QoS-Guaranteed Wavelength Allocation for WDM Networks with Limited-Range Wavelength Conversion

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Abstract

In this paper, we consider QoS-guaranteed wavelength allocation for WDM networks with limited-range wavelength conversion. In the wavelength allocation, the pre-determined number of wavelengths are allocated to each QoS class depending on the required loss probability. We evaluate the connection loss probability of each QoS class for single-hop and ring networks using continuous-time Markov chain and simulation. Numerical examples show that the proposed wavelength allocation method can provide significantly small connection loss probability for the highest priority class.

Keywords

QoS provisioning, Wavelength allocation, Wavelength routing network, Limited-range wavelength conversion, Continuous-time Markov chain

I. Introduction

In all-optical wavelength routing network, connections are established by wavelengths between end nodes and data are transmitted with the connections [1], [2], [3], [4], [5], [6]. Without opto-electronic-optic (O/E/O) conversion, a connection is established along several intermediate nodes which consist of optical switches with a capability of wavelength routing [7]. If nodes do not have the capability of wavelength conversion, the same wavelength is required at each link to establish connection between end nodes (*wavelength continuity constraint*) and the resulting connection blocking probability increases.

In [8], connection blocking probability in wavelength routing network without wavelength conversion has been considered with M/M/c/c queueing model. [7] has investigated the blocking probabilities of distributed wavelength assignment (DWA) algorithms in which random assignment algorithm and locally-most-used (LMU) algorithm have been considered with M/M/c/c based blocking models for ring networks.

On the other hand, if nodes have the capability of wavelength conversion, connection blocking probability is improved. In [9], [10], [11], the impact of wavelength conversion has been studied with analytical models and simulation.

Under the current technology, one of the popular conversion techniques is limited-range wavelength conversion which can convert input wavelength to some wavelength within a limited range. [12] has shown that four wavelength mixing (FWM) can convert an input wavelength into any output wavelength within 65nm which is the difference between the output and input wavelengths. In [13], connection blocking probability for all-optical wavelength routing network with FWM wavelength conversion has been investigated with a threshold model in which the FWM wavelength conversion capability is taken into consideration. In [14], first-fit algorithm has been considered for

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wavelength routing network with FWM wavelength conversion and blocking probability has been derived by layered-graph approach.

With the recent increase of Internet users and the diversity of network applications, QoS provisioning becomes increasingly important in all-optical wavelength routing network. In [15] and [16], the general approach for service-specific routing and wavelength allocation has been proposed. With the approach, a connection is established according to twofold metrics, i.e., QoS metrics (service requirements) and resource metrics (quality constraints). In this approach, wavelengths are classified into multiple groups which can support different services according to the quality attributes. As for QoS metrics, transmission quality, restoration, network management, and policies have been considered in [15] and [16].

In terms of QoS guarantee for connection loss probability, we have proposed a shared wavelength allocation method which works under FWM wavelength conversion, and have evaluated the performance of the method in [17]. However, with this method, the number of wavelengths which the highest priority class can utilize is restricted and the resulting loss probability of the highest priority class is not small enough to provide stringent QoS requirement.

In this paper, we develop the shared wavelength allocation method proposed in [17] to achieve further small connection loss probability for the highest priority class. In the improved method, the pre-determined number of wavelengths are allocated to each QoS class depending on the priority of loss probability as well as the previous method. However, the wavelength set for the highest class includes all wavelengths in a fiber so as to decrease the connection loss probability.

When connection of a QoS class is established along several links, an idle wavelength in the wavelength set of the class is allocated at each link. Here, we consider two wavelength selection rules according to which an idle wavelength is selected from the wavelength set for requested QoS class. The connection loss probability of each class greatly depends on the combination of the wavelength selection rules. We consider three combinations of wavelength selection rules and compare those in two wavelength routing networks: single-hop and ring networks.

As for the performance evaluation of the proposed method, we investigate connection loss probability of each QoS class in a single-hop wavelength routing network using continuous-time Markov chain and simulation. We also investigate the connection loss probability for ring network by simulation. In numerical examples, we show how the combination of wavelength selection rules affect the connection loss probability in the wavelength routing network.

The rest of the paper is organized as follows. Sect. II represents the QoS-guaranteed wavelength allocation method. In Sect. III, we present our analytical model in single-hop wavelength routing network and derive the connection loss probability of each QoS class. Numerical examples are shown in Sect. IV and conclusions are presented in Sect. V.

II. QoS-guaranteed Wavelength Allocation Method

In this section, we present our QoS-guaranteed wavelength allocation method in detail. We consider an all-optical wavelength routing network where each node has FWM wavelength conversion. Let W denote the number of wavelengths multiplexed into an optical fiber. According to [13] and [14], we assume that the range of FWM wavelength conversion for wavelength w_i $(1 \le i \le W)$ is from $w_{\max(1,i-\theta)}$ to $w_{\min(i+\theta,W)}$ $(0 \le \theta \le W-1)$ where θ is a non-negative integer and called threshold in the following. Note that the FWM wavelength conversions with $\theta = 0$ and $W-1$ are corresponding to no wavelength conversion and full wavelength conversion, respectively.

In this wavelength routing network, M QoS classes require different acceptable loss probabilities.

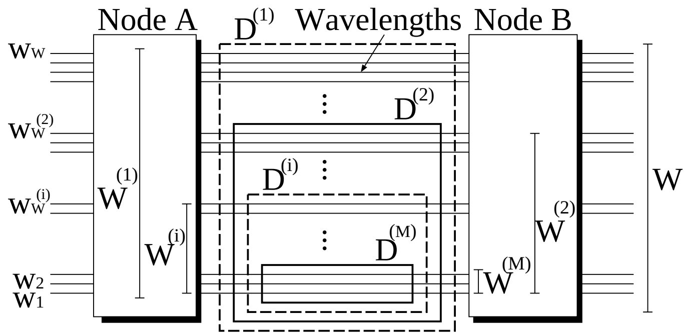

Fig. 1. QoS-guaranteed Wavelength Allocation.

TABLE I

THREE COMBINATIONS OF WAVELENGTH SELECTION RULES.

	class 1	class 2	other classes
Method 1	Rule 1	Rule 1	Rule 1
Method 2	Rule 2	Rule 1	Rule 1
Method 3	Rule 2	Rule 2	Rule 1

M QoS classes are numbered from 1 to M and class i has high priority over class j when $i < j$ and the class i requires smaller connection loss probability than class j. Therefore, connections of class 1 have the highest priority and require the smallest loss probability.

In our QoS-guaranteed wavelength allocation method, W wavelengths $\{w_1, \cdots, w_W\}$ are classified into M wavelength sets $D^{(i)}$ $(i = 1, \cdots, M)$. Let $W^{(i)}$ denote the number of wavelengths in $D^{(i)}$. Connection of class i is established using wavelength in $D^{(i)}$. Each $D^{(i)}$ and $W^{(i)}$ satisfies the followings.

$$D^{(M)} \subset \cdots \subset D^{(i)} \subset \cdots \subset D^{(1)}, \tag{1}$$

$$D^{(i)} = \{w_1, \cdots, w_{W^{(i)}}\}, \ \ 1 \leq i \leq M, \tag{2}$$

$$0 < W^{(M)} < \cdots < W^{(i)} < \cdots < W^{(1)} = W. \tag{3}$$

(3) implies that higher priority class can use more wavelengths and it is expected that the resulting connection loss probability of high priority class is small. Fig. 1 shows how W wavelengths are classified into M QoS classes in the proposed method.

Here, we consider two different rules of wavelength selection.

Rule 1: The wavelength with the *minimum* index number in $D^{(i)}$ is selected.

Rule 2: The wavelength with the *maximum* index number in $D^{(i)}$ is selected.

A connection of class i is established with an idle wavelength in $D^{(i)}$ at every link. Each QoS class follows either Rule 1 or Rule 2. It seems that the connection loss probability of each class greatly depends on the combination of the wavelength selection rules. Because the number of classes is M, there are 2^M combinations of the wavelength selection rules. In this paper, however, we consider three combinations shown in Table I. In Method 1, all classes follow Rule 1 and, in Method 2, class 1 follows Rule 2 and the other classes follow Rule 1. Classes 1 and 2 follow Rule 2 and other classes follow Rule 1 in Method 3. Note that the number of available wavelengths for lower priority classes than classes 1 and 2 for Method 1 is likely to be the smallest while that for Method 3 the largest.

Fig. 2. Single-hop network.

Here, we explain how a connection of each class is established between end nodes. As mentioned the above, W wavelengths $\{w_1, \cdots, w_W\}$ are multiplexed into a fiber at every link and each node has an FWM wavelength converter with threshold θ. At each link, W wavelengths are classified into M wavelength sets and wavelength set $D^{(i)}$ $(i = 1, \cdots, M)$ is allocated to class i. When $w_j \in D^{(i)}$ is selected for class i connection at some link, the conversion range for wavelength at the next link is from $w_{\max(1,j-\theta)}$ to $w_{\min(j+\theta,W^{(i)})}$. In this case, an available wavelength for the next link is selected according to either of the following two procedures based on first-fit algorithm [14].

Procedure 1: If class i $(i = 1, \cdots, M)$ follows Rule 1, an idle wavelength with the *minimum* index number in the set $\{w_{\max(1,j-\theta)}, \cdots, w_{\min(j+\theta,W^{(i)})}\}$ is selected.

Procedure 2: If class i $(i = 1, \cdots, M)$ follows Rule 2, an idle wavelength with the *maximum* index number in the set $\{w_{\max(1,j-\theta)}, \cdots, w_{\min(j+\theta,W^{(i)})}\}$ is selected.

If wavelength allocations in all links along the path succeed, lightpath connection is eventually established.

III. Performance Analysis

In this section, we evaluate the performance of the QoS-guaranteed wavelength allocation in a single-hop wavelength routing network (see Fig. 2). We use the following assumptions.

1. W wavelengths are multiplexed into a fiber at a link.
2. QoS metric is connection loss probability.
3. The number of QoS classes is M and class i $(i = 1, \cdots, M)$ has priority over class j if $i < j$.
4. Connections of class i arrive at the node according to a Poisson process with rate $\lambda^{(i)}$ and total arrival rate is $\lambda = \sum_{i=1}^{M} \lambda^{(i)}$.
5. Connection holding times of all classes are exponentially distributed with rate μ.
6. No queueing for connection request is permitted, that is, the connection is lost immediately after the connection establishment fails.

Let $B^{(i)}$ $(i = 1, \cdots, M)$ denote the wavelength set given by

$$B^{(i)} = \begin{cases} D^{(i)} - D^{(i+1)}, & i < M, \\ D^{(M)}, & i = M, \end{cases} \tag{4}$$

where $D^{(i)}$ is a wavelength set of class i. In addition, we define $\bar{W}^{(i)}$ $(i = 1, \cdots, M)$ as the number of wavelengths in a set $B^{(i)}$. We have

$$\bar{W}^{(i)} = \begin{cases} W^{(i)} - W^{(i+1)}, & i < M, \\ W^{(M)}, & i = M. \end{cases} \tag{5}$$

Let $N^{(i)}(t)$ $(i = 1, \cdots, M)$ denote the number of wavelengths which are utilized in $B^{(i)}$ at time t. Note that

$$0 \le N^{(i)} \le \bar{W}^{(i)}, \quad i = 1, \cdots, M. \tag{6}$$

We define the state of the link at time t as

$$(N^{(1)}(t), \cdots, N^{(i)}(t), \cdots, N^{(M)}(t)). \tag{7}$$

TABLE II

STATE TRANSITION RATE IN METHOD 1.

Current state: $(N^{(1)},\cdots,N^{(i)},\cdots,N^{(M)})$	Next state	Transition rate
$N^{(M)} < \bar{W}^{(M)}$	$(N^{(1)},\cdots,N^{(M)}+1)$	λ
$N^{(i)} < \bar{W}^{(i)}$for $\exists i \in \{1,\cdots,M-1\}$, $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1,\cdots,M\}$	$(N^{(1)},\cdots,N^{(i)}+1,\cdots,N^{(M)})$	$\sum_{m=1}^{i}\lambda^{(m)}$
$N^{(i)} > 0$	$(N^{(1)},\cdots,N^{(i)}-1,N^{(M)})$	$N^{(i)}\mu$

TABLE III

STATE TRANSITION RATE IN METHOD 2.

Current state: $(N^{(1)},\cdots,N^{(i)},\cdots,N^{(M)})$	Next state	Transition rate
$N^{(1)} < \bar{W}^{(1)}$	$(N^{(1)}+1,\cdots,N^{(M)})$	$\lambda^{(1)}$
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2,\cdots,M-1\}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{1,\cdots,i-1\}$, $N^{(k)} < \bar{W}^{(k)}$ for $\exists k \in \{i+1,\cdots,M\}$	$(N^{(1)},\cdots,N^{(i)}+1,\cdots,N^{(M)})$	$\lambda^{(1)}$
$N^{(M)} < \bar{W}^{(M)}$, $N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{1,\cdots,M-1\}$	$(N^{(1)},\cdots,N^{(M)}+1)$	$\sum_{m=2}^{M}\lambda^{(m)}$
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2,\cdots,M-1\}$, $N^{(j)} < \bar{W}^{(j)}$ for $\exists j \in \{1,\cdots,i-1\}$, $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1,\cdots,M\}$	$(N^{(1)},\cdots,N^{(i)}+1,\cdots,N^{(M)})$	$\sum_{m=2}^{i}\lambda^{(m)}$
$N^{(M)} < \bar{W}^{(M)}$, $N^{(i)} = \bar{W}^{(i)}$ for $\forall i \in \{1,\cdots,M-1\}$	$(N^{(1)},\cdots,N^{(M)}+1)$	λ
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2,\cdots,M-1\}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{1,\cdots,i-1\}$ $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1,\cdots,M\}$	$(N^{(1)},\cdots,N^{(i)}+1,\cdots,N^{(M)})$	$\sum_{m=1}^{i}\lambda^{(m)}$
$N^{(i)} > 0$	$(N^{(1)},\cdots,N^{(i)}-1,\cdots,N^{(M)})$	$N^{(i)}\mu$

Let U denote the state space of $(N^{(1)}(t),\cdots,N^{(M)}(t))$. From the above assumptions, $(N^{(1)}(t),\cdots,N^{(M)}(t))$ is a continuous-time Markov chain. Since we consider the queueing behavior in equilibrium, we omit t in the following. In Tables II, III and IV, we show transition rates from the state $(N^{(1)},\cdots,N^{(i)},\cdots,N^{(M)})$ in Methods 1, 2 and 3, respectively.

Let $\pi(N^{(1)},\cdots,N^{(M)})$ denote the steady state probability of $(N^{(1)},\cdots,N^{(M)})$. $\pi(N^{(1)},\cdots,N^{(M)})$ is uniquely determined by equilibrium state equations and following normalized condition

$$\sum_{(N^{(1)},\cdots,N^{(M)})\in U}\pi(N^{(1)},\cdots,N^{(M)}) = 1. \tag{8}$$

Equilibrium state equations for Method 2 are shown in A, however, those for other Methods are omitted due to page limitation.

With $\pi(N^{(1)},\cdots,N^{(M)})$, connection loss probability of class i which follows Rule 1, $P^{(i)}_{loss,1}$, and that of class i which follows Rule 2, $P^{(i)}_{loss,2}$, are given by

$$P^{(i)}_{loss,1} = \sum_{(N^{(1)},\cdots,N^{(i-1)})\in U^{(i-1)}}\pi(N^{(1)},\cdots,N^{(i-2)},N^{(i-1)},\bar{W}^{(i)},\bar{W}^{(i+1)},\cdots,\bar{W}^{(M)}), \tag{9}$$

$$P^{(i)}_{loss,2} = \sum_{(N^{(i+1)},\cdots,N^{(M)})\in \bar{U}^{(i+1)}}\pi(\bar{W}^{(1)},\cdots,\bar{W}^{(i-1)},\bar{W}^{(i)},N^{(i+1)},N^{(i+2)},\cdots,N^{(M)}). \tag{10}$$

TABLE IV

STATE TRANSITION RATE IN METHOD 3.

Current state: $(N^{(1)}, \cdots, N^{(i)}, \cdots, N^{(M)})$	Next state	Transition rate
$N^{(1)} < \bar{W}^{(1)}$	$(N^{(1)}+1, \cdots, N^{(M)})$	$\lambda^{(1)}$
$N^{(1)} < \bar{W}^{(1)}$, $N^{(2)} < \bar{W}^{(2)}$	$(N^{(1)}, N^{(2)}+1, \cdots, N^{(M)})$	$\lambda^{(2)}$
$N^{(1)} < \bar{W}^{(1)}$, $N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{3, \cdots, M-1\}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{2, \cdots, i-1\}$, $N^{(k)} < \bar{W}^{(k)}$ for $\exists k \in \{i+1, \cdots, M\}$	$(N^{(1)}, \cdots, N^{(i)}+1, \cdots, N^{(M)})$	$\lambda^{(2)}$
$N^{(M)} < \bar{W}^{(M)}$, $N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2, \cdots, M-1\}$	$(N^{(1)}, \cdots, N^{(M)}+1)$	$\sum_{m=3}^{M} \lambda^{(m)}$
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{3, \cdots, M-1\}$, $N^{(j)} < \bar{W}^{(j)}$ for $\exists j \in \{2, \cdots, i-1\}$, $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1, \cdots, M\}$	$(N^{(1)}, \cdots, N^{(i)}+1, \cdots, N^{(M)})$	$\sum_{m=3}^{i} \lambda^{(m)}$
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2, \cdots, M-1\}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{1, \cdots, i-1\}$, $N^{(k)} < \bar{W}^{(k)}$ for $\exists k \in \{i+1, \cdots, M\}$	$(N^{(1)}, \cdots, N^{(i)}+1, \cdots, N^{(M)})$	$\lambda^{(1)} + \lambda^{(2)}$
$N^{(M)} < \bar{W}^{(M)}$, $N^{(1)} < \bar{W}^{(1)}$ $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{2, \cdots, M-1\}$	$(N^{(1)}, \cdots, N^{(M)}+1)$	$\sum_{m=2}^{M} \lambda^{(m)}$
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{2, \cdots, M-1\}$, $N^{(1)} < \bar{W}^{(1)}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{2, \cdots, i-1\}$ $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1, \cdots, M\}$	$(N^{(1)}, \cdots, N^{(i)}+1, \cdots, N^{(M)})$	$\sum_{m=2}^{i} \lambda^{(m)}$
$N^{(M)} < \bar{W}^{(M)}$ $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{1, \cdots, M-1\}$	$(N^{(1)}, \cdots, N^{(M)}+1)$	λ
$N^{(i)} < \bar{W}^{(i)}$ for $\exists i \in \{3, \cdots, M-1\}$, $N^{(j)} = \bar{W}^{(j)}$ for $\forall j \in \{1, \cdots, i-1\}$ $N^{(k)} = \bar{W}^{(k)}$ for $\forall k \in \{i+1, \cdots, M\}$	$(N^{(1)}, \cdots, N^{(i)}+1, \cdots, N^{(M)})$	$\sum_{m=1}^{i} \lambda^{(m)}$
$N^{(i)} > 0$	$(N^{(1)}, \cdots, N^{(i)}-1, \cdots, N^{(M)})$	$N^{(i)}\mu$

Here, $U^{(i)}$ denotes the state space of $(N^{(1)}, \cdots, N^{(i)})$ and $\bar{U}^{(i)}$ the state space of $(N^{(i)}, \cdots, N^{(M)})$.

IV. Numerical Examples

In this section, we show some numerical examples for the QoS-guaranteed wavelength allocation in cases of Methods 1, 2 and 3. We consider two network topologies: single-hop and ring networks as shown in Figs. 2 and 3. In these networks, we assume that there is a fiber between two adjacent nodes and 32 wavelengths are multiplexed into a fiber. Moreover, we assume that the connection holding time is exponentially distributed with rate $\mu = 1$.

A. Single-hop network

In this subsection, we consider single-hop wavelength routing network as shown in Fig. 2. The connection loss probabilities of each QoS class are calculated by the analytical results in the previous section and by simulation.

A.1 Impact of total connection arrival rate

Fig. 4 shows how the total arrival rate of connections affects the connection loss probability for each QoS class. Here we assume that the number of QoS classes, M, is equal to three. 32 wavelengths are classified into $D^{(1)}$, $D^{(2)}$ and $D^{(3)}$ and the numbers of wavelengths in these sets are

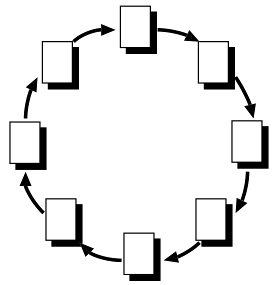

Fig. 3. Ring network.

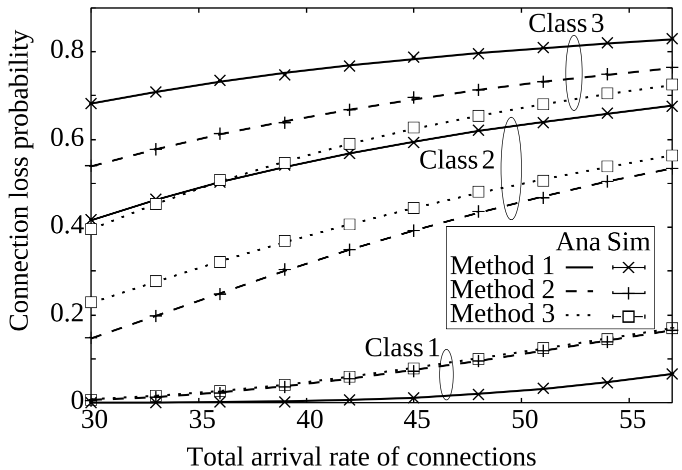

Fig. 4. Connection loss probability vs. total connection arrival rate for single-hop network.

given by $W^{(1)} = 32$, $W^{(2)} = 16$ and $W^{(3)} = 10$, respectively. In addition, we set $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = \lambda/3$. In this figure, lines and dots denote the results of the analysis and simulation, respectively.

From this figure, we observe that analytical and simulation results are almost the same regardless of the increase of total arrival rate and therefore the analytical results are effective for the evaluation of the connection loss probability under three combinations of selection rules.

We also see that the QoS-guaranteed wavelength allocation method provides multiple QoS classes in terms of the connection loss probability. The connection loss probability of class 1 for any Method is the smallest among three priority classes because connections of class 1 can utilize more wavelengths than those of the other classes. However, this results in the large loss probabilities of classes 2 and 3.

As for the effect of the combination of wavelength selection rules, the loss probability of class 1 for Method 1 is the smallest among three Methods. This is because the connections of class 1 with Method 1 are likely to utilize the largest number of wavelengths in $D^{(2)}$ and $D^{(3)}$ among three Methods.

A.2 Impact of wavelength allocation for each QoS class

Fig. 5 shows the relation between the connection loss probability and the number of wavelengths in $D^{(2)}$. Here, the connection loss probability is calculated with analytical results. In this figure, we assume that the number of QoS classes is three and that $\lambda = 30$ and $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = 10$.

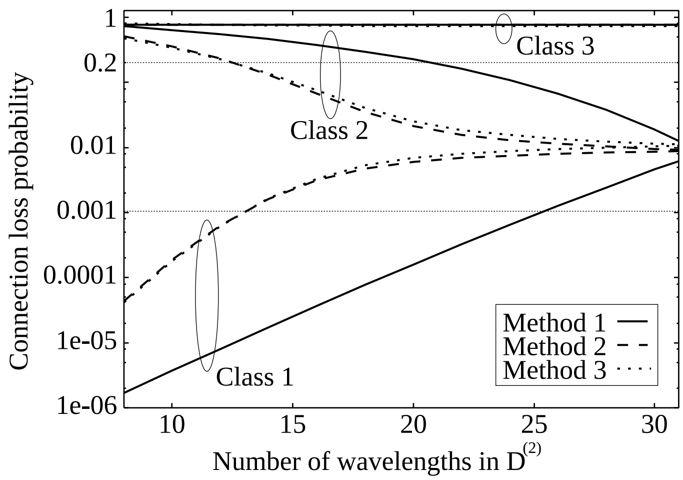

Fig. 5. Connection loss probability vs. number of wavelengths in $D^{(2)}$ for single-hop network.

To provide the almost same connection loss probability of class 3 for all Methods, we set $W^{(3)} = 7$ for Method 1, $W^{(3)} = 5$ for Method 2 and $W^{(3)} = 3$ for Method 3. In this figure, $W^{(2)}$ varies from 8 to 31 in which the inequalities (3) are satisfied.

From this figure, we observe that when $W^{(2)}$ becomes large, the connection loss probability of class 2 decreases as expected. On the other hand, the connection loss probability of class 1 increases because the increase of $W^{(2)}$ causes the decrease of $W^{(1)} - W^{(2)}$ which only class 1 can utilize.

To provide the QoS guarantee in which the connection loss probabilities are smaller than 0.001 and 0.2 for classes 1 and 2 respectively, Method 1 requires 21 wavelengths in $D^{(2)}$ and both Methods 2 and 3 require 13 wavelengths. That is, Method 1 requires larger wavelengths in $D^{(2)}$ than other Methods.

B. Ring network

In this subsection, we investigate the performance of the proposed method in ring network [1]. In the ring network, in addition to the assumptions in Section III, we assume that the number of nodes is $L = 10$ and that all nodes have the capability of FWM wavelength conversion with threshold θ. Moreover, the pair of source and destination nodes of arriving connection is distributed uniformly, i.e., each pair is selected with the same probability. In the case of ring network, the connection loss probability is calculated by simulation. We also evaluate the connection loss probability in no QoS-guaranteed network with FWM wavelength conversion by simulation.

B.1 Impact of total connection arrival rate

Fig. 6 shows how the total arrival rate of connections affects the connection loss probability for each QoS class in ring network. We assume that the number of QoS classes is equal to three and that $W^{(1)} = 32$, $W^{(2)} = 16$ and $W^{(3)} = 10$ for all Methods. We set $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = \lambda/3$ and $\theta = 10$.

From this figure, we observe that our proposed method provides multiple QoS classes in ring network as well as single-hop network. The connection loss probability of class 1 for any Method is

[1] We also investigated the performance of the proposed method in a mesh-torus network and obtained the results similar to those in the ring network. However, the results are omitted due to the page limitation.

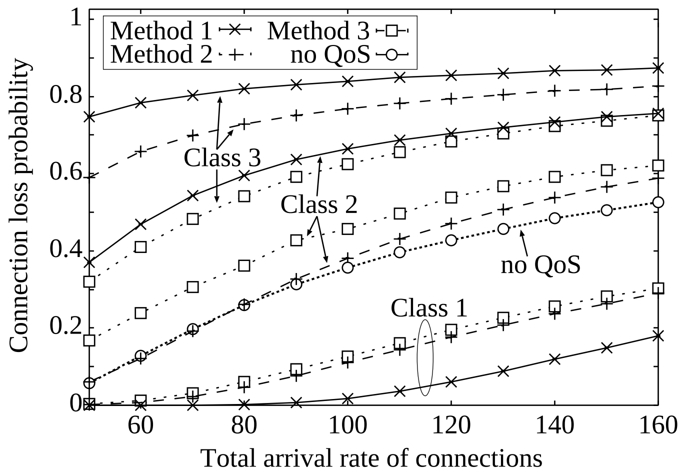

Fig. 6. Connection loss probability vs. total connection arrival rate for ring network.

smaller than that in no QoS-guaranteed network with FWM wavelength conversion. In addition, the loss probability of class 2 for Method 2 is almost the same as that in no QoS-guaranteed network. Therefore, the proposed method is effective to provide smaller connection loss probability for the highest priority class than no QoS-guaranteed FWM conversion.

B.2 Impact of connection arrival rate of each class

In this subsection, we investigate how the arrival rate of each class affects the loss probability of class 1 in ring network. Here, we assume that the number of QoS classes is three and that the threshold is equal to ten. When $\lambda^{(i)}$ ($i = 1, 2,$ and 3) is a variable parameter, $\lambda^{(j)}$'s ($j \neq i$) are constant and equal to 20. We set $W^{(1)} = 32$, $W^{(2)} = 20$ and $W^{(3)} = 10$ for Method 1, $W^{(1)} = 32$, $W^{(2)} = 8$ and $W^{(3)} = 4$ for Method 2, and $W^{(1)} = 32$, $W^{(2)} = 9$ and $W^{(3)} = 3$ for Method 3. In the above setting, when the arrival rates of all classes are 20, the loss probabilities of class 1 for all Methods become almost the same.

Figs. 7 and 8 show how the connection arrival rate of each class affects the connection loss probability of class 1. From Fig. 7, we observe that the connection loss probabilities of class 1 for all Methods show the same tendency. On the other hand, in Fig. 8, we can see that connection loss probability for Method 1 increases as the arrival rate of class 2 becomes large. However, loss probabilities for Methods 2 and 3 are almost constant when the arrival rate of class 2 is larger than 10. In Method 1, all classes follow Rule 1 and hence the arrival rate of class 2 affects the loss probability of class 1. In Methods 2 and 3, class 1 follows Rule 2 and the impact of the arrival rate of class 2 is small. From both figures, Methods 2 and 3 are robust in the sense of keeping the connection loss probability of class 1 constant despite the increase of arrival rate of the other classes.

When the arrival rate of class 1 is large, our proposed method does not provide smaller connection loss probability than that in no QoS-guaranteed network. In this case, we should reallocate small number of wavelengths for the second priority class.

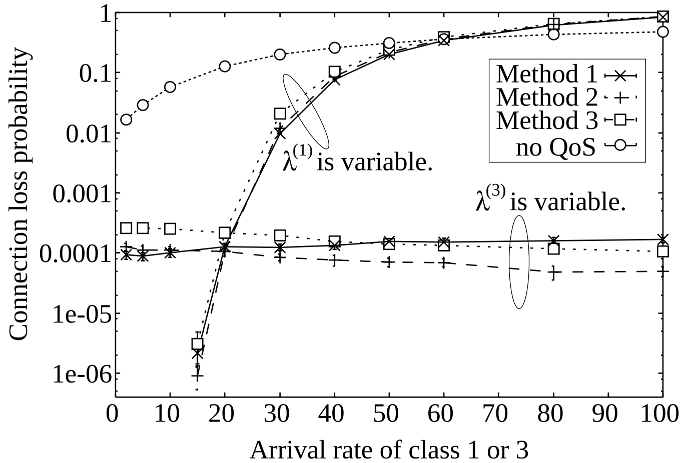

Fig. 7. Connection loss probability vs. arrival rate of classes 1 or 3.

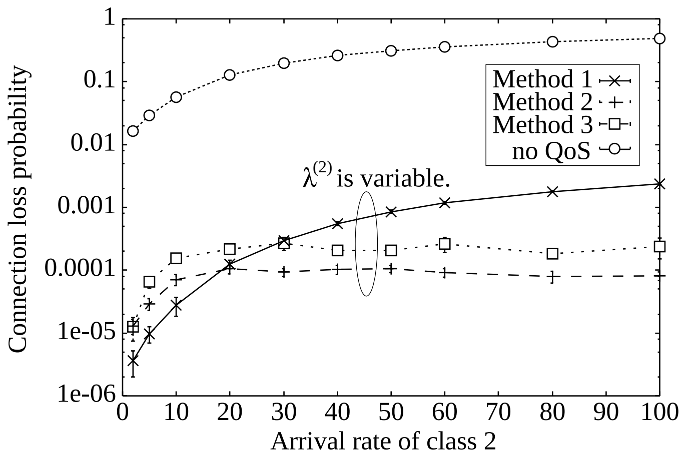

Fig. 8. Connection loss probability vs. arrival rate of class 2.

B.3 Impact of threshold

Fig. 9 shows how the threshold of FWM wavelength conversion affects the connection loss probability for the QoS-guaranteed wavelength allocation method. Here the number of QoS classes is $M = 3$. Moreover we assume that $\lambda = 60$ and $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = 20$. We set $W^{(1)} = 32$, $W^{(2)} = 19$, and $W^{(3)} = 7$ for Method 1, $W^{(1)} = 32$, $W^{(2)} = 10$, and $W^{(3)} = 3$ for Method 2, and $W^{(1)} = 32$, $W^{(2)} = 10$, and $W^{(3)} = 5$ for Method 3 so that connections of class 1 for three Methods have almost the same loss probability when the threshold is equal to zero.

From Fig. 9, we observe that each Method provides different loss probability for each QoS class in the ring network. With our proposed method, the connection loss probability of class 1 becomes smaller than that in the case without QoS priority irrespective of threshold. Moreover we can see that the loss probabilities of class 1 for all Methods decrease as the threshold becomes large. As shown in Procedures 1 and 2 in Sect. III, the increase of threshold results in the large number of available wavelengths on the next link. Connection loss probability of other classes do not decrease

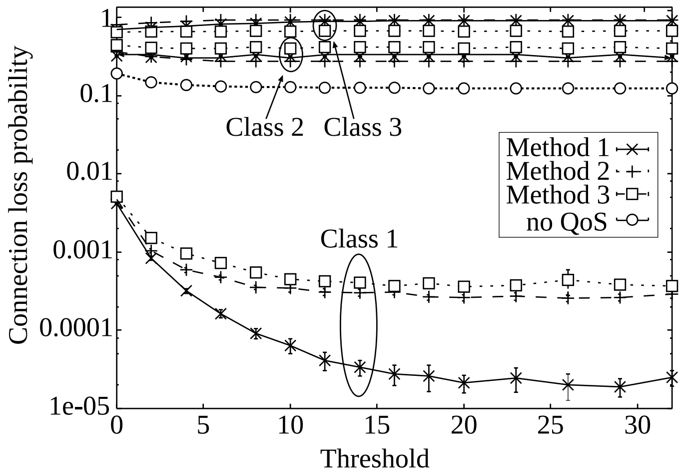

Fig. 9. Connection loss probability vs. threshold for ring network.

so much because the number of available wavelengths on the next link is restricted.

As for the combination of wavelength selection rules, Method 1 is effective to provide the smallest loss probability for class 1 when the threshold becomes large. Method 2 provides smaller loss probability for class 1 than Method 3 but the difference is not large.

V. Conclusions

In this paper, we have proposed a QoS-guaranteed wavelength allocation method which provides multiple QoS classes for the connection loss probability. We have considered three combinations of wavelength selection rules and have compared the performance of those in single-hop and ring networks.

In numerical examples, we have shown that the proposed method significantly provides small connection loss probability for the highest priority class in these two networks. Furthermore, in ring network, our proposed method provides much smaller connection loss probability for the highest priority class than that in no QoS-guaranteed network with FWM wavelength conversion.

As for the wavelength selection rules, Method 1 tends to give smaller connection loss probability for the highest priority class than Methods 2 and 3. However, Method 1 is affected by the arrival rates of lower priority classes. On the other hand, connection loss probabilities for the highest priority class under Methods 2 and 3 are not affected so much by the arrivals of other priority classes and this robustness seems to be preferred for QoS provisioning in terms of connection loss probability.

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Appendix

I. Equilibrium state equations for Method 2

Let $1_{\{X\}}$ denote the indicator function of event X, that is,

$$1_{\{X\}} = \begin{cases} 1, & \text{if } X \text{ occurs,} \\ 0, & \text{otherwise,} \end{cases}$$

When $M = 3$ for Method 2, equilibrium state equations are as follows.

$$\lambda\pi(0,0,0) = \mu\left\{\pi(1,0,0) + \pi(0,1,0) + \pi(0,0,1)\right\}, \tag{11}$$

$$\begin{aligned}(\lambda + N^{(1)}\mu)\pi(N^{(1)},0,0) &= \mu\left\{\pi(N^{(1)},1,0) + \pi(N^{(1)},0,1)\right\} \\ &+1_{\{N^{(1)}<\bar{W}^{(1)}\}}(N^{(1)}+1)\mu\pi(N^{(1)}+1,0,0) + \lambda^{(1)}\pi(N^{(1)}-1,0,0), \quad (N^{(1)}>0),\end{aligned} \tag{12}$$

$$\begin{aligned}(\lambda + N^{(2)}\mu)\pi(0,N^{(2)},0) &= \mu\left\{\pi(1,N^{(2)},0) + \pi(0,N^{(2)},1)\right\} \\ &+1_{\{N^{(2)}<\bar{W}^{(2)}\}}(N^{(2)}+1)\mu\pi(0,N^{(2)}+1,0) + \lambda^{(2)}\pi(0,N^{(2)}-1,0), \quad (N^{(2)}>0),\end{aligned} \tag{13}$$

$$\begin{aligned}(\lambda + N^{(3)}\mu)\pi(0,0,N^{(3)}) &= \mu\left\{\pi(1,0,N^{(3)}) + \pi(0,1,N^{(3)})\right\} \\ &+1_{\{N^{(3)}<\bar{W}^{(3)}\}}(N^{(3)}+1)\mu\pi(0,0,N^{(3)}+1) + (\lambda^{(2)}+\lambda^{(3)})\pi(0,0,N^{(3)}-1), \quad (N^{(3)}>0),\end{aligned} \tag{14}$$

$$\begin{aligned}\{\lambda + (N^{(2)}+N^{(3)})\mu\}\pi(0,N^{(2)},N^{(3)}) &= \mu\pi(1,N^{(2)},N^{(3)}) \\ &+1_{\{N^{(2)}<\bar{W}^{(2)}\}}(N^{(2)}+1)\mu\pi(0,N^{(2)}+1,N^{(3)})\end{aligned}$$

$$
\begin{aligned}
&+1_{\{N^{(3)}<\bar{W}^{(3)}\}}(N^{(3)}+1)\mu\pi(0,N^{(2)},N^{(3)}+1)+(\lambda^{(2)}+\lambda^{(3)})\pi(0,N^{(2)},N^{(3)}-1)\\
&+1_{\{N^{(3)}=\bar{W}^{(3)}\}}\lambda^{(2)}\pi(0,N^{(2)}-1,N^{(3)}),\quad (N^{(2)},N^{(3)}>0), \qquad (15)\\
&\{\lambda+(N^{(1)}+N^{(2)})\mu\}\pi(N^{(1)},N^{(2)},0)=\mu\pi(N^{(1)},N^{(2)},1)\\
&+1_{\{N^{(1)}<\bar{W}^{(1)}\}}(N^{(1)}+1)\mu\pi(N^{(1)}+1,N^{(2)},0)+1_{\{N^{(2)}<\bar{W}^{(2)}\}}(N^{(2)}+1)\mu\pi(N^{(1)},N^{(2)}+1,0)\\
&+\lambda^{(1)}\pi(N^{(1)}-1,N^{(2)},0)+1_{\{N^{(1)}=\bar{W}^{(1)}\}}\lambda^{(1)}\pi(N^{(1)},N^{(2)}-1,0),\quad (N^{(1)},N^{(2)}>0), \qquad (16)\\
&\{\lambda+(N^{(1)}+N^{(3)})\mu\}\pi(N^{(1)},0,N^{(3)})=\mu\pi(N^{(1)},1,N^{(3)})\\
&+1_{\{N^{(1)}<\bar{W}^{(1)}\}}(N^{(1)}+1)\mu\pi(N^{(1)}+1,0,N^{(3)})+1_{\{N^{(3)}<\bar{W}^{(3)}\}}(N^{(3)}+1)\mu\pi(N^{(1)},0,N^{(3)}+1)\\
&+\lambda^{(1)}\pi(N^{(1)}-1,0,N^{(3)})+(\lambda^{(2)}+\lambda^{(3)})\pi(N^{(1)},0,N^{(3)}-1),\quad (N^{(1)},N^{(3)}>0), \qquad (17)\\
&\left\{1_{\{\Gamma\}}\lambda^{(1)}+1_{\{\Theta\}}\lambda^{(2)}+1_{\{N^{(3)}<\bar{W}^{(3)}\}}\lambda^{(3)}+(N^{(1)}+N^{(2)}+N^{(3)})\mu\right\}\pi(N^{(1)},N^{(2)},N^{(3)})=\\
&+1_{\{N^{(1)}<\bar{W}^{(1)}\}}(N^{(1)}+1)\mu\pi(N^{(1)}+1,N^{(2)},N^{(3)})\\
&+1_{\{N^{(2)}<\bar{W}^{(2)}\}}(N^{(2)}+1)\mu\pi(N^{(1)},N^{(2)}+1,N^{(3)})\\
&+1_{\{N^{(3)}<\bar{W}^{(3)}\}}(N^{(3)}+1)\mu\pi(N^{(1)},N^{(2)},N^{(3)}+1)+\lambda^{(1)}\pi(N^{(1)}-1,N^{(2)},N^{(3)})\\
&+(\lambda^{(2)}+\lambda^{(3)})\pi(N^{(1)},N^{(2)},N^{(3)}-1)+1_{\{N^{(1)}=\bar{W}^{(1)}\}}\lambda^{(1)}\pi(N^{(1)},N^{(2)}-1,N^{(3)})\\
&+1_{\{N^{(3)}=\bar{W}^{(3)}\}}\lambda^{(2)}\pi(N^{(1)},N^{(2)}-1,N^{(3)})\\
&+1_{\{N^{(2)}=\bar{W}^{(2)},N^{(3)}=\bar{W}^{(3)}\}}\lambda^{(1)}\pi(N^{(1)},N^{(2)},N^{(3)}-1),\qquad (N^{(1)},N^{(2)},N^{(3)}>0). \qquad (18)
\end{aligned}
$$

In (18), the sets of events Γ and Θ are given by

$$
\begin{aligned}
\Gamma&=\{N^{(1)}<\bar{W}^{(1)}\}\cup\{N^{(2)}<\bar{W}^{(2)}\}\cup\{N^{(3)}<\bar{W}^{(3)}\},\\
\Theta&=\{N^{(2)}<\bar{W}^{(2)}\}\cup\{N^{(3)}<\bar{W}^{(3)}\}.
\end{aligned}
$$