QoS Provisioning with Shared Wavelength Allocation for Limited-range Wavelength Conversion

Takuji Tachibana and Shoji Kasahara

Abstract

With the explosive growth of the Internet, QoS provisioning becomes increasingly important in all-optical wavelength routing network. In this paper, we consider connection loss probability as QoS metrics and propose a wavelength allocation method to provide multiple QoS classes in terms of the connection loss probability. With our method, wavelengths are classified into two types of sets, dedicated wavelength sets and shared wavelength set, and connections are established using idle wavelengths within either set at each node. The performance of our proposed method depends on the capability of wavelength conversion and we also consider how the method is applied to a wavelength routing network with limited-range wavelength conversion capability. To evaluate the performance of our method at node in the network, we model the system with our method as a two-stage queueing system and calculate the connection loss probability of each class with equivalent random method (EQRM). Moreover, we evaluate the performance of the method for ring and mesh-torus networks by simulation. Numerical example show that the shared wavelength allocation method is effective regardless of network topology and network scalability.

Index Terms: All-optical wavelength routing network, QoS provisioning, limited-range wavelength conversion, two-stage queueing model.

I. Introduction

Wavelength division multiplexing (WDM) can readily support ultra-high-speed data transmission with many hundreds of gigabits per second (Gbps) on a single optical fiber. However, opto-electronic-optic (O/E/O) conversion is bottleneck. To resolve the bottleneck, all-optical wavelength routing network have been studied and developed [1]. In all-optical wavelength routing network, connections are established using wavelengths between end nodes and data are transmitted with connections [2], [3], [4], [5], [6], [7].

With the explosive growth of the Internet, a number of users utilize a variety of applications in all-optical wavelength routing network and hence QoS provisioning becomes increasingly important. In [8], the signal degradations due to the length of established connection has been considered and connections are established by wavelengths which can provide sufficient QoS. In [9], the routing problem has been studied in terms of multiple QoS metrics such as bandwidth and delay and it has been shown that the problem is NP-complete.

In [3] and [10], the general approach for service-specific routing and wavelength allocation has been proposed. With the approach, connection is established according to twofold metrics, i.e., QoS metrics (service requirements) and resource metrics (quality constraints). As for QoS metrics, transmission quality, restoration, network management, and policies have been considered and those QoS can be guaranteed. However, to the best of our knowledge, QoS provisioning for connection loss probability in all-optical wavelength routing network have not been considered.

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In this paper, we focus on the connection loss probability as QoS metrics and propose a shared wavelength allocation method to provide multiple QoS classes in terms of the connection loss probability.

In the shared wavelength allocation method, wavelengths consists of multiple dedicated wavelength sets and a shared wavelength set. Each QoS class can utilize wavelengths within its dedicated wavelength set. To provide multiple QoS classes for the connection loss probability, wavelengths are classified into dedicated wavelength sets such that the dedicated wavelength set of high priority class includes more wavelengths than that of low priority class. When a connection request arrives at node, one of available wavelengths in the dedicated wavelength set for its priority class is allocated to the connection. If there are no available wavelengths in the dedicated wavelength set, one of wavelengths in the shared wavelength set is allocated to the connection. Since shared wavelengths are utilized by all classes, it is expected that the shared wavelengths decrease the total connection loss probability.

Since a connection may utilize dedicated and shared wavelengths along its route, wavelength conversion between those wavelengths is required at intermediate nodes. As a result, the wavelength conversion capability of each node affects the performance of the proposed method. The wavelength conversion is classified into two categories: full-range wavelength conversion and limited-range wavelength conversion [1], [11], [12], [13], [14]. Full-range wavelength conversion can convert any input wavelength to any output wavelength and hence our proposed method is applicable. However, it is difficult to provide the full-range wavelength conversion under the current technology [11].

The popular conversion technique is limited-range wavelength conversion which can convert input wavelength to the wavelength among a limited number of wavelengths. With limited-range wavelength conversion, our proposed method is not directly applicable due to the restriction of wavelength conversion capability. In this paper, we also consider how to apply the shared wavelength allocation method to the all-optical wavelength routing network with limited-range wavelength conversion capability. To be more precise, wavelengths are classified into multiple wavelength subsets in advance, and then the shared wavelength allocation method is applied to each subset.

To evaluate the performance of our proposed method, we investigate connection loss probability of each QoS class using approximation analysis and simulation. In the approximation analysis, we model the proposed method at node in wavelength routing network as a two-stage queueing model which has multiple primary stations and single secondary station. Using equivalent random method (EQRM), the connection loss probability of each QoS class is calculated. We also investigate the performance of the method for ring and mesh-torus networks by simulation. In numerical examples, we show how the shared wavelength allocation method affects the connection loss probability in the wavelength routing network with limited-range wavelength conversion.

The rest of the paper is organized as follows. Section II explains the shared wavelength allocation method and how to apply the proposed method to the node with limited-range wavelength conversion. In Section III, to investigate the performance of the shared wavelength allocation method, we present our analytical model at node in wavelength routing network and evaluate the connection loss probability with EQRM. Numerical examples are shown in Section IV and conclusions are presented in Section V.

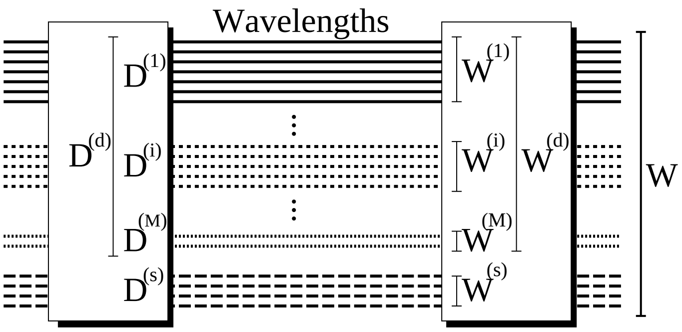

Fig. 1. Shared wavelength allocation method.

II. Shared Wavelength Allocation Method for Limited-range Wavelength Conversion

A. Shared Wavelength Allocation Method

In this section, we explain the shared wavelength allocation method. First, we consider an all-optical wavelength routing network where each node has a full-range wavelength conversion capability and W wavelengths are multiplexed into an optical fiber. M QoS classes in terms of connection loss probability are provided and each QoS class requires different acceptable loss probability. M QoS classes are numbered from 1 to M and class i has high priority over class j when $i < j$. That is, connections of class 1 have the highest priority and require the smallest loss probability. For simplicity, we call a connection of class i i-connection.

In the shared wavelength allocation method, W wavelengths are classified into two wavelength sets: one is the dedicated wavelength set $D^{(d)}$ which includes $W^{(d)}$ wavelengths and the other is the shared wavelength set $D^{(s)}$ which includes $W^{(s)}$ wavelengths (see Fig. 1). Here $W^{(d)} + W^{(s)} = W$. In the following, we call wavelengths in the dedicated wavelength set dedicated wavelengths and wavelengths in the shared wavelength set shared wavelengths.

The dedicated wavelength set $D^{(d)}$ is further classified into M dedicated wavelength subsets $D^{(i)}$ $(i = 1, 2, \cdots, M)$ and i-connection can use dedicated wavelengths in the subset $D^{(i)}$. There are $W^{(i)}$ wavelengths in the dedicated wavelength subset $D^{(i)}$ and we assume that $W^{(i)}$ satisfies

$$W^{(M)} < \cdots < W^{(i)} < \cdots < W^{(1)}, \tag{1}$$

and

$$\sum_{i=1}^{M} W^{(i)} = W^{(d)}. \tag{2}$$

Inequalities of (1) imply that higher priority class can use more wavelengths and may have smaller connection loss probability.

On the other hand, shared wavelengths in $D^{(s)}$ are utilized by any i-connection when there is no idle dedicated wavelength in $D^{(i)}$. At each node in wavelength routing network, wavelength for i-connection is chosen according to the following procedure.

Procedure I:

step 1: If there is at lease one idle wavelength in $D^{(i)}$, an idle wavelength in $D^{(i)}$ is chosen to establish i-connection.

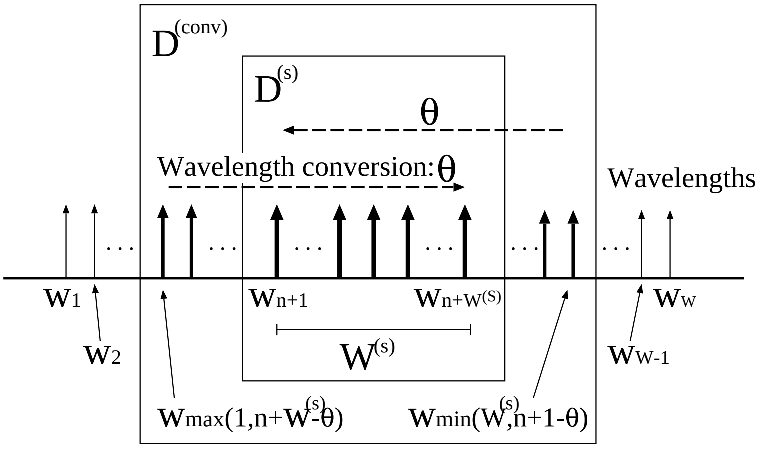

Fig. 2. Relation of $W^{(s)}$, $W^{(conv)}$, and θ.

step 2: If there is no available wavelength in $D^{(i)}$ and there is at least one idle wavelength in $D^{(s)}$, an idle shared wavelength in $D^{(s)}$ is chosen to establish i-connection.

step 3: If there is no available wavelength in both $D^{(i)}$ and $D^{(s)}$, i-connection is lost.

i-connection is eventually established only when all intermediate nodes allocate wavelengths for the i-connection.

As we mentioned in the Introduction, the shared wavelength allocation method depends on wavelength conversion capability. In the next subsection, we develop our proposed method for the all-optical wavelength routing network with limited-range wavelength conversion.

B. Shared Wavelength Allocation under Limited-range Wavelength Conversion

As for limited-range wavelength conversion, a four wavelength mixing (FWM) converter has been considered because it does not depend on the modulation format and the bit rate [15]. In this paper, we also consider FWM limited-range wavelength conversion. According to [1] and [11], we assume that the range of FWM limited-range wavelength conversion for wavelength w_i $(1 \leq i \leq W)$ is from $w_{\max(1,i-\theta)}$ to $w_{\min(i+\theta,W)}$ 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-range wavelength conversion, respectively.

Since FWM wavelength conversion is restricted to threshold θ, whether any wavelength in $D^{(i)}$ is converted to shared wavelength in $D^{(s)}$ or not depends on how to choose wavelengths for the shared wavelength set $D^{(s)}$. To understand the relation of W, $W^{(s)}$ and θ, we first consider the case where the whole wavelength set $\{w_1, \cdots, w_W\}$ consists of one dedicated wavelength set and one shared wavelength set. In the following, we assume that the shared wavelength set $D^{(s)}$ contains successive wavelengths w_{n+1},w_{n+2},$\cdots$, and $w_{n+W^{(s)}}$ for some n (see Fig. 2). From the constraint of wavelength conversion due to θ, the minimum index number of the wavelength which can be converted to any wavelength in $D^{(s)}$ is $\max\{1, n+W^{(s)}-\theta\}$ and the maximum one is $\min\{W, n+1+\theta\}$. That is, any wavelength in the set

$$D^{(conv)} = \Big\{w_{\max\{1,n+W^{(s)}-\theta\}}, w_{\max\{2,n+W^{(s)}-\theta+1\}}, \cdots, w_{n+1}, \cdots, w_{n+W^{(s)}}, \cdots,$$
$$w_{\min\{W-1,n+\theta\}}, w_{\min\{W,n+1+\theta\}}\Big\},$$

can be converted to any wavelength in $D^{(s)}$. If $D^{(conv)}$ is a subset of $\{w_1, \cdots, w_W\}$, the minimum and maximum indices are given by $n+W^{(s)}-\theta$ and $n+1+\theta$, respectively. In this case, the number of wavelengths in $D^{(conv)}$ is equal to

$$2(\theta+1) - W^{(s)} \equiv W^{(conv)}. \tag{3}$$

Note that $W^{(conv)}$ decreases as $W^{(s)}$ increases.

When $W \leq W^{(conv)}$, any wavelength in $\{w_1, \cdots, w_W\}$ can be converted to a shared wavelength in $D^{(s)}$ and this is equivalent to the full-range wavelength conversion. Therefore it is easy to apply the shared wavelength allocation method to this case.

If $W > W^{(conv)}$, there are some wavelengths which cannot be converted to shared wavelength in $D^{(s)}$ due to the restriction of θ and we cannot directly apply the shared wavelength conversion. Now consider the classification of the whole wavelength set into subsets such that we can apply the shared wavelength conversion. Suppose that the whole wavelength set is classified into N subsets $(D_1, \cdots, D_N)$. We introduce the following notations.

W_n: The number of wavelengths in D_n $(1 \leq n \leq N)$.
$D_n^{(i)}$: The dedicated wavelength set of class i $(1 \leq i \leq M)$ in D_n.
$W_n^{(i)}$: The number of wavelengths in $D_n^{(i)}$.
$D_n^{(s)}$: The shared wavelength set in D_n.
$W_n^{(s)}$: The number of wavelengths in $D_n^{(s)}$.

Note that

$$\sum_{n=1}^{N} W_n = W, \qquad \sum_{i=1}^{M} W_n^{(i)} + W_n^{(s)} = W_n, \quad 1 \leq n \leq N,$$
$$\sum_{n=1}^{N} W_n^{(i)} = W^{(i)}, \quad 1 \leq i \leq M,$$

and

$$\sum_{n=1}^{N} W_n^{(s)} = W^{(s)}.$$

For simplicity, we assume that for all m and n $(m \neq n)$,

$$|W_m - W_n| \leq 1. \tag{4}$$

That is, the number of wavelengths in D_n is almost the same as others. We also assume that for all m and n $(m \neq n)$,

$$|W_m^{(s)} - W_n^{(s)}| \leq 1. \tag{5}$$

From the inequality (4) ((5)), W_n $(W_n^{(s)})$ is given by $\lceil W/N \rceil$ $(\lceil W^{(s)}/N \rceil)$ or $\lfloor W/N \rfloor$ $(\lfloor W^{(s)}/N \rfloor)$ where $\lceil x \rceil$ $(\lfloor x \rfloor)$ is the ceil (floor) function of x. From (3), each wavelength in D_n is converted to any wavelength in $D_n^{(s)}$ if W_n and $W_n^{(s)}$ satisfy

$$W_n \leq 2(\theta+1) - W_n^{(s)}, \quad 1 \leq n \leq N. \tag{6}$$

Since $W_n \geq \lfloor W/N \rfloor$ and $W^{(s)} \geq \lfloor W^{(s)}/N \rfloor$, we obtain

$$\left\lfloor \frac{W}{N} \right\rfloor + \left\lfloor \frac{W^{(s)}}{N} \right\rfloor \leq 2(\theta+1). \tag{7}$$

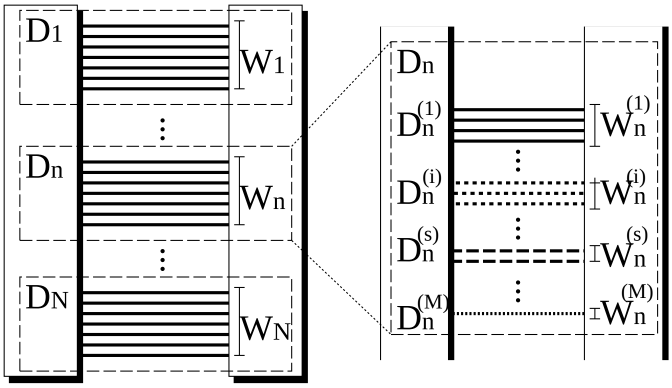

Fig. 3. Application to limited-wavelength conversion.

Note that in general, $\lfloor x \rfloor \leq x < \lfloor x \rfloor + 1$, and hence

$$\lfloor x \rfloor > x - 1.$$

Applying this inequality to (7) yields

$$\frac{W}{N} + \frac{W^{(s)}}{N} - 2 < 2(\theta + 1), \tag{8}$$

and finally we obtain

$$N > \frac{W + W^{(s)}}{2(\theta + 2)}. \tag{9}$$

Therefore, given W, $W^{(s)}$ and θ, N is determined by

$$N = \left\lfloor \frac{W + W^{(s)}}{2(\theta + 2)} \right\rfloor + 1. \tag{10}$$

To apply the shared wavelength allocation method, each subset D_n is further classified into $D_n^{(i)}$ $(1 \leq i \leq M)$ and $D_n^{(s)}$ (see Fig. 3).

A newly arriving i-connection selects D_n according to subset selection strategy. In this paper, we consider random strategy and first-fit one. In the random strategy, D_n is selected randomly with probability $1/N$. The first-fit strategy selects the wavelength subset with the smallest index number such that the subset has idle wavelengths for the connection. Note that first-fit strategy gives smaller loss probability than random one. Since the wavelength allocation procedure depends on the subset selection strategy, we propose the following two procedures.

Procedure II-A (Random strategy):

step 1: A wavelength subset D_n is selected among N subsets according to random strategy to establish i-connection.

step 2: If there is at least one idle wavelength in $D_n^{(i)}$, an idle wavelength in $D_n^{(i)}$ is chosen.

step 3: If there is no available wavelength in $D_n^{(i)}$ and there is at least one idle shared wavelength in $D_n^{(s)}$, an idle shared wavelength in $D_n^{(s)}$ is chosen.

step 4: If there is no available wavelength in both $D_n^{(i)}$ and $D_n^{(s)}$, i-connection is lost.

Procedure II-B (First-fit strategy):

step 1: $n = 1$.

step 2: If there is at least one idle wavelength in $D_n^{(i)}$, an idle wavelength in $D_n^{(i)}$ is chosen.

step 3: If there is no available wavelength in $D_n^{(i)}$ and there is at least one idle shared wavelength in $D_n^{(s)}$, an idle shared wavelength in $D_n^{(s)}$ is chosen.

step 4: If $n < N$ and there is no available wavelength in both $D_n^{(i)}$ and $D_n^{(s)}$, then $n \to n+1$ and go to step 2.

step 5: If $n = N$ and there is no available wavelength in both $D_N^{(i)}$ and $D_N^{(s)}$, i-connection is lost.

III. Performance analysis

In this section, we analyze the performance of the shared wavelength allocation method at node in all-optical wavelength routing network with limited-range wavelength conversion. The following assumptions are made for our analysis.

1. The number of wavelengths at each link is W.
2. QoS parameter is connection loss probability.
3. The number of QoS classes is M and class i has priority over class j $(i < j)$.
4. Connections of class i arrive at node according to a Poisson process with parameter $\lambda^{(i)}$ and total arrival rate at node is $\Lambda = \sum_{i=1}^{M} \lambda^{(i)}$.
5. Connection holding time of class i is exponentially distributed with rate $\mu^{(i)}$.
6. No queueing for arriving connection is permitted, that is, the connection is lost immediately after the connection establishment fails.
7. All nodes in the network have FWM limited-range wavelength converter.
8. The threshold for FWM wavelength conversion is θ.
9. W wavelengths are classified into N subsets where N is determined by (10).
10. Random strategy is used to select a wavelength subset D_n among N subsets.

Now we consider the wavelength subset D_n. The D_n consists of $D_n^{(i)}$'s, the dedicated wavelength sets for i-connections $(1 \leq i \leq M)$, and $D_n^{(s)}$, the shared wavelength set. A shared wavelength in $D_n^{(s)}$ is allocated to newly arriving i-connection when there are no available wavelengths in $D_n^{(i)}$. We model this as a two-stage queueing system illustrated in Fig. 4.

The two-stage queueing system has M primary service stations and one secondary service station. The ith primary station is corresponding to $D_n^{(i)}$, the dedicated wavelength set of i-connection, and the number of servers of ith primary station is $W_n^{(i)}$ which is the number of dedicated wavelengths in $D_n^{(i)}$. Note that all primary stations have no waiting rooms and hence these are loss systems.

On the other hand, the secondary station corresponds to the shared wavelength set $D_n^{(s)}$ and has $W_n^{(s)}$ servers. In the following, $D_n^{(i)}$ implies the ith primary station and $D_n^{(s)}$ the secondary station.

We assume that i-connection arrives at the node according to a Poisson process with rate $\lambda^{(i)}$. Due to the random strategy, arriving i-connection chooses the wavelength subset D_n with probability $P_n^{(i)} = 1/N$. Hence i-connections arrive at D_n according to a Poisson process with rate $\lambda_n^{(i)} = P_n^{(i)}\lambda^{(i)}$. The connection holding time of i-connection is exponentially distributed with rate $\mu^{(i)}$.

An i-connection arrives at the primary station $D_n^{(i)}$ and enters one of idle servers in $D_n^{(i)}$ if those exist. After completion of holding time of the i-connection, the connection leaves the system. If there are no idle servers in $D_n^{(i)}$, the i-connection becomes overflow and it goes to the secondary station $D_n^{(s)}$. If there are also no idle servers in $D_n^{(s)}$, the i-connection is lost.

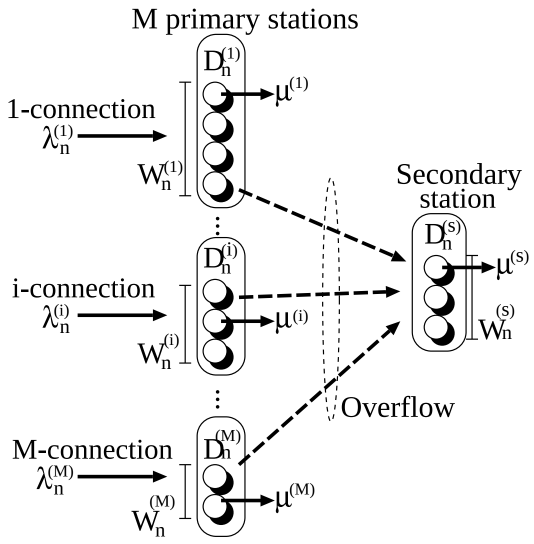

Fig. 4. Two-stage queueing model for D_n.

In general, a two-stage queueing model with Poisson input, exponential service and one primary station is analyzable and we can recursively calculate the probability that an arriving connection is eventually lost. First we summarize the recursive calculation of the loss probability for the two-stage queueing model with one primary station [16]. The readers are referred to [16] for details.

We assume the followings. The system has one primary station and one secondary station. The numbers of servers in primary and secondary stations are c and l, respectively. The customer arrives at the primary station according to a Poisson process with rate λ. The service time of servers in both primary and secondary stations is exponentially distributed with rate μ.

Let B_c denote the blocking probability at the primary station with the number of servers in the primary station equal to c. Then B_c is calculated by the following recursion as a function of c [16]

$$B_{c+1} = \frac{aB_c}{aB_c + c + 1}, \quad c = 0, 1, 2, \cdots, \tag{11}$$

$$B_0 = 1, \tag{12}$$

where a is the offered load at the primary station and given by $a = \lambda/\mu$.

Let m_c denote the offered load to the secondary station. Then m_c is given by

$$m_c = aB_c, \tag{13}$$

and from (11), we obtain

$$m_{c+1} = \frac{am_c}{m_c + c + 1}, \quad c = 0, 1, 2, \cdots, \tag{14}$$

where $m_0 = a$.

We define P_j as the proportion of time that there are j overflowed customers in the secondary system. We also define π_j as the proportion of overflowed arrivals who find j overflowed customers in the secondary system. The loss probability of overflowed customers at secondary station is given by

$$\pi_l = \frac{m_{c+l}}{m_c}. \tag{15}$$

Note that if $l = \infty$, that is, the secondary station has infinite servers, the distribution $\{P_j\}$ has mean m_c and variance

$$V_c \equiv \left\{1 - m_c + \frac{a}{m_c + c + 1 - a}\right\} m_c. \tag{16}$$

If there are M primary stations, the loss probability of the overflowed customers at the secondary station cannot be calculated using (15). Hence we use the EQRM to calculate the loss probability [16], [17]. The EQRM provides the approximation of the loss probability in this case.

In the EQRM, the two-stage queueing model with multiple primary stations is identified with the two-stage one with an equivalent single primary station in the sense that a secondary station with infinite servers has the same mean and variance of the number of customers in the secondary station for this single primary station as it had for the original collection of multiple primary stations.

Let m_i and V_i $(1 \leq i \leq M)$ denote the mean and variance of the number of customers in the secondary station generated by ith primary station, and m and V be the corresponding quantities generated by the collection of M primary stations. Then we obtain

$$m = \sum_{i=1}^{M} m_i, \quad V = \sum_{i=1}^{M} V_i. \tag{17}$$

The equivalent primary station is expressed with (c, a) such that m and V in (17) are equal to m_c in (14) and V_c in (16), respectively. Once (c, a) is determined, the loss probability at the secondary station is approximated by (15).

Now we apply the EQRM to our case. Our goal is to calculate the probability that an arriving i-connection at node is eventually lost. First, we focus on the two-stage queueing system in D_n.

Let $B_k^{(D_n^{(i)})}$ denote the blocking probability at the dedicated wavelength set $D_n^{(i)}$ with k dedicated wavelengths. Since $D_n^{(i)}$ has $W_n^{(i)}$ dedicated wavelengths, $B_{W_n^{(i)}}^{(D_n^{(i)})}$ is required and this can be calculated recursively with (11) and (12) where the offered load a is given by

$$a = \frac{P_n^{(i)} \lambda^{(i)}}{\mu^{(i)}} \quad (\equiv a_n^{(i)}). \tag{18}$$

Let $m_k^{(D_n^{(i)})}$ denote the offered load to the shared wavelength set $D_n^{(s)}$ generated from $D_n^{(i)}$. We can calculate $m_{W_n^{(i)}}^{(D_n^{(i)})}$ from (14) with $a_n^{(i)}$ in (18).

We define $V_k^{(D_n^{(i)})}$ denote the variance of the number of used wavelengths in the shared wavelength set $D_n^{(s)}$ given that $D_n^{(s)}$ has infinite wavelengths and that $D_n^{(i)}$ has k dedicated wavelengths for i-connection. Then, from (16), $V_{W_n^{(i)}}^{(D_n^{(i)})}$ is calculated by

$$V_{W_n^{(i)}}^{(D_n^{(i)})} = \left\{1 - m_{W_n^{(i)}}^{(D_n^{(i)})} + \frac{a_n^{(i)}}{m_{W_n^{(i)}}^{(D_n^{(i)})} + W_n^{(i)} + 1 - a_n^{(i)}}\right\} m_{W_n^{(i)}}^{(D_n^{(i)})}. \tag{19}$$

Let (W_n^p, a_n^p) denote the equivalent single primary station. We find (W_n^p, a_n^p) numerically such that

$$m_{W_n^p} = \sum_{i=1}^{M} m_{W_n^{(i)}}^{(D_n^{(i)})}, \tag{20}$$

Fig. 5. One-hop network.

$$V_{W_n^p} = \sum_{i=1}^{M} V_{W_n^{(i)}}^{(D_n^{(i)})}, \tag{21}$$

where $m_{W_n^p}$ and $V_{W_n^p}$ are calculated by (14) and (16), respectively.

Once (W_n^p, a_n^p) is obtained, the probability that an arriving connection is eventually lost is given by

$$P_L^{(D_n)} = \frac{m_{W_n^p + W_n^{(s)}}}{m_{W_n^p}}. \tag{22}$$

The loss probability of i-connection at D_n is given by

$$P_{L,i}^{(D_n)} = \frac{m_{W_n^{(i)}}^{(D_n^{(i)})}}{m_{W_n^p}} P_L^{(D_n)}, \tag{23}$$

where $m_{W_n^{(i)}}^{(D_n^{(i)})}/m_{W_n^p}$ is the proportion that the overflowed connection to the shared wavelength set in D_n is class i. Finally, the loss probability of i-connection at node level is given by

$$P_{L,i} = \sum_{n=1}^{N} P_n^{(i)} P_{L,i}^{(D_n)}. \tag{24}$$

IV. Numerical Examples

In this section,we show some numerical examples for the shared wavelength allocation method under limited-range wavelength conversion. Three network topologies are considered: (i) one-hop network, (ii) ring network and (iii) mesh-torus network. The performance metric is connection loss probability. In the case of one-hop network, the connection loss probability is calculated by the EQRM and compared with simulation result. In the cases of ring and mesh-torus networks, the connection loss probability is calculated by simulation. In our simulation, we assume that the followings in addition to the assumptions in Section III.

1. The number of nodes in the network is L.
2. Point-to-point traffic is assumed.
3. The pair of source and destination nodes of arriving connection is distributed uniformly, i.e., each pair is selected with the same probability.

A. One-hop Network

In this subsection, we consider one hop network with $L = 2$ as shown in Fig. 5.

We assume that the number of QoS classes M is equal to three and that $\mu^{(1)} = \mu^{(2)} = \mu^{(3)} = 1.0$. We consider random strategy and connections are established according to Procedure II-A.

Fig. 6 shows how the shared wavelength allocation method provides multiple QoS classes in terms of connection loss probability. In this figure, we set $W = 32$, $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)}$, $\theta = 9$, and

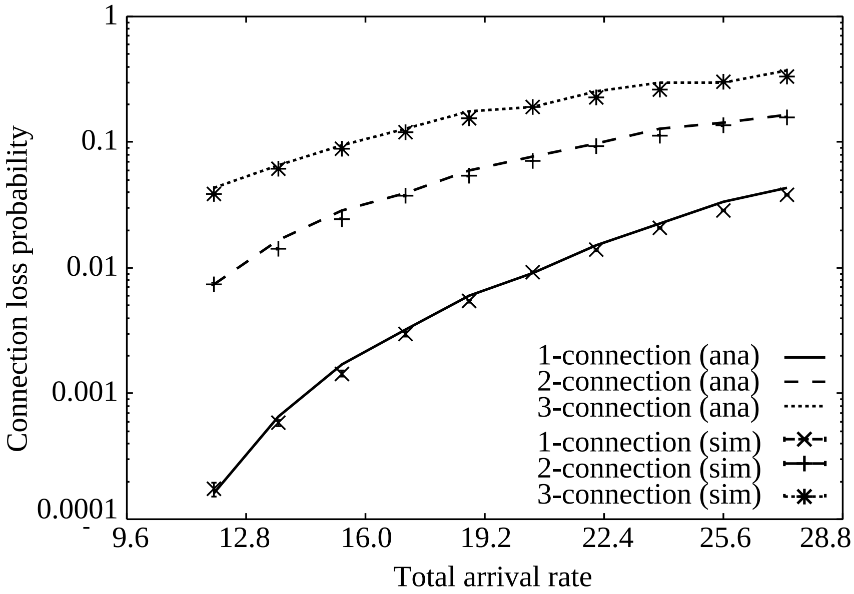

Fig. 6. QoS provisioning with shared wavelength allocation method for one-hop network: $L = 2, W = 32, \theta = 9, and W^{(s)} = 8$.

$W^{(s)} = 8$. From (10), we classify W wavelengths into $N = 2$ wavelength subsets and wavelengths are classified into two wavelength subsets D_1 and D_2 as follows.

$$\begin{pmatrix} W_1^{(1)}, & W_1^{(2)}, & W_1^{(3)}, & W_1^{(s)} \\ W_2^{(1)}, & W_2^{(2)}, & W_2^{(3)}, & W_2^{(s)} \end{pmatrix} = \begin{pmatrix} 7, & 4, & 1, & 4 \\ 7, & 4, & 1, & 4 \end{pmatrix}.$$

In Fig. 6, linear curves and dots denote the results of the approximation analysis with EQRM and simulation, respectively. From this figure, we observe that these two results are almost the same regardless of the increase of total arrival rate and that the EQRM provides good approximation in this case.

We also see that connection loss probability of each class increases as the total arrival rate becomes large. With our proposed method, however, the loss probability of the highest priority class 1 is lower than others even when the total arrival rate is large. At the same time, the loss probability of the lowest priority class 3 is still higher than others. As we expected, the shared wavelength allocation method can provide different connection loss probability for each QoS class.

Fig. 7 shows the connection loss probability versus the number of shared wavelengths $W^{(s)}$. Here we set $W = 60$ and $\theta = 60$. In this case, we can change $W^{(s)}$ from 0 to 60 keeping $N = 1$. We also assume that $(W^{(1)}, W^{(2)}, W^{(3)}, W^{(s)}) = (\frac{W-W^{(s)}}{2}, \frac{W-W^{(s)}}{3}, \frac{W-W^{(s)}}{6}, W^{(s)})$. This keeps the following relation

$$W^{(1)} : W^{(2)} : W^{(3)} = 3 : 2 : 1. \tag{25}$$

In terms of connection arrival rate of each class, we set $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = 14.0$.

In Fig. 7, linear curves represent the results of the EQRM approximation and dots represent simulation results. In addition to the loss probability of each class, the total loss probability of connections regardless of QoS classes is plotted.

When the number of shared wavelengths $W^{(s)}$ is small, the connection loss probability of the highest priority class 1 is quite small while the connection loss probabilities of classes 2 and 3

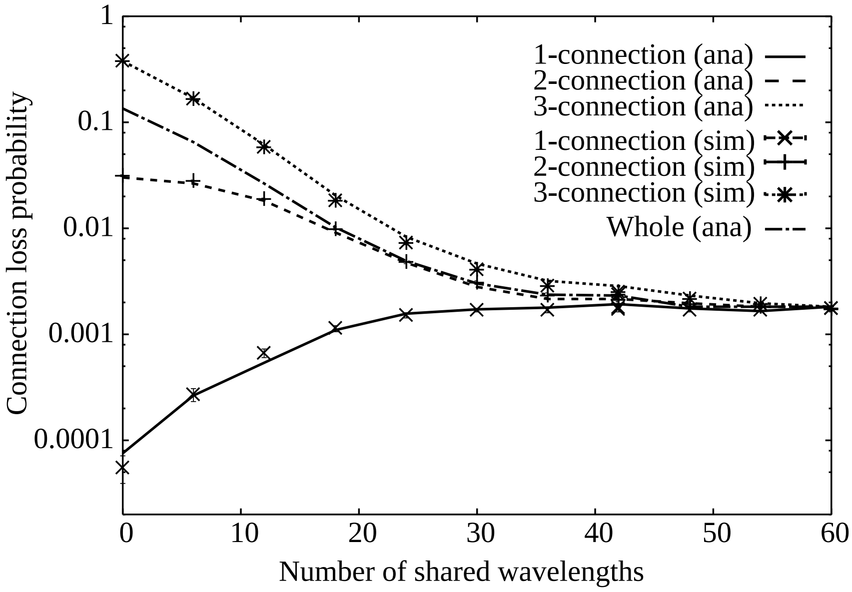

Fig. 7. Impact of shared wavelengths for one-hop network: $L = 2$, $W = 60$, and $\theta = 60$.

are high. As $W^{(s)}$ increases, the connection loss probability of class 1 becomes large and those of classes 2 and 3 become small. In addition, large $W^{(s)}$ decreases the whole connection loss probability. When $W^{(s)}$ increases, however, the loss probabilities of all classes become the same and the shared wavelength allocation method can not provide multiple QoS classes in terms of loss probability.

It is known that a development of FWM wavelength conversion technology or a new wavelength conversion technology is required to increase θ and resulting cost is quite expensive. Therefore we have to decide the optimal number of shared wavelengths $W^{(s)}$ considering the QoS requirement of each class, the wavelength conversion capability, and the resulting cost.

The approximation of the EQRM provides the significant information to determine the value of $W^{(s)}$.

B. Ring Network

In this subsection, we investigate the performance of the shared wavelength allocation method for ring network by simulation. As stated in [4], ring topology provides the worst performance among the topologies which have the same numbers of nodes and wavelengths. Here, we consider a unidirectional ring network as shown in Fig. 8.

In this subsection, we assume that $M = 3$ and $\mu^{(1)} = \mu^{(2)} = \mu^{(3)} = 1.0$. To select a wavelength subset, we use first-fit strategy.

Fig. 9 shows how total connection arrival rate affects connection loss probability of each QoS class. In this figure, we set $L = 10$, $W = 32$, $\theta = 9$, and $W^{(s)} = 8$. According to (10), $N = 2$ and wavelengths are classified as follows;

$$\begin{pmatrix} W_1^{(1)}, & W_1^{(2)}, & W_1^{(3)}, & W_1^{(s)} \\ W_2^{(1)}, & W_2^{(2)}, & W_2^{(3)}, & W_2^{(s)} \end{pmatrix} = \begin{pmatrix} 6, & 4, & 2, & 4 \\ 6, & 4, & 2, & 4 \end{pmatrix}. \tag{26}$$

We also assume that $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)}$.

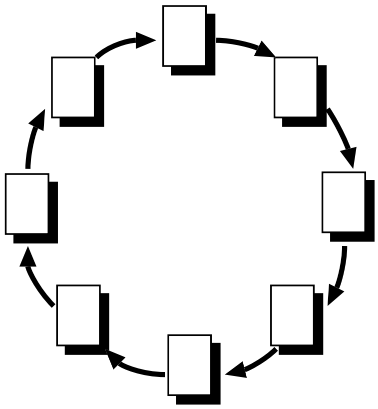

Fig. 8. Ring network.

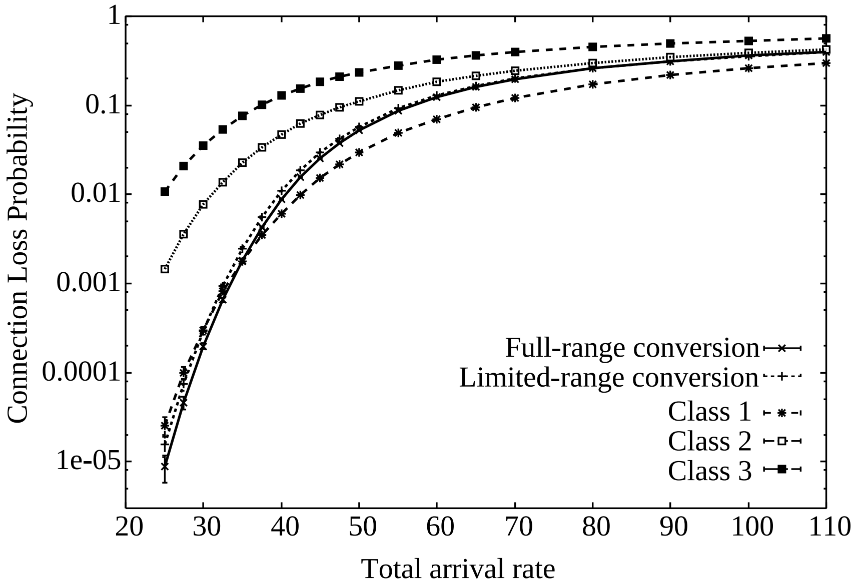

Fig. 9. Connection loss probability vs. total arrival rate for ring network: $L = 10$, $W = 32$, $\theta = 9$, and $W^{(s)} = 8$.

We also consider the loss probabilities under the following two cases; (a) full-range wavelength converters are used, and (b) FWM limited-range wavelength converters are used but our method is not applied. In both cases, QoS classes are not taken into consideration and the loss probability of connections under single class is calculated by simulation. Connection arrival rate in these two network is the same as the total arrival rate Λ.

From Fig. 9, we observe that our proposed method can also provide different connection loss probability for each QoS class in the ring network. The connection loss probability of the case (b) is always larger than that of the case (a). The shared wavelength allocation method can provide smaller loss probability for the highest class 1 and provide better quality of service for loss probability than full-range wavelength conversion.

On the other hand, the connection loss probabilities of classes 2 and 3 are larger than that in the case of FWM limited-range wavelength conversion. This is due to the small numbers of dedicated

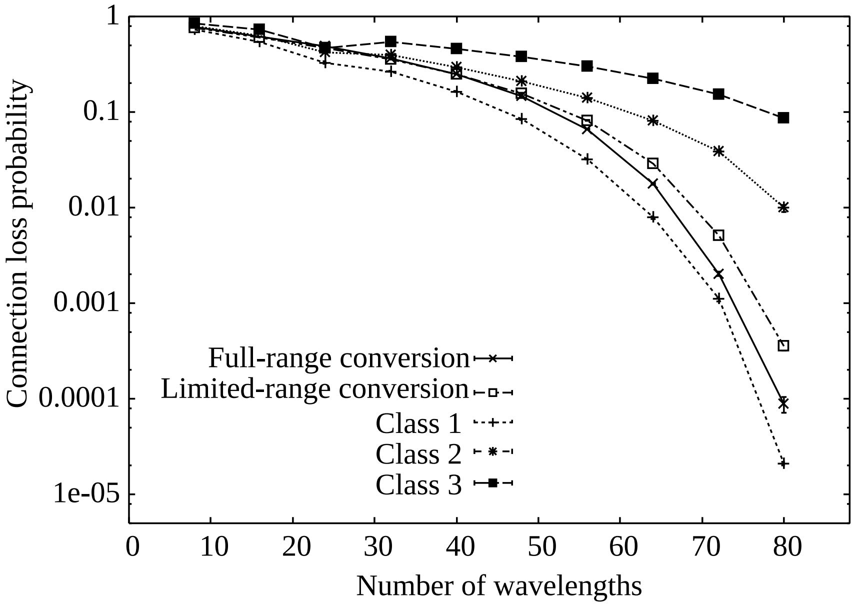

Fig. 10. Connection loss probability vs. the number of wavelengths for ring network: $L = 10$ and $\theta = 4$.

wavelengths of both classes.

When the total arrival rate is small, the loss probability in the case of full-range wavelength conversion is close to that of class 1. As the total arrival rate increases, the loss probability in the case of full-range wavelength conversion is close to that of class 2. Hence our proposed method is more effective in heavy traffic condition.

Next we investigate the impact of the number of total wavelengths on our proposed method. Fig. 10 shows how the number of wavelengths affects the connection loss probability of each class. In this figure, we set $L = 10$, $\theta = 4$, and $\lambda^{(1)}$=$\lambda^{(2)} = \lambda^{(3)} = 100/3$.

The number of wavelengths W increases with increments of eight wavelengths. When $W = 8k$ $(k = 1, 2, \cdots)$, we set $W^{(s)} = 2k$ and W_n wavelengths are classified as follows;

$$(W_n^{(1)}, W_n^{(2)}, W_n^{(3)}, W_n^{(s)}) = (3, 2, 1, 2), \quad 1 \le n \le k.$$

From Fig. 10, we observe that the connection loss probability of each QoS class decreases as the number of wavelengths becomes large. The loss probability of class 1 decreases as well as that in the case of full-range wavelength conversion while the loss probabilities of classes 2 and 3 less decrease than that of class 1.

Even if θ is fixed due to the constraint of wavelength conversion technology or cost, our method can provide multiple QoS classes in terms of connection loss probability and lower loss probability can be achieved by increasing the number of wavelengths.

C. Mesh-torus Network

Finally, we consider an $n \times n$ mesh-torus network [10], [4] as shown in Fig. 11. The number of nodes in this network is $L = n \times n$ and those nodes are connected with bidirectional links. Three QoS classes are provided with the shared wavelength allocation method. We also set $\mu^{(1)} = \mu^{(2)} = \mu^{(3)} = 1.0$.

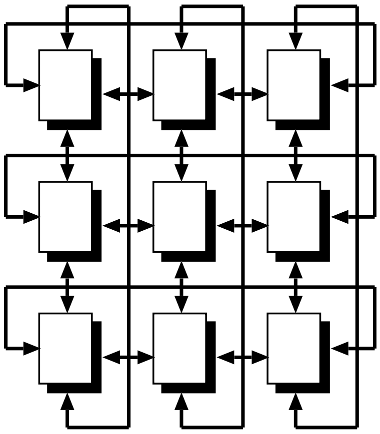

Fig. 11. Mesh-torus network.

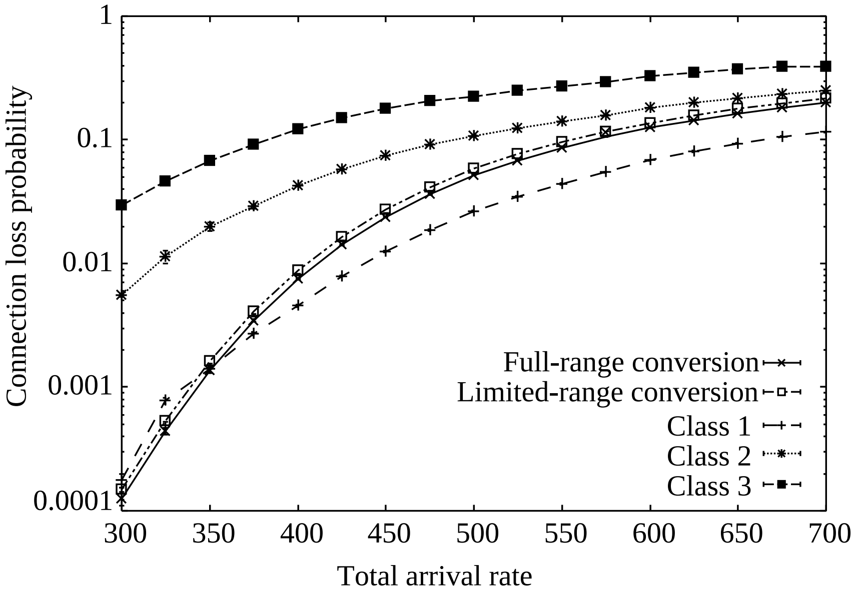

Fig. 12. Connection loss probability vs. total arrival rate for mesh-torus network: $L = 25$, $W = 32$, $\theta = 9$, and $W^{(s)} = 8$.

As is the case with [4], connections are established between source and destination nodes using the deterministic routing algorithm as follows. We define D_x and D_y as the shortest distance in the number of links from source node to destination node along the x and y axes, respectively. When $D_x \geq D_y$, we choose a link on the x axis as the next one to get close to the destination node. When $D_x < D_y$, a link on the y axis is chosen. We repeat this procedure until D_x and D_y become zero.

We also consider the two cases of full-range wavelength conversion and FWM limited-range wavelength conversion where our proposed method is not applied. Moreover first-fit strategy is used to select a wavelength subset and the performance of our method is evaluated by simulation.

Fig. 12 shows the connection loss probability versus the total connection arrival rate. We set $W = 32$, $n = 5$, i.e., $L = 25$ and $\theta = 9$. When $W^{(s)} = 8$, we apply our proposed method as shown in (26). In terms of connection arrival rates, $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)}$.

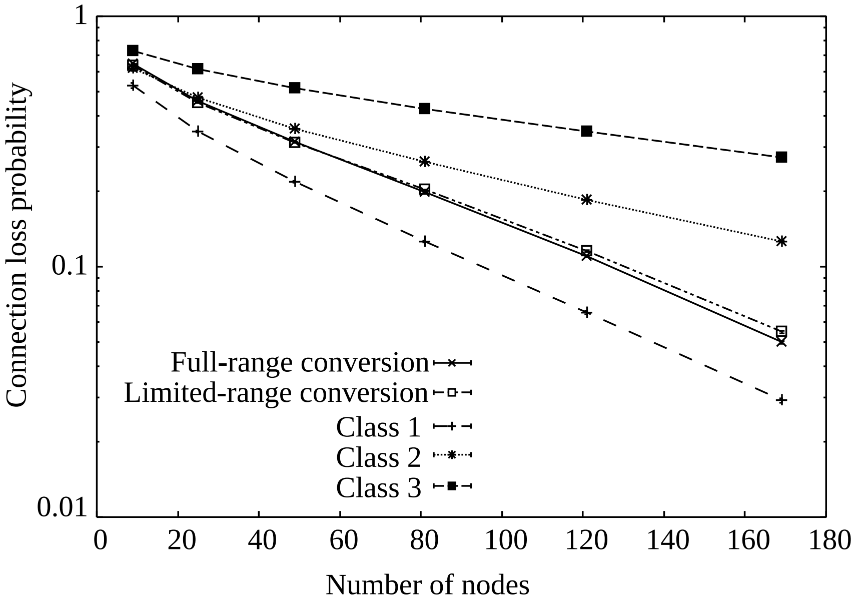

Fig. 13. Connection loss probability vs. number of nodes for mesh-torus network: $W = 32$, $\theta = 9$, and $W^{(s)} = 8$.

From Fig. 12, we find that the shared wavelength allocation method can also provide multiple QoS classes for connection loss probability in the mesh-torus network. We further observe that the loss probability of each class in the mesh-torus network shows the same tendency as that in the ring network. Hence our proposed method is effective despite of network topology.

Fig. 13 shows how the number of nodes in mesh-torus network affects the connection loss probability of each class. In this figure, we set $W = 32$, $\theta = 9$ and $W^{(s)} = 8$. Our method is applied as shown in (26). Moreover we assume that $\lambda^{(1)} = \lambda^{(2)} = \lambda^{(3)} = 400$.

In this figure, multiple QoS classes are always provided in terms of the connection loss probability. Hence our method is applicable for a large mesh-torus network under the limited-range wavelength conversion. In addition, the class 1 connection achieves the lowest loss probability even when the number of nodes are large.

From Figs. 12 and 13, we conclude that our proposed method is quite efficient even when the network has large number of nodes and is highly congested.

V. Conclusion

In this paper, we have proposed the shared wavelength allocation method to provide multiple QoS classes in terms of connection loss probability. Because our method is affected by the wavelength conversion capability, we have considered how the method is applied under the limited-range wavelength conversion. We have modeled the system with our method as a two-stage queueing system and calculated the connection loss probability of each class with the equivalent random method (EQRM). Then we have evaluated the performance of the method under three network topology; one-hop, ring, and mesh-torus networks.

From numerical examples, we have found that our method can provide multiple QoS classes in terms of the loss probability. Moreover our method is efficient for the scalability of network under the restriction of wavelength conversion capability.

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