Performance of Alternate Routing Methods in All–Optical Switching Networks

Hiroaki Harai, Masayuki Murata and Hideo Miyahara

Department of Informatics and Mathematical Science
Graduate School of Engineering Science, Osaka University
Toyonaka, Osaka 560, Japan

Abstract

We study routing methods in all–optical switching networks. In all–optical switching networks, the connection with more hops encounters more call blocking, and it is especially true in optical networks with no wavelength conversions. We therefore consider an alternate routing method with limited trunk reservation in which connections with more hops are prepared more alternate routes. Through developing an approximate analytic approach, we show that our method keeps good performance when compared with the existing alternate routing methods, and also that the fairness among connections can be improved. Further performance improvement is investigated by introducing a wavelength assignment policy and a dynamic routing method. An effectiveness of the proposed method is investigated through simulation.

1 Introduction

An amount of traffic that a network should handle is rapidly growing due to the recent advancement of multimedia computing and communication technologies. However, switching systems based on the current electronic technology cannot provide enough capacity to meet those requirements. An all–optical switching technology thus becomes important for future very high speed networks. In the optical switching network, switching nodes can be expected to have throughput of an order of gigabit per second. Moreover, no optical from/to electronic conversion is required. Recently, a lightpath architecture is proposed for optical switching based on a circuit–switching method in [1-4]. In the lightpath architecture, network nodes perform demultiplexing and linear operation such as power dividing and amplification on optical signals, which makes it possible to perform all operations in the optical domain and to simplify the network management (Fig. 1).

A main problem in optical networks is that the wavelength conversion at the optical node is difficult. Then, the same wavelength should be assigned to the connection on all the links along the route if a capability of wavelength conversion is not provided at the switching node. In [1,

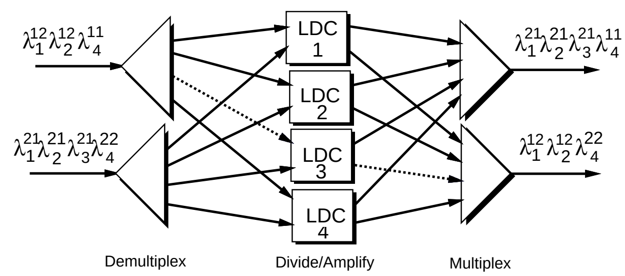

Figure 1: A switching process at a node

2], the performances of a fixed routing method with and without wavelength conversions are compared, and it is shown that the fixed routing method without wavelength conversions remarkably degrades performance in terms of call blocking probability through approximate analysis and simulation techniques. The alternate routing method and the dynamic routing method including LLR (least loaded routing) are then introduced in [2, 3, 5] to improve performance by providing more routes for each connection. In the alternate routing, if there is no available wavelength on the primary route, the secondary route is examined to seek the available wavelength. If it is found, the connection is established along the secondary route.

In this paper, we consider a new class of alternate routing to achieve high network performance as well as to improve a fairness among connections with different numbers of hop counts. In general, the connection with shorter hop counts is likely to be accepted while the one with more hops encounters more call blocking. It is because the latter requires to reserve more links at the connection setup time. It is especially true in optical networks with no wavelength conversions since the same wavelength must be available along the route. In fact, the authors in [1, 2] show that in optical networks without wavelength conversions, the performance is considerably degraded as the number of hop counts is increased. In order to sustain the performance degradation of connections with more hops, an *Rsv* (Wavelength Reservation) and a *Thr* (Protecting Threshold) methods are proposed in [2]. In the former method, a given

0-8186-7780-5/97 $10.00 1997 IEEE

number of wavelengths on each link is dedicated to connections with more hops while in the latter, the connections with shorter hops are assigned an idle wavelength only if the number of idle wavelengths on the link is at or above a given threshold. However, both methods degrade the overall network performance (i.e., call blocking probabilities averaged over all connections) due to the use of dedicated wavelengths for specific connections, which results in decrease of wavelength utilization. In this paper, we consider an *alternate routing method with limited trunk reservation* (a *limited alternate routing method* for short) in which connections with more hops are provided more alternate routes in proportion to the number of hop counts. By this method, we can expect the performance improvement of connections with more hops at the expense of larger blocking probabilities of ones with shorter hops, leading to improve a fairness among connections. Another notable feature obtained in our method is that overall network performance can also be improved as will be shown later.

A key issue in our method is how to determine the number of alternative routes dependent on the number of hop counts. In Section 2, we develop an approximate analytic approach for alternate routing methods including our proposed one. It is performed by extending an existing approach developed for the fixed routing [1, 2]. We then exhibit the effectiveness of our method by comparing with the conventional fixed routing and alternate routing, in which a fixed number of alternative routes is provided with every connection.

A wavelength assignment is a unique problem of optical networks. When the several wavelengths are available on the route, which one is better to be chosen for good performance? In our approximate analysis, we make an assumption that the wavelength is chosen randomly. However, in such a case, more call blocking tends to occur for later arriving connections with more hops. We can expect to decrease a call blocking probability by introducing the first–fit policy in which the available wavelength is always sought from the same wavelength on every route. By this policy, the connection with more hops can have more occasions to find the available wavelength on the route. In Section 3, through simulation experiments, we show that the routing method with first–fit wavelength assignment can slightly improve performance when compared to the one with random wavelength assignment.

Last, we investigate further performance improvement by introducing a dynamic routing. In this study, we focus on the combination of routing selection and wavelength assignment, which has not been paid much attention in the past literature. In the alternate routing, its route is determined by the predefined order. In the dynamic routing, on the other hand, its route and wavelength are determined by monitoring the global state of the network resources, more specifically the number of free wavelengths on all links. We will show the grade of performance improvement by our dynamic method in Section 4.

Finally, Section 5 presents our conclusions and future works.

2 Approximate Analysis and Performance of Alternate Routing Methods

2.1 Analytic Model

We introduce the following notations to describe our alternate routing method and its analysis.

(1) A network consists of J links, each of which has W wavelengths.

(2) By introducing m_j for the number of idle wavelengths on link j, the network state can be represented as $\mathbf{m} = (m_1, m_2, \cdots, m_J)$. The state space is $\mathcal{M} = \{0, \cdots, W\} \times \cdots \times \{0, \cdots, W\}$.

(3) Any route R is a subset of the link set $\{1, 2, \cdots, J\}$. The number of hop counts for route R is denoted as $h(R)$.

(4) Denote $R_a^{(i)}$ for i th route between source/destination pair a. In our model, it is assumed that every route for each source/destination pair does not share the same link in order to simplify description. The number $r(R_a^{(i)})$ of wavelengths is reserved for the route $R_a^{(i)}$. (See the next subsection for our routing method.)
Let $\mathcal{R}^{(1)}$ denote a set of primary routes. In alternate routing, let us denote $\mathcal{R}^{(i)}$ for the set of i th routes. Further, we introduce $\mathcal{R}_j^{(i)}$ denoting the set of i th routes that employ link j . Moreover, $P_j^{(i-)}$ is introduced for representing the i th route of route P_j that employs link j .

(5) In the analysis, we will assume that connection setup requests arrive at route $R_a^{(1)}$ following a Poisson distribution with rate $e_{R_a^{(1)}}$. The holding times of all connections are assumed to be exponentially distributed with unit mean.

2.2 Alternate Routing Method with Limited Reservation

An outline of our alternate routing method is performed when the connection setup request of the source/destination pair a arrives.

(I) The following connection setup procedure is performed for routes $R_a^{(i)}, i = 1, \ldots, n_a$, where n_a represents the number of routes provided for source/destination pair a.

(I-i) Determine the available number of wavelengths, m, for links on route $R_a^{(i)}$. If wavelength conversion is allowed, m is the minimum number of idle wavelengths on the link on route $R_a^{(i)}$. If

0-8186-7780-5/97 $10.00 1997 IEEE

wavelength conversion is not permitted, on the other hand, m is the number of idle wavelengths through all links on the route.

(I-ii) If the number of idle wavelengths is larger than the number of reserved wavelengths on i th route, i.e., if $m > r(R_a^{(i)})$ for m determined in Step (I-i), the connection is established using a wavelength selected randomly from idle wavelengths (m) on that route. If $m \le r(R_a^{(i)})$, the connection is not accepted on route $R_a^{(i)}$ and next $(i+1)$ th route is examined.

(II) If the connection cannot be established on any route of $R_a^{(i)}, i = 1, \ldots, n_a$, the connection request is blocked.

2.3 Numerical Algorithm

Let X_j be the random variable for the number of idle wavelengths on link j in steady state. The corresponding density is denoted as

$$q_j(m_j) = \mathrm{P}(X_j = m_j), \qquad m_j = 0, \cdots, W$$

To make an analysis tractable, we assume that random variables $X_1, X_2, \cdots, X_J$ are independent;

$$q(\mathbf{m}) = \prod_{j=1}^{J} q_j(m_j), \qquad \mathbf{m} \in \mathcal{M}.$$

Furthermore, we assume that the interarrival time for the next connection setup request is exponentially distributed with parameter $\alpha_j(m_j)$ if there are m_j idle wavelengths on link j [5]. It follows that

$$q_j(m_j) = \frac{W(W-1)\cdots(W-m_j+1)}{\alpha_j(1)\alpha_j(2)\cdots\alpha_j(m_j)} q_j(0), \qquad m_j = 1, \cdots, W \tag{1}$$

where

$$q_j(0) = \left[1 + \sum_{m_j=1}^{W} \frac{W(W-1)\cdots(W-m_j+1)}{\alpha_j(1)\alpha_j(2)\cdots\alpha_j(m_j)}\right]^{-1} \tag{2}$$

We then determine the steady state probabilities $\{q(\mathbf{m}) : \mathbf{m} \in \mathcal{M}\}$ using the algorithm below.

(i) Choose $\alpha_j(\cdot), j = 1, \cdots, J$ arbitrarily for all links.

(ii) Determine $\{q(\mathbf{m}) : \mathbf{m} \in \mathcal{M}\}$ using Eqs.(1) and (2).

(iii) Calculate $\alpha_j(\cdot), j = 1, \cdots, J$ which will be described in the following subsection.

(iv) Calculate the blocking probability L_a for all source–destination pair a (see Eq. (3)). If new values of L_a are converged to the older ones, the iteration is terminated. Otherwise go to Step (ii) for next iteration.

2.4 Determination of $\alpha_j(m_j)$ without Wavelength Conversions

We extend the analysis for fixed routing based on a reduced load approximation method in [1, 3, 5] to the alternate routing in all–optical switching networks. In this subsection, we show the case where wavelength conversions are not provided.

When the wavelength conversion is not allowed on the node, the same wavelength must be idle throughout the route for connection establishment. We introduce $u_i(m_j; P_j)$ which represents the probability that when the number m_j of wavelengths is idle on link j, i wavelengths are available on the route P_j that includes link j. By letting the link set of P_j be $\{j, j_1, j_2, \cdots, j_{h(P_j)-1}\}$, the probability $u_i(m_j; P_j)$ is given by the following equation [3].

$$\begin{aligned} u_i(m_j; P_j) = \sum_{m_{j_1}=0}^{W} \sum_{m_{j_2}=0}^{W} \cdots \sum_{m_{j_{h(P_j)-1}}=0}^{W} & q_{j_1}(m_{j_1}) q_{j_2}(m_{j_2}) \cdots q_{j_{h(P_j)-1}}(m_{j_{h(P_j)-1}}) \\ & \times p_i^{h(P_j)}(m_j, m_{j_1}, m_{j_2}, \cdots, m_{j_{h(P_j)-1}}) \end{aligned}$$

where $p_i^n(\cdot)$ is determined by the following recursive relation [3].

$$\begin{aligned} & p_i^n(m_{j_1}, m_{j_2}, m_{j_3}, \cdots, m_{j_n}) \\ & \qquad = \sum_{k=0}^{W} p_i^2(k, m_{j_n})\, p_k^{n-1}(m_{j_1}, m_{j_2}, \cdots, m_{j_{n-1}}) \end{aligned}$$

$$p_i^2(x,y) = \begin{cases} \beta(x,y,i), & \text{if } x \ge i, \quad y \ge i, \\ & \quad x + y - i \le W, \\ & \quad 0 \le x, y \le W \\ 0, & \text{otherwise} \end{cases}$$

The conditional probability $\beta(x,y,n)$ is the probability that there exist n available wavelengths under the condition that x and y wavelengths are available on successive two links. From [1], $\beta(x,y,n)$ is given by

$$\begin{aligned} \beta(x,y,n) = & \left(\prod_{i=1}^{n} \frac{y-i+1}{n-i+1}\right) \left(\prod_{i=1}^{x} \frac{x-i+1}{W-i+1}\right) \\ & \times \left(\prod_{i=1}^{x-n} \frac{W-y-i+1}{x-n-i+1}\right). \end{aligned}$$

Now, we focus on some link j. By considering all primary routes traversing link j, the corresponding arrival rate of connection requests at link j is given as

$$\sum_{P_j \in \mathcal{R}_j^{(1)}} e_{P_j} \left(1 - u_0(m_j; P_j)\right).$$

If link j is included in some secondary routes, overflowing connection requests from the primary routes should also taken into account. Such a case takes place when $m_j > r(P_j)$ and contribution of such a rate becomes

$$\sum_{P_j \in \mathcal{R}_j^{(2)}} e_{P_j^{(1-)}} v_0\left(P_j^{(1-)}\right) \left[\sum_{k=r(P_j)+1}^{W} u_k(m_j; P_j)\right]$$

where

$$v_i\left(P_j\right) = \sum_{m_j=0}^{W} q_j(m_j) u_i(m_j; P_j).$$

If link j is included in some tertiary routes, overflow rate from secondary routes becomes

$$\sum_{P_j \in \mathcal{R}_j^{(3)}} e_{P_j^{(1-)}} v_0\left(P_j^{(1-)}\right)$$
$$\times \left[1 - \sum_{k=r(P_j^{(2-)})+1}^{W} v_k\left(P_j^{(2-)}\right)\right]$$
$$\times \left[\sum_{k=r(P_j)+1}^{W} u_k(m_j; P_j)\right].$$

In a similar way, overflow rate can be also determined in the case where the route P_j traversing link j is i th route. By introducing $r(P_j^{(1-)}) \equiv 0$, we have the following equation by collecting all the rates in the above.

$$\alpha_j(m_j) = \sum_{l=1}^{\max n_a} \left[\sum_{P_j \in \mathcal{R}_j^{(l)}} e_{P_j^{(1-)}} \right.$$
$$\times \left\{\prod_{n=1}^{l-1}\left[1 - \sum_{k=r(P_j^{(n-)})+1}^{W} v_k(P_j^{(n-)})\right]\right\}$$
$$\left. \times \left[\sum_{k=r(P_j)+1}^{W} u_k(m_j; P_j)\right]\right]$$

where $\max n_a$ is a maximum number of alternate routes provided for route P_j traversing link j.

Finally, we derive the blocking probability. The probability that a connection cannot be established on the primary route $R_a^{(1)}$ is given by

$$\sum_{m_j=0}^{W} q_j(m_j) u_0(m_j; R_a^{(1)}).$$

By letting the above probability be $v_0(R_a^{(1)})$, the probability that the connection cannot be established on the secondary route is then determined as

$$v_0(R_a^{(1)}) \times \left\{1 - \sum_{k=r(R_a^{(2)})+1}^{W} v_k(R_a^{(2)})\right\}.$$

If n_a routes are provided for some source/destination pair a, the blocking probability L_a then becomes

$$L_a = v_0(R_a^{(1)}) \times \prod_{l=2}^{n_a}\left\{1 - \sum_{k=r(R_a^{(l)})+1}^{W} v_k(R_a^{(l)})\right\}$$

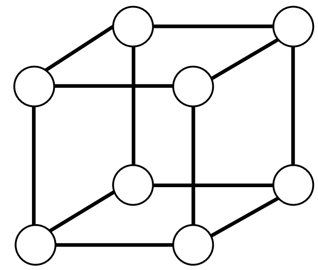

Figure 2: The network model (1)

$$= \prod_{l=1}^{n_a}\left\{1 - \sum_{k=r(R_a^{(l)})+1}^{W} v_k(R_a^{(l)})\right\}. \quad (3)$$

2.5 Numerical Examples and Discussions

In this subsection, we first assess the accuracy of our approximation approach. Then, numerical examples are provided to discuss the effect of the alternate routing method.

2.5.1 Assessment of Approximation

To assess the accuracy of the approximate analysis, we compare with simulation results by using the following model. The network model is depicted in Fig. 2 in which the bidirectional link connects two adjacent nodes. To clearly demonstrate the dependence of blocking probabilities on hop counts of routes, we limit generation of connection setup requests only at the source/destination pairs satisfying the following conditions.

(1) If there exists a 1-hop route between source/destination pair, it is used as the primary route. One of 3-hop routes is used as the secondary one (since we do not have 2-hop routes in this case). The tertiary route is not provided.

(2) If a smallest hop is two, it is used as the primary route. Another 2-hop route is used as the secondary route. The tertiary route is not provided.

(3) If the route with more than three hops is the shortest one, it is used as the primary route and the second and third shortest routes are used as the alternate routes. The forth route is not provided.

We note here that for brevity, the source/destination pair satisfying conditions (1) through (3) in the above are also referred to as 1-hop, 2-hop and 3-hop connections, respectively.

Alternative routes for each source/destination pair are set to have no common links. In simulation, the arrival rate, e_R, of connections setup request at all source/destination pairs are identical. Table 1 shows parameter sets we have used for comparison. In the table, the parameter, $r(R^{(i)})$, means that on i th route of h-hop route, the connection is allowed to be established only if the number of idle wavelengths on the route is larger than $r(R^{(i)})$. The symbol "–" for $r(R^{(i)})$ shows that i th route is not provided in the cases

Table 1: Parameter sets for comparison (1)

		$r(R^{(1)}), r(R^{(2)}), r(R^{(3)})$		
type	W	for 1-hop	for 2-hop	for 3-hop
type 1	4	$0, 4, -$	$0, 0, -$	$0, 0, 0$
type 2	8	$0, 2, -$	$0, 0, -$	$0, 0, 1$

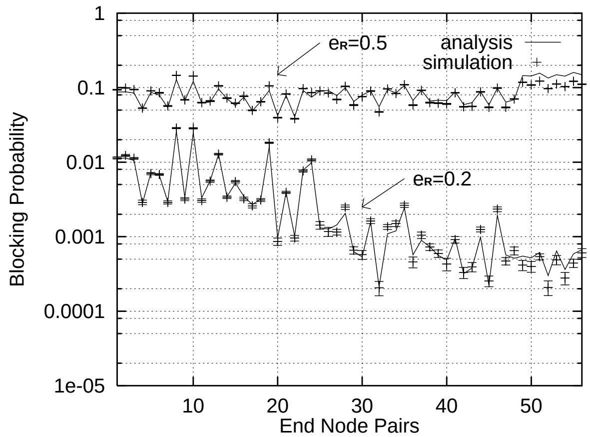

Figure 3: Comparison between analysis and simulation results (type 1)

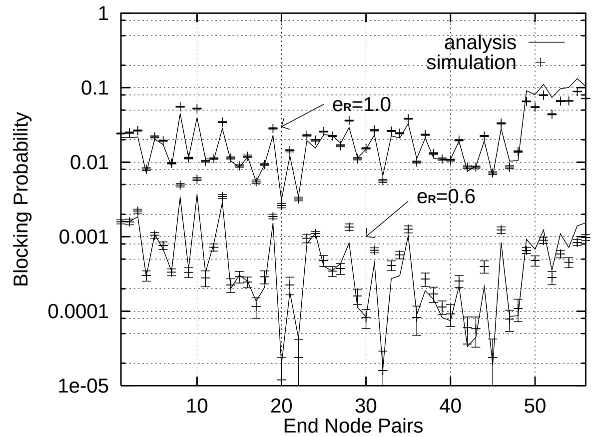

Figure 4: Comparison between analysis and simulation results (type 2)

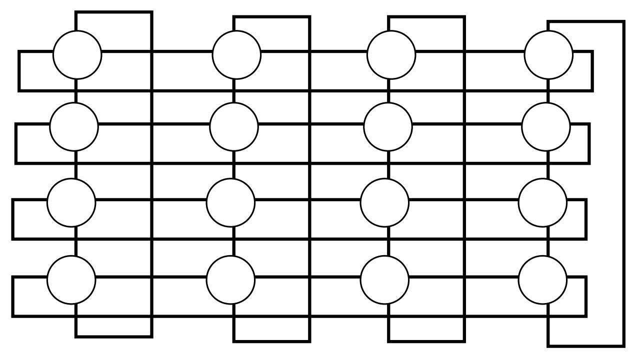

Figure 5: The network model (2)

of fixed and alternate routing methods.

Figures 3 and 4 present the results for different numbers of wavelengths, $W = 4$ and 8. The horizontal axis in the figures shows the index of the source/destination pair; indices from 1 to 24, from 25 to 48, and from 49 to 56, correspond to the source/destination pair satisfying the above conditions (1), (2), and (3), respectively. The vertical axis shows the blocking probability at each source/destination pair. In the approximate analysis, iteration is required and the convergence criteria was set to be 10^{-6} for the blocking probabilities. Simulation results are given with 95% confidence intervals. From two figures, we can observe that blocking probabilities of 3-hop connections obtained through the analysis are slightly overestimated than those by simulation. However, analytic results in other conditions are in good agreement with simulation results.

2.5.2 Numerical Results and Discussions

In what follows, we compare three routing methods based on our analytic approach. Connection setup requests only arrive at the source/destination pairs which satisfies one of conditions described in Subsection 2.5.1. Figure 5 depicts our network model, consisting of 16 nodes. Overall blocking probabilities (averaged over all source/destination pairs) and the blocking probabilities dependent on the hop count of the primary route are used as performance measures.

We employ the following routing methods for comparison purposes. Parameter sets for each routing method are shown in Table 2.

(a) Fixed routing: no alternate route is provided.

(b) Alternate routing: two routes (one for the primary route and another for the secondary route) are always provided regardless of the number of hops of the route. When the primary (or secondary) route has at least one idle wavelength, the connection is established.

(c) Limited alternate routing: the number of alternate routes is controlled by parameter $r(R^{(i)})$. Its difference from ordinary alternate routing in the above is that 1-hop connections are less likely to be established on the secondary routes. Further, 3-hop connections are provided with the tertiary route while not in the alternate routing. We will use two sets of parameters (see (c-1) and (c-2) in the table).

Figures 6 through 9 correspond to the above four cases.

Table 2: parameter sets for comparison (2)

	$r(R^{(1)}), r(R^{(2)}), r(R^{(3)})$		
Method	for 1-hop	for 2-hop	for 3-hop
(a)fixed	$0, -, -$	$0, -, -$	$0, -, -$
(b)alternate	$0, 0, -$	$0, 0, -$	$0, 0, -$
(c-1)limited	$0, 1, -$	$0, 0, -$	$0, 0, 1$
(c-2)limited	$0, 2, -$	$0, 1, -$	$0, 0, 1$

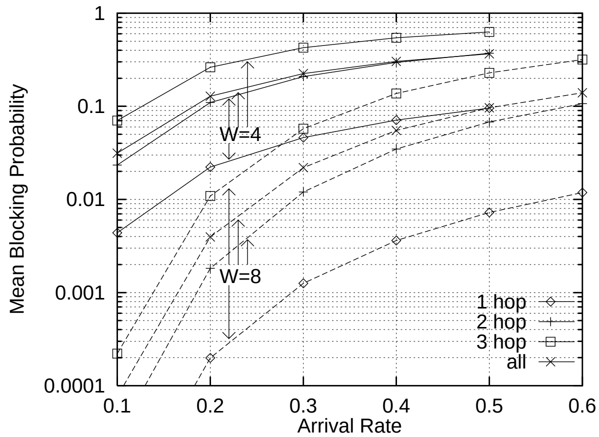

Figure 6: (a) fixed routing method

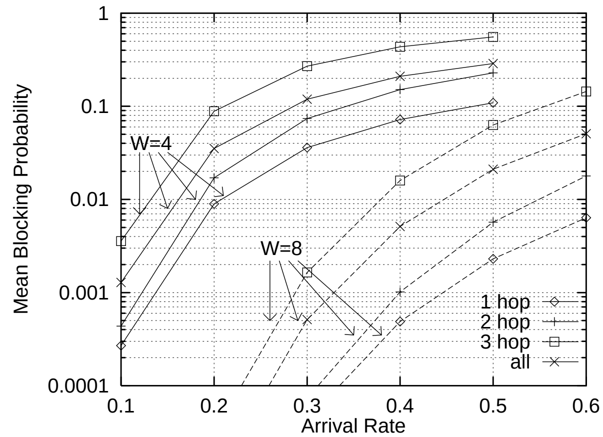

Figure 7: (b) alternate routing method

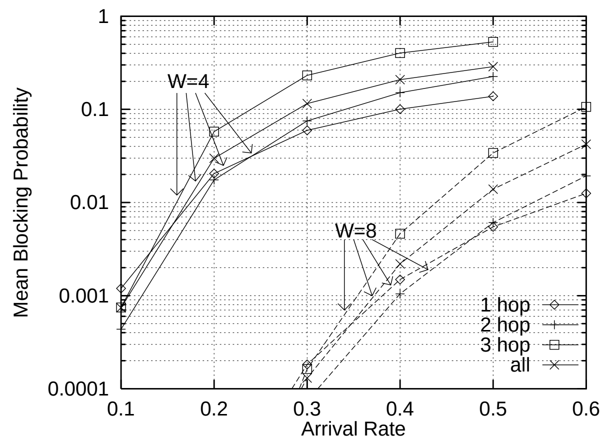

Figure 8: (c-1) limited alternate routing method

In the figures, we plot overall blocking probabilities as well as average blocking probabilities dependent on the number of hop counts to observe the fairness among connections. The arrival rates are identical among all source/destination pairs. In all figures, two cases for the number of wavelengths on each link are shown, i.e., $W = 4$ and 8.

Figures 6 and 7 show the analytic results of (a) fixed routing method and (b) alternate routing method, respectively. By comparing two figures, we can observe that blocking probability is improved by introducing alternate routes. However, in both routing methods, the differences in blocking probabilities between 1-hop and 3-hop connections are beyond an order of magnitude.

We next compare (b) alternate routing method (Fig. 7) and (c-1) limited alternate routing method (Fig. 8). As can be seen from the figures, our limited alternate routing method decreases an average blocking probability of 3-hop connections (labeled by "3-hop" in the figure) as expected. More notably, an overall blocking probability ("all") is also improved by limiting the call acceptance of 1-hop connections, which leads to more call establishments of 3-hop connections. As a consequence, our limited alternate routing method can improve the fairness among connections with different numbers of hop counts. This tendency is remarkable when the traffic load is low. The last figure (Fig. 9) shows that fairness can be further improved by adjusting parameters as shown in the row (c-2) in Table 2. This fairness property is established by less acceptance of 1-hop and 2-hop connections (i.e., $r(R^{(2)}) = 2$ for all 1-hop connections and $r(R^{(2)}) = 1$ for all 2-hop connections).

3 Effects of Wavelength Assignment Policies

In the previous section, we have assumed that the wavelength is randomly chosen if the multiple wavelengths are available on the route. However, a wavelength assignment is one of important issues in all–optical switching networks. In this section, we investigate the effect of following wavelength assignment policies by simulation.

(i) Random Assignment:
If a multiple number of wavelengths is available on the examined route between source/destination pair, the assigned wavelength is chosen randomly.

(ii) First–Fit Assignment:
The wavelength is assigned according to a predefined order [1]. In simulation, we assume that the wavelengths are indexed and the free wavelength with the smallest index is selected.

(iii) MaxWave Assignment [4]:
In the above two policies, the wavelength to be assigned is sought from the available wavelengths only on the predetermined (fixed or alternate) route. On the contrary, in the MaxWave policy, the wavelength is determined according to the usage status of wavelengths in the whole network. Namely, when a connection setup request arrives, the most used wavelength in the whole network is first selected. Then it is examined whether the selected wavelength is free on the route or not. If not, the secondly used wave-

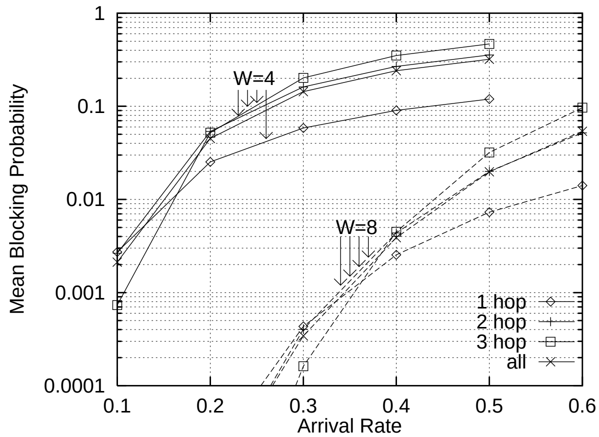

Figure 9: (c-2) limited alternate routing method

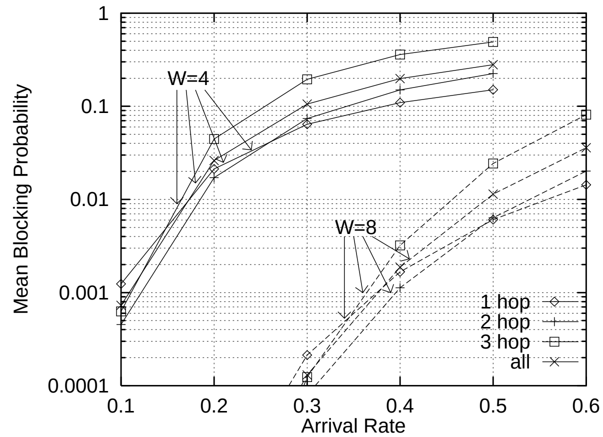

Figure 10: Blocking probability of (i) random policy

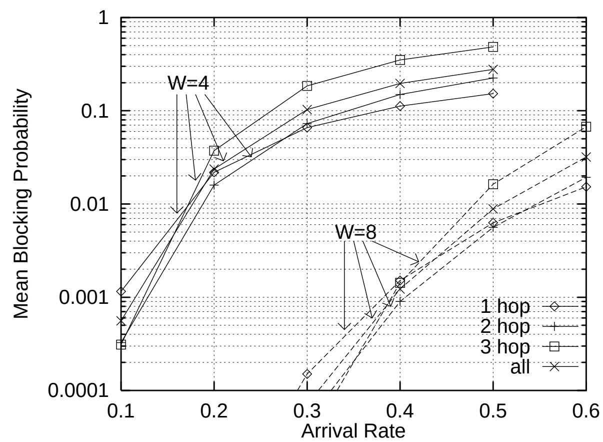

Figure 11: Blocking probability of (ii) first–fit policy

length is sought for a possible use to establish the connection, and so on. In this policy, the usage status of the wavelengths in the whole network should be maintained, which is different from the above two policies where the availability of the wavelength on the route is only examined. By the MaxWave policy, it is expected that some wavelengths with large indices are left unused in the network, which is likely to be used for the more hop connections.

In the current section, we treat this policy only for comparison purposes. A dynamic routing method which maintains the network global state will be further investigated in the next section.

Since the authors in [1] has compared random and first–fit assignment policies for fixed routing, our investigation in this section is devoted to the alternate routing method. We use the (c-1) limited alternate routing in Table 2 as the routing method, and it is applied to the network model depicted in Fig. 5.

Figures 10 and 11 show the simulation results for the random and the first–fit wavelength assignment policies. The result of the MaxWave policy is omitted due to space limitation. The number of connection setup requests at each source/destination pair during each simulation run is 100,000. By comparing the random and first–fit wavelength assignment policies, it is observed that the first–fit policy can improve the blocking probability of the connections with more hops (labeled by “3-hop” in Fig. 11) as one expects. However, it is very limited.

We also observe that performance of the MaxWave policy is very close to that of the first–fit policy. In the first–fit policy, the wavelength with the smaller index is likely to be used for the connection setup, and such a wavelength assignment policy is only applied to the selected route, not considering the usage of wavelengths in the whole network. However, we can observe from the figures that the wavelength assignment policy used in the first–fit policy is sufficient for the network model which we have tried. One point we should note here is that in the MaxWave policy, the order of routes examined for the wavelength assignment is preordered. In the next section, we will investigate the dynamic routing method in which the wavelength assignment and the routing determination are considered at the same time.

4 An Effect of Dynamic Routing

In the previous section, we have investigated the effects of wavelength assignments in the alternate routing method. In this section, we introduce the dynamic routing method in which the wavelength assignment as well as the route selection are determined according to the current global network status, i.e., the usage status of the wavelengths in the whole network. Since the dynamic routing requires the control overhead including the introduction of the center node which maintains the network global state, the main objective of the current section is limited to confirm how the performance can be improved by introducing such a dynamic routing method.

Basically, our dynamic routing method is an extension of the MaxWave policy mentioned in the previous section. The multiple routes are provided for each source/destination pair. Then, for each route, the number of free wavelengths is checked and selected in conjunction with the usage status of the wavelengths in the whole network. We introduce following notations to describe our dynamic routing method more specifically.

(i) For each wavelength $\lambda_i (1 \leq i \leq W)$, the number of links on which the wavelength is idle is counted, and it is denoted by β_i. A set of the wavelengths is represented by $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$ and a set of the corresponding number of links is denoted by $\mathcal{B} = \{\beta_1, \beta_2, \ldots, \beta_W\}$.

(ii) Let a set of routes provided for a source/destination pair a be $\mathcal{S}_a = \{S_1, S_2, \ldots, S_{n_a}\}$ where n_a is a number of routes on which a connection can be established for the pair a. A set of the corresponding number of hop counts is denoted by $\mathcal{H} = \{h_1, h_2, \ldots, h_{n_a}\}$. When the connection setup request arrives at the source/destination pair a, the number of free wavelengths on route S_i is denoted as γ_i. Then, we have a set of $\Gamma = \{\gamma_1, \gamma_2, \ldots, \gamma_{n_a}\}$.

(iii) To determine the route and the wavelength, we have the number of idle links for each wavelength in the whole network ($\mathcal{B}$) and the information on each route. For the latter, we consider the available number of wavelengths (Γ) and the number of hop counts ($\mathcal{H}$). We then introduce a constant α_1 $(0 \leq \alpha_1 \leq 1)$ and a function θ_j to represent the weighted sum of the above three variables;

$$\delta_{ij} = \alpha_1 \beta_i + (1 - \alpha_1)\theta_j(\gamma_j, h_j),$$

where the function θ_j is related to the local information regarding the possible routes for the source/destination pair a, i.e., θ_j is a function of the hop counts h_j and the available number of wavelength γ_j. We then choose δ_{ij} with a smallest value to establish a connection using the wavelength λ_i on the route S_j.

Note that when the hop count of each route is not taken into account, $\theta_j(\gamma_j, h_j)$ may be given as $W - \gamma_j$. Then, the smaller value of α_1 gives a preference on the available number of the wavelength on the route. Or, we may set δ_{ij} as $\alpha_2 (0 \leq \alpha_2 \leq 1)$,

$$\delta_{ij} = \alpha_1 \beta_i + (1 - \alpha_1)\{\alpha_2(W - \gamma_j) + (1 - \alpha_2)h_j\}.$$

by introducing another constant α_2 to incorporate the hop counts of the route. On the other hand, a larger value of α_1 selects the wavelength which is more used in the network. As an example, we illustrate Fig. 12 where cases of $\alpha_1 = 0.25$ and 0.5 are shown. We further notice that $\alpha_1 = 0$ corresponds to the case where the usage status of wavelength in the whole network is not considered. In this case, the wavelength may be examined in the order of $\lambda_1, \ldots, \lambda_W$ which leads to the first-fit wavelength assignment policy presented in the previous section.

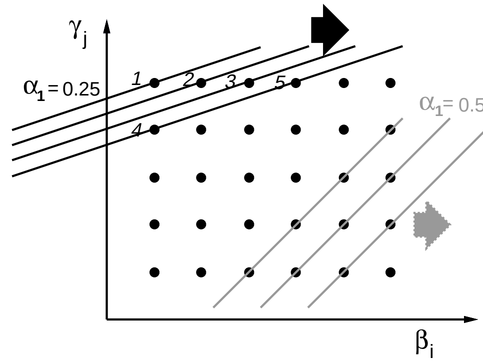

Figure 12: Selected order of wavelength and route in dynamic routing

The network performs the following steps at the connection setup request time for the source/destination pair a.

(I) Update the usage status of the wavelengths in the whole network $\mathcal{B} = \{\beta_1, \beta_2, \ldots, \beta_W\}$. However, if constant $\alpha_1 = 0$, this step is not performed.

(II) Evaluate the number of idle wavelengths $\Gamma = \{\gamma_1, \gamma_2, \ldots, \gamma_{n_a}\}$ on the route set $\mathcal{S}_a = \{S_1, S_2, \ldots, S_{n_a}\}$. If every route has no available wavelength, i.e., if $\gamma_1 = \gamma_2 = \ldots = \gamma_{n_a} = 0$, the request is blocked.

(III) Calculate δ_{ij} to order the set of routes and wavelengths. A smallest value of δ_{ij} is chosen to establish a connection using the wavelength λ_i on the route S_j. If two or more sets of δ_{ij} are identical, then first choose the wavelength with the smallest β_i. If the order is not still determined, choose the route with the largest $\alpha_2(W - \gamma_j) + (1 - \alpha_2)h_j$ secondly. If it is impossible to establish the connection on the selected combination of the route and the wavelength, the next δ_{ij} is examined.

Now, we compare the dynamic and alternate routing methods. In simulation, the network model depicted in Fig. 5 is used to compare the alternate routing method using first-fit wavelength assignment and the above dynamic routing method. Simulation was run until 100,000 connection setup requests are generated for every source/destination pair. For the weighted function δ_{ij}, we have used

$$\delta_{ij} = \alpha_1 \beta_i + (1 - \alpha_1)\theta_j(\gamma_j, h_j),$$

where

$$\theta_j(\gamma_j, h_j) = W - \gamma_j,$$

since the effect of consideration on hop counts was little in our model setting.

Figure 13 shows results dependent on the number of wavelengths on each link. In this case, α_1 is set to be

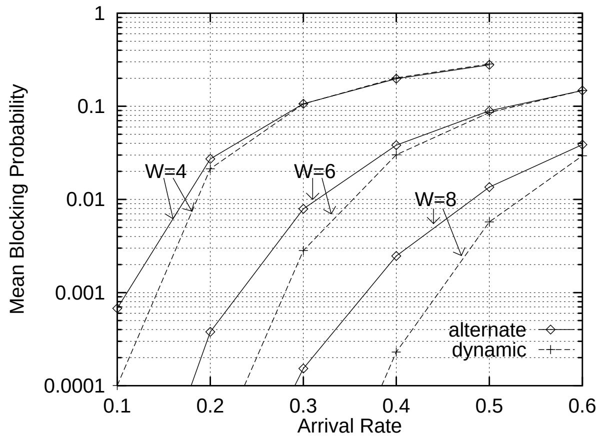

Figure 13: Comparison between alternate and dynamic routing

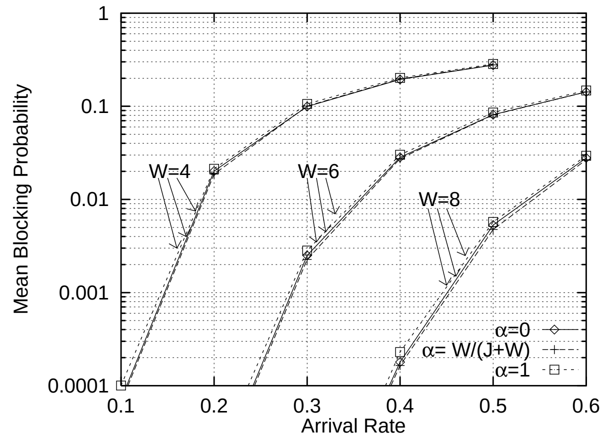

Figure 14: Performance of the dynamic routing dependent on α_1

1. That is, $\mathcal{B}$ is considered to determine the wavelength, and the route is chosen according to the predetermined order. From the figure, we can observe that the dynamic routing outperforms the alternate routing as traffic load becomes low. The dynamic routing method also becomes efficient with the larger number of wavelengths. It is due to the fact that some specific wavelengths are likely to be idle by increasing wavelengths. It may conclude that if we have enough wavelengths on each link, the dynamic routing method can be useful. However, the effect becomes limited as the number of wavelengths is small, and in that case the alternate routing with the first-fit wavelength assignment is sufficient.

We next show results for three different values of constant $\alpha_1 = 0, W/(J+W)$, and 1 in Fig. 14. Recalling that J represents the number of links in the whole network, the value $\alpha_1 = W/(J+W)$ corresponds to the case where both the number of idle links for each wavelength ($\mathcal{B}$) and the available number of wavelengths on each route (Γ) are equally weighted. Figure 14 shows that the equally weighted case ($\alpha_1 = W/(J+W)$) outperforms the other two cases, but the degree of performance improvement is very limited. That is, the dynamic routing is efficient, but a selection method of wavelengths and routes does not affect the performance with significant differences. Of course, such a conclusion cannot be drawn unless extensive evaluation is carried out using various network topologies, which should be a future research topic.

5 Concluding Remarks

In this paper, we have proposed a new class of alternate routing method in all–optical switching networks. We have developed a new approximate analytic approach for the alternate routing method including our proposed method. Numerical results have shown that our routing method can improve overall blocking probability as well as a fairness among connections with different numbers of hop counts. We have also investigated the effect of the wavelength assignment method. Performance improvement can be observed by introducing the first-fit method even for the alternate routing, but the network global information (i.e., the available number of wavelengths in the whole network required in the MaxWave method) is not necessary. The effect of introducing the dynamic routing method has also been investigated, showing that the dynamic routing method is efficient when traffic load is low or many wavelengths are prepared on the link.

In this paper, we have only shown results for one example network. More discussions are required for the various network configurations.

References

[1] M. Kovačević and A. Acampora, "Benefits of Wavelength Tramslation in All–Optical Clear–Channel Networks," *IEEE J. Select. Areas in Commun.*, vol. 13, pp. 868–880, June 1996.

[2] A.Birman and A.Kershenbaum, "Routing and Wavelength Assignment Methods in Single–Hop All–Optical Networks with Blocking," *IEEE INFOCOM '95*, pp. 431–438, 1995.

[3] A. Birman, "Computing Approximate Blocking Probabilities for a Class of All–Optical Networks," *IEEE J. Select. Areas in Commun.*, vol. 13, pp. 852–857, June 1996.

[4] I. Chlamtac, A. Ganz, and G. Karmi, "Purely Optical Networks for Terabit Communication," *IEEE INFOCOM '89*, pp. 887–896, 1989.

[5] S.-P. Chung, A. Kashper, and K. W.Ross, "Computing Approximate Blocking Probabilities for Large Loss Networks with State-Dependent Routing," *IEEE/ACM Transactions on Networking*, vol. 1, pp. 105–115, February 1993.