A wavelength assignment method for distributed wavelength-routed networks using a circular wavelength-list

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***Abstract*— One promising approach to the effective utilization of wavelength division multiplexing networks is to transfer data on an on-demand basis. That is, when a data transfer request arises at a source node, one wavelength is dynamically reserved between the source and destination nodes, and a lightpath is configured between the nodes. Setting up a lightpath consists of three phases: (1) routing, (2) wavelength assignment, and (3) wavelength reservation. In this paper, we focus on wavelength assignment. In a distributed wavelength-routed network, a lightpath request is blocked when its assigned wavelength is already occupied by another lightpath request due to a propagation delay between the nodes. Conventional studies assume that a wavelength for the lightpath is selected randomly in the distributed lightpath setup method. However, this random selection method causes unnecessary blocks of lightpath requests, even when the arrival rate of requests is low. In this paper, we develop a novel method for assigning wavelengths, based on the first-fit algorithm. In our proposed method, the intermediate nodes forecast the wavelength that will be selected at the destination node, so that the subsequent lightpath requests avoid the forecasted wavelengths. The forecasted wavelength is thus kept available until the corresponding request reserves it, which prevents wavelength conflicts with other lightpath requests. Computer-simulated performance comparison showed that our method reduces the blocking probability by more than one order of magnitude compared to random selection.**

I. Introduction

Demands on optical networks that use wavelength division multiplexing (WDM) technology have increased with the growing volume of Internet traffic, and these networks have been the subject of much research [1], [2].

Two main types of networks, opaque and all-optical, are widely considered. A main drawback of opaque networks, which require optical-electronic-optical (O-E-O) conversion or regeneration at every intermediate node, is the high cost of the additional O-E-O converters at the intermediate nodes. Moreover, data transmission is delayed by the processing speed of these converters. Therefore, all-optical networks that do not require electronic processing in the network are expected to be used in the infrastructure of the next-generation Internet.

However, the bursty nature of Internet traffic makes the large bandwidth provided by WDM technology difficult to fully utilize. For instance, Internet traffic varies substantially during work hours but decreases late at night. Therefore, even if we prepare one lightpath between nodes (e.g., for transporting the day traffic), traffic may decrease and not require the lightpath (e.g., for transporting the night traffic). Considering the bursty nature of the traffic, one promising approach to utilize WDM networks effectively is to transfer the data on an on-demand basis. That is, when a data transfer request arises at the source node, a wavelength is dynamically reserved between the source and destination nodes, and a lightpath is configured. After the data transmission finishes using the lightpath, the lightpath is immediately torn down. This dynamic establishment of lightpaths increases the bandwidth efficiency for transporting the Internet's traffic.

There are two approaches to setting up lightpaths: centralized and distributed. In the centralized approach, one management node controls the setup or release of lightpaths. On the other hand, in the distributed approach, each node works independently. The centralized approach can utilize the network resources more efficiently because a special node manages all of the lightpath requests. However, it has two problems. One is low scalability: the processing capability of the management node limits the network size. Another is poor survivability: when the management node breaks down, we cannot establish new lightpaths. Unlike the centralized approach, the distributed approach has high scalability and robust survivability. In this study, we focused on the distributed wavelength-routed WDM networks.

In the distributed approach, setting up a lightpath consists of three phases: (1) routing, (2) wavelength assignment, and (3) wavelength reservation. The first and second phases are also known as *routing and wavelength assignment* (RWA) problem, which determines which route the lightpath goes through and which wavelength is assigned for the lightpath. Extensive research has been done on this problem [3]–[6]. For the third phase, two wavelength reservation methods have been developed to set up the lightpath in a distributed manner [7]. In both methods, the lightpaths are established by exchanging control packets between source and destination nodes. The actual reservation of the link resources is performed while the control packet is traveling from either the source node to the destination node (i.e., in a forward direction), or from the destination node to the source node (i.e., in a backward direction). Several studies have been done on reservation schemes to reduce the blocking probability for lightpath requests [8]–[12].

Several algorithms have been proposed for wavelength assignment problem (For example, SPREAD or MAX–SUM algorithms. See details for [5].) However, conventional studies on wavelength assignment problem do not consider the blocking during wavelength reservation process. Without this blocking, how to spread lightpath requests on links is an essential for wavelength assignment problem [13], [14].

In the distributed networks, the end node does not know which wavelength should be assigned to the lightpath. The selected wavelength may already be occupied by other node pairs. In such a case, the reservation is blocked at the intermediate node (Figure 1). This is because the node does not know when and where other lightpath requests arrive. Conventional studies assume that a wavelength for the lightpath is selected randomly in the distributed lightpath setup method [7]–[12]. However, this random selection causes unnecessary blocks of lightpath requests, even when the arrival rate of requests is low [15], [16]. Therefore, a more efficient wavelength assignment method for distributed wavelength–routed networks is needed.

In this paper, we propose a novel wavelength assignment method that is based on the first-fit algorithm to reduce the blocking probability during wavelength reservation process. In this method, wavelengths are put in order of their indexes. This wavelength list can be reordered according to information from the intermediate nodes. The wavelength at the top of the list is selected for lightpath establishment. The intermediate nodes forecast the wavelength that will be selected at the destination node so that the subsequent lightpath requests avoid using the forecasted wavelengths. By doing this, the forecasted wavelength is kept available until the corresponding request reserves it, which prevents wavelength conflicts with other lightpath requests. We used computer simulation to evaluate our method, and confirmed that it can be used to select wavelengths more efficiently than the random selection method, reducing the blocking probability.

The rest of the paper is organized as follows. In Section 2, we outline wavelength-routed WDM networks and the conventional wavelength assignment method. In Section 3, we present a new wavelength assignment method, and evaluate our proposed method by computer simulation in Section 4. Finally, we conclude our discussion in Section 5.

II. Distributed Wavelength-routed WDM Networks

The physical topology of our network model consists of optical cross-connects (OXCs) that are connected by optical fibers. An optical fiber has $W + 1$ wavelength channels: one used as a control channel and the others used as data channels. The control channel carries the control signal (or

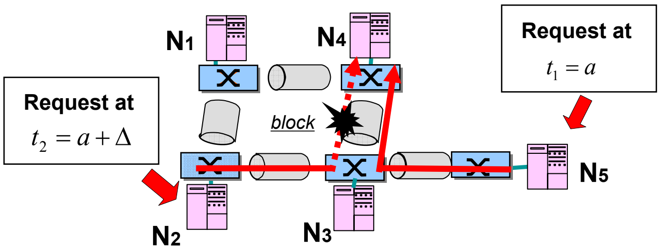


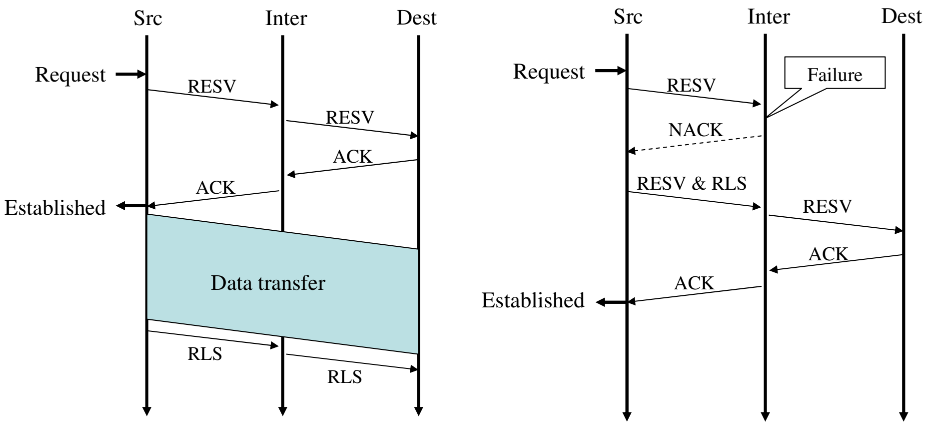
Fig. 1. Distributed wavelength–routed WDM networks: blocking occurs when two or more lightpath requests arrive almost at the same time.

control packet), and the control packet sets up and/or tears down the lightpath. The control channel carries the control signal (or control packet), and the control packet sets up and/or tears down the lightpath. Distributed networks do not have a central controller; each node controls routing and wavelength assignment in cooperation with the neighboring nodes. Our research focuses on the wavelength assignment and wavelength reservation, but not on the routing problem. Since the wavelength assignment is closely related to the wavelength reservation method, we first describe the wavelength reservation method in the distributed wavelength-routed WDM networks.

A. Distributed wavelength reservation method

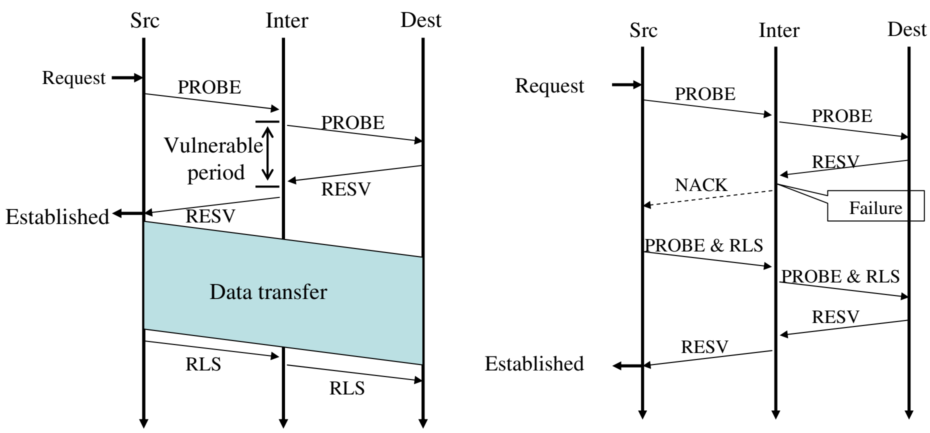
The distributed wavelength reservation method is mainly categorized into two reservation schemes: *forward reservation* and *backward reservation*. Figures 2 and 3 illustrate *forward reservation* and *backward reservation* respectively.

- *Forward reservation method*
  In the forward reservation method, the source node sends a reserve–request (RESV) packet when a lightpath setup request arises. The RESV packet reserves a wavelength from the source node to the destination node. More specifically, it reserves a wavelength at every intermediate node that is in the source-destination path. First, the source node selects a wavelength for reservation from an available wavelength group in the next link and sends a RESV packet toward the destination node. When an intermediate node receives the RESV packet, it extracts a candidate wavelength for the lightpath from the wavelength information in the control packet. Then, it checks the next link to determine whether the candidate wavelength is available. If it is available, the intermediate node reserves the wavelength and forwards the RESV packet to the next node. The lightpath is established as soon as the RESV packet reaches the destination node.
- *Backward reservation method*
  The backward reservation method reserves network resources more accurately. The source node sends a PROBE packet before reserving a wavelength. This PROBE packet collects information on usage of wavelengths along the forward path, but does not reserve wavelengths



(a) Forward reservation (successful case) (b) Forward reservation (retrial case)

Fig. 2. Distributed lightpath establishment: Forward reservation



(a) Backward reservation (successful case) (b) Backward reservation (fail case)

Fig. 3. Distributed lightpath establishment: Backward reservation

at this time. Every intermediate node that receives a PROBE packet determines whether each wavelength written in the packet is available in the next link. If a wavelength is unavailable or in use, that wavelength is removed from the available list in the PROBE packet. When the destination node receives the PROBE packet, it will know which wavelengths are currently available in the source-destination path. Based on this information, the destination node determines a wavelength for reservation and then sends a RESV packet toward the source node.

In the forward reservation, since the source node only knows which wavelength is currently available in the first intermediate link, there is no guarantee that the selected wavelength will be also available in each subsequent link . When the reservation fails, an intermediate node discards the RESV packet and sends back a NACK packet immediately. This packet informs the source node that reservation failed at an intermediate node. In this case, the source node must send a RLS packet to tear down the partially-finished lightpath. The failed case is illustrated in Figure 2(b).

In the backward reservation, although the reservation is more precise due to the PROBE-based reservation, reservation failure is still unavoidable in two instances. The first one is PROBE failure. If no wavelength is available through the entire path, the PROBE packet carries an empty set, so the destination node cannot find a wavelength for reservation. In this case, the destination node returns a NACK packet and the source node recognizes that the reservation was failed. In this paper, we do not consider wavelength conversion facilities.

That is, a lightpath uses the same wavelength along the entire path, which is known as *the wavelength continuity constraint* [17].

The second instance of failure is congestion between RESV packets. Because of the propagation delay, the information collected by a PROBE packet may be different from the current link state. There is no guarantee that a wavelength that was free a few minutes ago is still available. In dynamic WDM networks, the link state changes from moment to moment. It is impossible for edge nodes to know the current link state exactly. If the destination node sends a RESV packet based on outdated information, the reservation may fail because the wavelength has been already reserved by another source-destination pair. Figure 3(b) shows this instance of reservation failure.

B. Approaches for wavelength assignment in distributed WDM networks

Unlike centralized networks, distributed networks do not have a central controller. All the nodes in the distributed network have to work autonomously. Therefore, the source and destination nodes do not know which wavelength is available along their corresponding route. The backward reservation solves this problem by using PROBE packets that collect the information on currently available wavelengths along the forward path. With the PROBE packet, the destination node knows which wavelength is available along the path, and can choose it. However, even if we use the PROBE-based inspection, a possibility remains of requests being blocked because the information collected by PROBE packets is outdated due to the link propagation delay or processing delay at each node.

According to K. Lu et al. and Arakawa et al., the mean blocking probability of the backward reservation is analyzed numerically [15], [16]. Two kinds of blocking have been observed:

forward blocking: Blocking in the forward direction, due to insufficient network capacity. This kind of blocking occurs when the destination node finds (from the information collected by a PROBE packet) that no wavelength is available between the source and destination nodes.

backward blocking: Blocking in the backward direction, due to a “vulnerable period” [18] between the PROBE packet passing an intermediate node and the RESV packet reaching that node (See Figure 3(a)). This kind of blocking occurs when a RESV packet arrives at an intermediate node and the node finds that the wavelength written in the packet has already been reserved by another lightpath request that has arrived earlier.

According to these observations, we can calculate the blocking probability, B, as:

$$B = B^F + (1 - B^F) \times B^B, \quad (1)$$

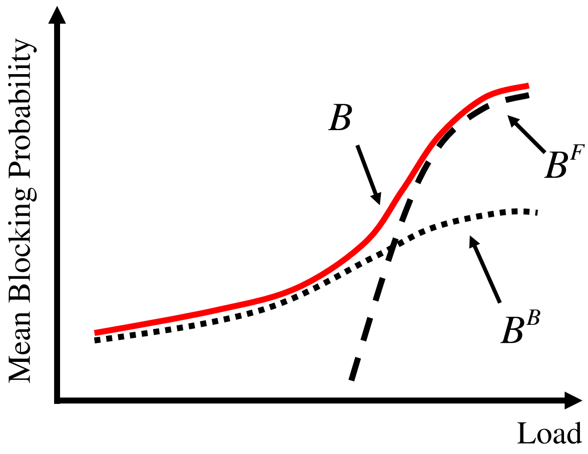


Fig. 4. Wavelength Assignment

where B^F is caused by forward blocking and B^B is caused by backward blocking. Figure 4 indicates an outline of the blocking probability. In the figure, backward blocking makes the blocking probability relatively high even when the traffic load is quite low. Forward blocking is inevitable since the wavelength resources are insufficient: only using a wavelength converter or selecting an alternative route would improve the situation.

The technology of wavelength conversion is still immature and expensive. Backward blocking can be reduced without this expensive technology if we prevent the PROBE information becoming out-of-date. Moreover, backward blocking has a large influence when traffic is lower load, which is the operational range of practical use. Consequently, reducing backward blocking is critically important for high-speed lightpath communications.

III. Wavelength Assignment Method using Circular Wavelength List

A. Proposal for the Wavelength Assignment Method

In the conventional backward reservation, the destination node selects an available wavelength for a lightpath randomly. Here, “available” means “available when the PROBE packet forwarded”. At that time, there is no guarantee that the selected wavelength will still be available when the corresponding RESV packet arrives at the intermediate node. If we can prevent the other connection requests reserving the selected wavelength during the vulnerable period, this “available” will mean “available until the RESV packet reaches the intermediate node”. In such a case, backward blocking would not occur. To reduce the backward blocking, we propose a novel wavelength assignment method in which the connection requests generated later avoid the wavelengths that have been selected by the connection requests generated earlier. The

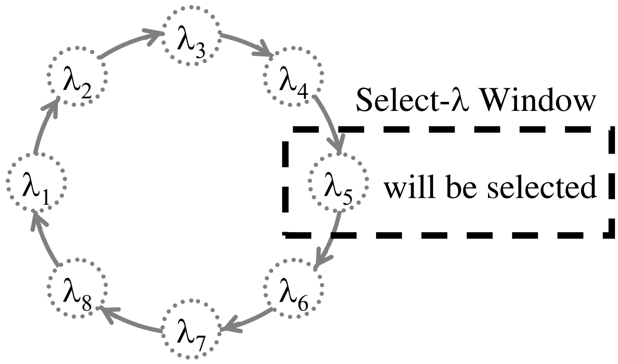


Fig. 5. Wavelength Ring (Number of wavelength W=8, initial wavelength=λ_5)

features of our proposal are a first-fit-like algorithm adapted to the link state and forecasting wavelengths used for reservation at the intermediate nodes. First, our proposal removes the reservation initiative from the destination node. In the existing methods, the reservation wavelength is selected randomly at the destination node, a process that causes unnecessary blocks. In our proposed method, the wavelength for the reservation is determined automatically based on the link state by which the PROBE packet passed. The destination node has no need to select a wavelength, but only pick up the wavelength from the PROBE packet. Each PROBE packet has a cyclical wavelength list that is arranged in order of wavelength index (i.e., $\lambda_W \rightarrow \lambda_{W-1} \rightarrow \cdots \rightarrow \lambda_2 \rightarrow \lambda_1 \rightarrow \lambda_W \rightarrow \lambda_{W-1} \rightarrow \cdots$). We call it a circular wavelength list (Figure 5). While the PROBE packet travels from source to destination nodes, the circular wavelength list is produced according to its probed information. When the PROBE packet reaches the destination node, the wavelength at the selection window in the list is selected for the RESV packet. By using the circular wavelength list, it becomes easier to find a wavelength for reservation because calculating the random algorithm at the destination node is unnecessary. Furthermore, the intermediate node can forecast wavelengths that will be selected by incoming PROBE packets.

To forecast which wavelengths will be used, when the intermediate node forwards the PROBE packet, it checks the selection window in the circular wavelength list, and knows which wavelength this PROBE packet will select. After forecasting, the intermediate node writes the result in its Wavelength Forecast Table. A PROBE packet that arrives afterward can refer to the table and know which wavelengths the earlier PROBE packets want to use. At that time, the PROBE packet compares the wavelengths with its own selection window. If the same wavelength is found in its own selection window, the PROBE packet rotates the wavelength list until it finds a different wavelength from those in the wavelength forecast table. By using these circular wavelength lists and forecasting wavelengths, our proposed method can prevent the selected wavelength being reserved by other connection requests.

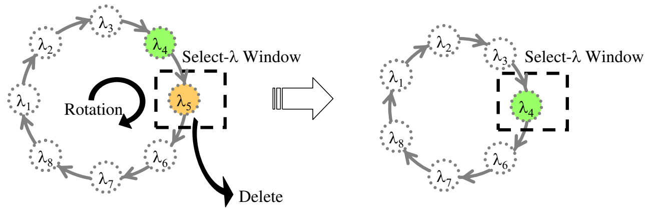


Fig. 6. Update the wavelength ring (When the top wavelength is deleted)

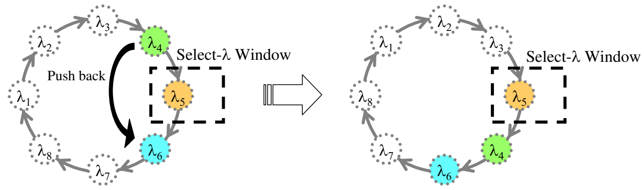


Fig. 7. Update the wavelength ring (When the wavelength is set to "undesirable")

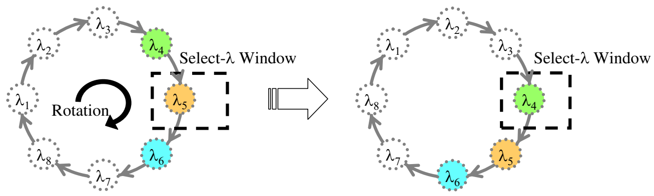


Fig. 8. Update the wavelength ring (When the top wavelength is set to "undesirable")

The details of our proposal are described as follows.

1) Behavior of the source node
   - (S1) Receive connection request.
   - (S2) Create a PROBE packet.
   - (S3) Check the wavelength availability in the next link.
   - (S4) Determine the initial wavelength of the wavelength ring. Randomly determine the initial wavelength of the wavelength list.
   - (S5) Forward the PROBE packet.
2) Behavior of the intermediate node
   - (I1) Receive the PROBE packet.
   - (I2) Probe the wavelength availability.
   - (I3) Check the Wavelength Forecast Table in the previous link and the next link.
     - If the forecasted wavelength is found: Set the wavelength "undesirable".
     - Otherwise: Proceed to the next step.
   - (I4) Update the wavelength ring.
     - If a wavelength has been reserved by the other requests: Delete the wavelength from the ring. If the wavelength is at the select–λ window, circulate the ring (Figure 6).
     - If a wavelenth is set to "undesirable": Reorder the ring. Insert the wavelength at bottom of the cyclical

list (Figure 7). If the wavelength is at the select–λ window, circulate the ring (Figure 8).

- If the wavelength at the select–λ window has changed:Send update message towards the source node. The update message updates the wavelength forecast table of the intermediate node which the PROBE packet passed through.

(I5) Update the Wavelength Forecast Table by checking the wavelength ring of the packet.

(I6) Forward the PROBE packet toward downstream nodes.

3) Behavior of the destination node

(D1) Receive the PROBE packet.

(D2) Probe the wavelength availability in the previous link.

(D3) Check the Wavelength Forecast Table.

- If the forecasted wavelength is found: Set the wavelength "undesirable".
- Otherwise: Proceed to the next step.

(D4) Update the wavelength ring (Same as (I4)).

(D5) Pick up the reservation wavelength that is at the select–λ window in the wavelength ring.

(D6) Return the RESV packet toward the source node.

IV. Simulation Evaluation

A. Simulation Model

To evaluate the performance of the proposed method, we compared it with random assignment in the backward reservation method. We used the NSFNET (Figure 9) as a simulation topology. The number of wavelengths on each link was set to $W+1$. Each link had the same propagation delay, L_D. The route between a node–pair is prepared by the minimum hop routing algorithm. Data transfer requests arrived according to the Poisson process, and the lightpath holding time was assumed to be exponentially distributed with mean $1/\mu$ [ms]. In this simulation, we did not consider the reservation retrial, and we evaluated our proposal in terms of the blocking probability.

B. Results of NSFNET Network

Figure 10 shows the result when W=16, $1/\mu$=100ms and L_D=0.1ms. The upper bound is the result when link propagation delay was set to 0 [ms]. Without the link propagation delay, backward blocking did not occur. Our proposed method reduces the blocking probability by more than one order of magnitude compared to random selection. In our method, lightpath requests that arrive later can avoid the wavelength that have been selected by earlier requests. Consequently, the selected wavelengths are still available when the RESV packets of earlier requests reach the intermediate nodes. Our proposed assignment method therefore greatly improves the blocking probability when the arrival rate is low. However, compared to the upper bound, backward blocking was still observed. This is because the link propagation delay delayed the update of the wavelength forecast table and the information in the table became outdated. When the wavelength forecast table is out-of-date, the lightpath requests cannot avoid wavelength conflict.

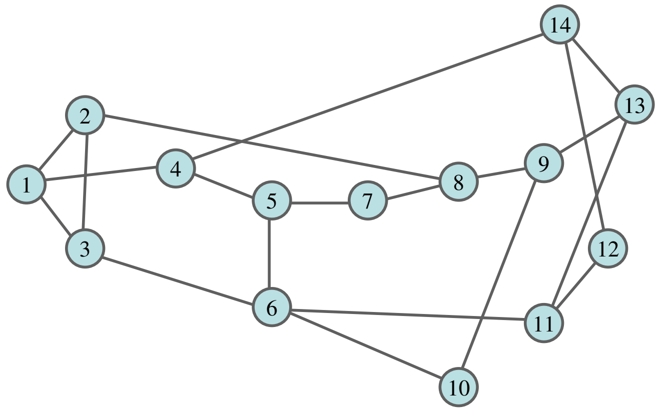


Fig. 9. NSFnet

Figure 11 shows the result when W was set to 32. By increasing the number of wavelengths, the performance of the random selection was improved. The performance of our proposed method also improved because in our method, the initial wavelength of the circular wavelength list is selected randomly. Our proposal is very effective regardless of the number of the wavelength.

Figure 12 shows the result when L_D was set to 1.0 ms. When the link propagation delay is long, the influence of the backward blocking becomes clearer since the PROBE information is outdated by the long propagation delay. In this case, the update of the wavelength forecast table in our proposed method was also delayed. As a result, the performance of both the random and proposed methods worsened compared to the results in Figure 10. However, our proposed method is still effective even when the link propagation delay becomes longer. To see this more clearly, we show the blocking probability dependent on L_D in Figure 13. Here, we set arrival rate 1.0e-06, and the results when W is set to 16 and 32 are presented in the figure. The difference between the random and proposed method is still significant.

When we concentrate on the results of $W = 16$, the result of proposed method show a similar curve with that of random method. However, by comparing the results of $W = 32$ and $W = 16$ for each method, we observe that its difference of proposed method is larger than the difference of random method. The reason is explained as follows. In our method, the blocking, more specifically backward blocking, at a node occur only when the information in the wavelength forecast table at the node became outdated *and* subsequent lightpath request circulates the wavelength-list, and its resulting select–λ window matches the outdated wavelength. As the length of the list increases, the probability that the resulting select–λ window matches to the outdated wavelengths decreases. Thus, the difference becomes large as the number of wavelengths increases in our proposed method.

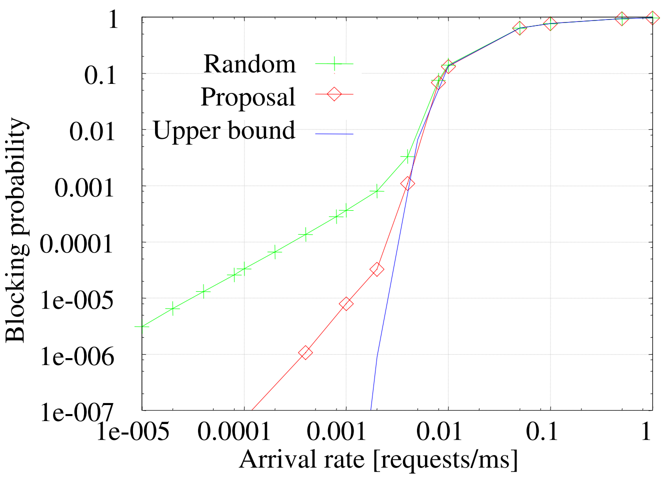


Fig. 10. Blocking probability (W=16, $1/\mu$=100ms, L_D=0.1ms)

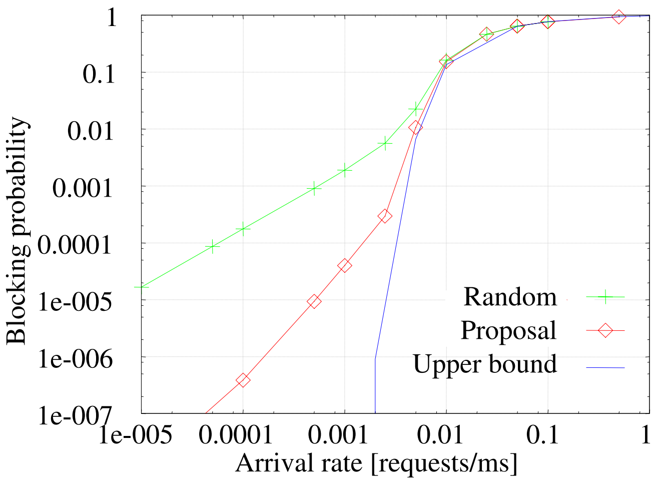


Fig. 12. Blocking probability (W=16, $1/\mu$=100ms, L_D=1.0ms)

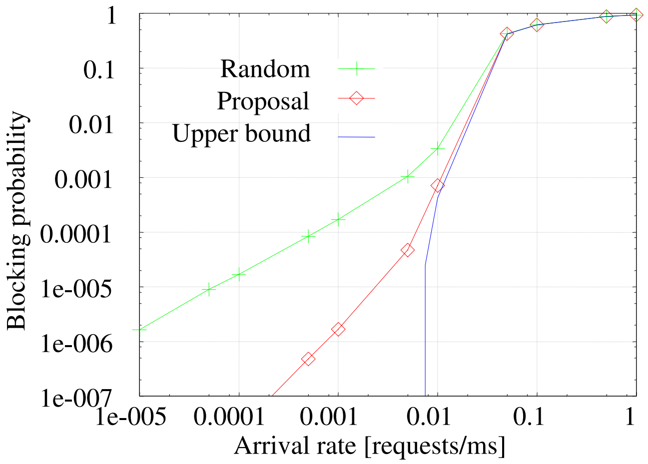


Fig. 11. Blocking probability (W=32, $1/\mu$=100ms, L_D=0.1ms)

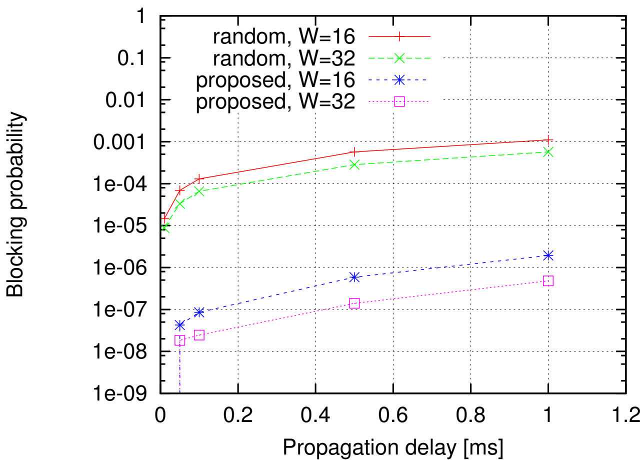


Fig. 13. Impact of propagation delay ($1/\mu$=100ms)

V. Conclusion

Lightpath establishment consists of routing, wavelength assignment, and wavelength reservation phases. In this paper, we have proposed a novel wavelength assignment method for distributed wavelength-routed WDM networks. Conventional studies assume that a wavelength for the lightpath is selected randomly. However, this random selection method causes unnecessary blocks of lightpath requests, due to the vulnerable period. In other words, when the end node selects a wavelength randomly, the reservation may be blocked because lightpath requests that pass through the same link may select the same wavelength. To reduce these unnecessary blocks, in our proposed method, the intermediate node forecasts which wavelength will be selected by the incoming PROBE packet. The result is then communicated to subsequent PROBE packets pass through the node. Owing to this communication of wavelength information, the lightpath requests that pass through the same link can consistently select different wavelengths. We evaluated the blocking probability of our method compared to random assignment. The results confirmed that our proposed method can greatly reduce the reservation blocking when the arrival rate is low. Some research issues remain. First, in this paper, we have assumed that the routes for lightpaths are predetermined. Although our method can be applied to any routing algorithm, we should evaluate the distributed routing algorithms and clarify which algorithm is suitable for our proposed method. Second, our wavelength assignment method employs a new data structure: a circular wavelength list. This may introduce an additional computational complexity to the intermediate node because the circular wavelength list is updated at every intermediate node. We have to evaluate the overhead of this control.

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