hop Preemption

In this subsection, we compare the intermediate-hop preemption with the last-hop preemption presented in Sect. 2. Figures 8(a) and (b) show the overall burst loss probabilities and the standard deviation ratios for the intermediate-hop preemption and the last-hop one, respectively. Here, the number of nodes N is 6, 9, 12, and 15, and the number of



(a) Impact of burst arrival rate λ on burst loss probability.



(b) Impact of burst arrival rate λ on standard deviation ratio.

Fig. 8 Comparison of the proposed method and the last-hop preemption method.

wavelengths W is 16.

From Eq. (2), (α, β) of the proposed method is set to (4,4) for $N = 6$, (6,6) for $N = 9$, (7,7) for $N = 12$, and (8,8) for $N = 15$. On the other hand, in the last-hop preemption, α is set to three for $N = 6$, two for $N = 9$, two for $N = 12$, and two for $N = 15$, where each value of α can provide the smallest $\delta_{last}/\delta_{IR-e}$ among all values of α when $P_{overall}$ is close to 0.001.

From Fig. 8(a), we find that the overall burst loss probability is large (small) when the burst arrival rate is large (small), as expected. We also find that the overall burst loss probability for the proposed method is almost the same as that for the last-hop preemption regardless of the burst arrival rate.

On the other hand, from Fig. 8(b), we find that the standard deviation ratios change significantly depending on the burst arrival rate, and that the ratios are large when the burst arrival rate is large or small. When the burst arrival rate is small, the congestion is not likely to occur and the preemption is not likely to be performed. When the burst arrival rate is large, bursts are likely to be lost and the effective of the preemption is small. As a result, the standard deviation ratio becomes small with a moderate burst arrival rate.

Nevertheless, the standard deviation ratio for the proposed method is much smaller than that for the last-hop preemption regardless of the burst arrival rate in all cases.

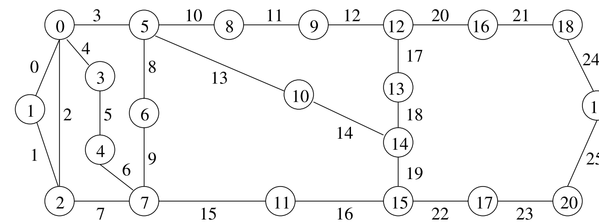


Fig. 9 ARPA2 network.

Hence our proposed method can improve the fairness more significantly than the last-hop preemption.

4.2 ARPA2 Network

We also investigate the performance of the intermediate-hop preemption for the ARPA2 network shown in Fig. 9. Each node has a full-range wavelength conversion capability and the distance between adjacent nodes is 200 km. In this network, we assume that the number of wavelengths is W and that the transmission speed of a wavelength is 10 Gbps. A static route between ingress and egress nodes is chosen according to the minimum hop routing. We assume that the processing time of a control packet δ is equal to 1.0 ms. As is the case with the previous Sect. 4.1, an available wavelength is selected at random and a preempted burst is also randomly selected.

4.2.1 Uniform Traffic Case

In this subsection, we consider the case of uniform traffic where burst arrival rate for each pair of source and destination nodes is the same. Here, we assume that a burst arrives at each node according to a Poisson process with rate λ and that the destination node is chosen by equal probability 1/20. Moreover, the burst size is exponentially distributed with the mean 5 Mbytes. Note that the maximum number of hops of a burst for this network is seven. We consider three cases of W = 16, 64, and 128. The other assumptions are the same as the ring network in the previous subsection.

Table 6 shows the $\delta_{inter}/\delta_{IR-e}$ of the IR-e and the top three $\delta_{inter}/\delta_{IR-e}$'s for the intermediate-hop preemption in cases of W = 16, 64, and 128. λ is set to 1/3780 for W = 16, 1/630 for W = 64, and 1/273 for W = 128. Note that the mean total hop-number of a burst of this network is 3.4, and that the recommended (α, β) given by (2) is (4, 4).

From this table, we observe the same tendency as the ring network of the previous subsection. Therefore, the intermediate-hop preemption improves unfairness in terms of the loss probabilities of bursts with different numbers of hops under the network in which the arrival rates of bursts with different hop-numbers are not the same. Moreover, we find that that the recommended (α, β) obtained from (2) is also effective for the ARPA2 network. From Table 6, we can observe that the recommended (α, β) = (4,4) obtained from (2) is also effective regardless of the number of wavelengths.

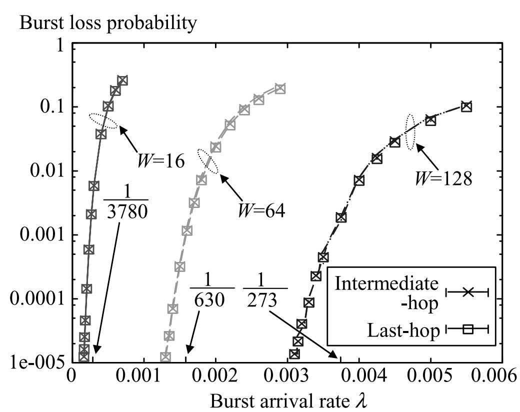
In addition, we compare the intermediate-hop preemp-

Table 6 Standard deviation for IR-e and top three standard deviation ratios for the proposed method in uniform traffic case (W = 16, 64 and 128).

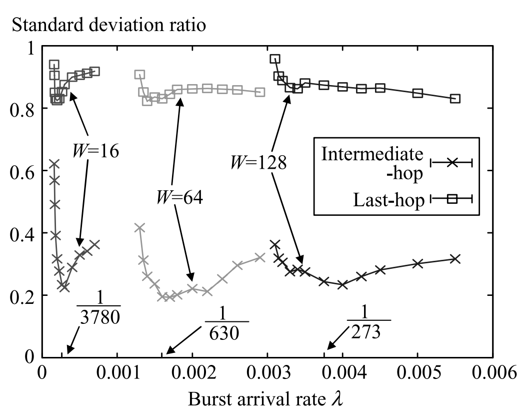
W	(α,β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
16	IR-e	1	2.0767×10^{-3}
	$(4,4)$	0.25096	2.1228×10^{-3}
	$(5,4)$	0.26046	2.1207×10^{-3}
	$(5,3)$	0.39642	2.1641×10^{-3}
64	IR-e	1	9.9623×10^{-4}
	$(5,4)$	0.12725	1.0266×10^{-3}
	$(4,4)$	0.15933	1.0296×10^{-3}
	$(6,4)$	0.27767	1.0192×10^{-3}
128	IR-e	1	1.8316×10^{-3}
	$(5,4)$	0.17862	1.9042×10^{-3}
	$(4,4)$	0.21688	1.9105×10^{-3}
	$(6,4)$	0.27495	1.8863×10^{-3}

Table 7 Standard deviation for IR-e and top three standard deviation ratios for the proposed method in non-uniform traffic case (W = 16, 64 and 128).

W	(α,β)	$\delta_{inter}/\delta_{IR-e}$	$P_{overall}$
16	IR-e	1	5.7787×10^{-3}
	$(4,4)$	0.08651	5.9012×10^{-3}
	$(5,4)$	0.13209	5.8886×10^{-3}
	$(5,3)$	0.23618	6.0154×10^{-3}
64	IR-e	1	7.7440×10^{-3}
	$(4,4)$	0.09696	7.9839×10^{-3}
	$(5,4)$	0.13655	7.9536×10^{-3}
	$(5,3)$	0.32112	8.2184×10^{-3}
128	IR-e	1	1.6570×10^{-2}
	$(4,4)$	0.11700	1.7248×10^{-3}
	$(5,4)$	0.14601	1.7181×10^{-3}
	$(5,3)$	0.36744	1.8013×10^{-3}



(a) Impact of burst arrival rate λ on burst loss probability.



(b) Impact of burst arrival rate λ on standard deviation ratio.

Fig. 10 Comparison of the proposed method and the last-hop preemption method in uniform traffic case (ARPA2 network).

tion with the last-hop preemption. Figures 10(a) and (b) show the overall burst loss probabilities and the standard deviation ratios for the intermediate-hop preemption and the last-hop one, respectively. In the proposed method, (α,β) is also set to (4,4). On the other hand, in the last-hop preemption, α is set to two for W = 16 and 64, and three for W = 128, where each value of α can provide the smallest $\delta_{last}/\delta_{IR-e}$ among all values of α when $P_{overall}$ is close to 0.001.

From these figures, we find that the overall burst loss probability for the proposed method is almost the same as that for the last-hop preemption regardless of the burst arrival rate. In addition, we find that the standard deviation ratios become small for a moderate burst arrival rate, and that the standard deviation ratio for the proposed method is much smaller than that for the last-hop preemption in all cases.

4.2.2 Non-uniform Traffic Case

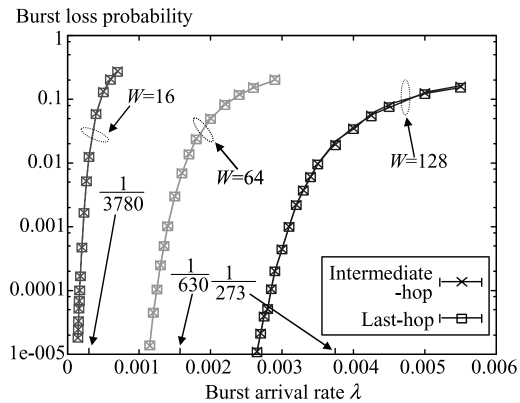
We consider the case of non-uniform traffic where burst arrival rates are different. Here, we assume that a burst arrives at node i ($i = 0, \cdots, 20$) according to a Poisson process with λ_i, which is given by

$$\lambda_i = \begin{cases} \lambda/2, & i \equiv 0 \pmod 3, \\ \lambda, & i \equiv 1 \pmod 3, \\ 3\lambda/2, & i \equiv 2 \pmod 3. \end{cases} \tag{3}$$

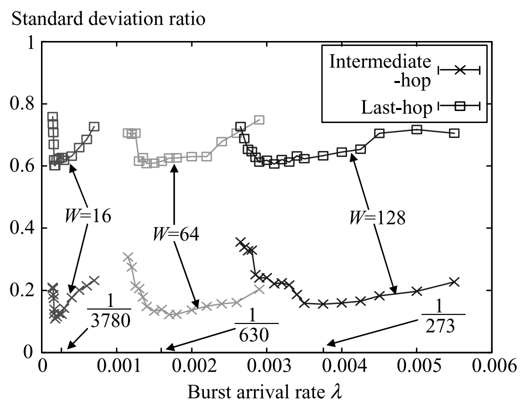
Note that the total arrival rate for the non-uniform traffic case is the same as that for the uniform traffic case in the previous subsection.

The destination node of a burst is also chosen by equal probability 1/20. Moreover, the burst size is exponentially distributed with the mean 5 Mbytes. The maximum number of hops of a burst for this network is seven. We consider three cases of W = 16, 64, and 128. We uses the same parameters and assumptions as the uniform traffic case in the Sect. 4.2.1. The mean total hop-number of a burst of this network is about 3.19, and hence the recommended (α,β) is (4, 4) from (2).

Table 7 shows the $\delta_{inter}/\delta_{IR-e}$ of the IR-e and the top three $\delta_{inter}/\delta_{IR-e}$'s for the intermediate-hop preemption in cases of W = 16, 64, and 128. From Table 7, we can observe that the recommended (α, β) = (4,4) obtained from (2) is the most effective for the ARPA2 network regardless of the number of wavelengths. Therefore, even in the non-uniform traffic case, the recommended (α,β) is effective.



(a) Impact of burst arrival rate λ on burst loss probability.



(b) Impact of burst arrival rate λ on standard deviation ratio.

Fig. 11 Comparison of the proposed method and the last-hop preemption method in non-uniform traffic case (ARPA2 network).

Finally, we compare the intermediate-hop preemption with the last-hop preemption in the non-uniform traffic case. Figures 11(a) and (b) show the overall burst loss probabilities and the standard deviation ratios for both the methods, respectively. In the intermediate-hop preemption, (α,β) is set to (4,4). In the last-hop preemption, α is set to two for $W = 16$ and 64, and three for $W = 128$, where each value of α can provide the smallest $\delta_{last}/\delta_{IR-e}$ among all values of α when $P_{overall}$ is close to 0.001.

From these figures, we also find that the impact of the burst arrival rate λ on the performances of the proposed method and the last-hop preemption is almost the same as that in the uniform traffic case. The standard deviation ratio for the intermediate-hop preemption is much smaller than that for the last-hop preemption, regardless of the burst arrival rate. These results show that the proposed method is more effective than the last-hop preemption even in the non-uniform traffic case.

5. Conclusion

In this paper, we proposed the intermediate-hop preemption based on the number of transit hops with two thresholds. The intermediate-hop preemption improves unfairness of burst loss probability among different numbers of hops. We evaluated the performance of the intermediate-hop preemption in a uni-directional ring network and an ARPA2 network. Numerical examples showed that the intermediate-hop preemption is more effective for the improvement of unfairness than the last-hop preemption. We also proposed the formula for the thresholds in terms of the mean hop-number, with which better fairness performance is expected. Numerical examples also showed the effectiveness of the formula in various cases in terms of the number of nodes, the number of wavelengths, the network topology, and the traffic condition.

Acknowledgment

This research was supported in part by the International Communications Foundation (ICF), Japan Society for the Promotion of Science under Grant-in-Aid for Scientific Research (C) No. 18560375, and Japan Society for the Promotion of Science under Grant-in-Aid for Young Scientists (B) No. 19760255.

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