Distributed wavelength reservation method for fast lightpath setup in WDM networks

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Abstract— **A promising approach to the effective utilization of wavelength division multiplexed networks is to transfer data on an on-demand basis using fast wavelength reservation. Data can then be transferred using the assigned wavelength channel. However, if wavelength reservation fails, the lightpath setup delay, which is defined as the time from when the data–transfer request arises at the source node to when the lightpath between the source–destination pair is successfully established, is seriously affected since retrials of wavelength reservation are in turn delayed by propagation delays. In this paper, we propose a new wavelength reservation method to reduce lightpath setup delay. Whereas conventional methods reserve a wavelength in either the forward or backward direction, we propose to reserve it in both directions. We used computer simulations to compare our proposed method with existing methods. The results showed that our method was more efficient except under high traffic loads.**

Keywords— **WDM network, lightpath, forward reservation, backward reservation, retrial**

I. Introduction

The improvement of wavelength division multiplexing (WDM) technology enlarges bandwidth and enables optical networks to support the increasing Internet traffic. At the same time, optical systems utilizing *Optical Closs–Connects* (OXCs) or *Optical Add–Drop Multiplexer* (OADM) have emerged. These systems enable data transfer to be performed entirely in optical domain. Without these facilities, optical networks can be opaque networks which need *optical–electronic–optical* (O-E-O) conversion or regeneration at every intermediate nodes. The main drawback of such networks is the high cost of the additional O-E-O converters at the intermediate nodes. Moreover, data transmission will be delayed by the processing speed of the converters. Therefore, the networks utilizing the all-optical systems have been brought to great attention. Our focused wavelength–routed WDM network is one of these all-optical networks. Employing OXCs in WDM networks, we can establish all optical connections or *lightpath* [1], between source and destination nodes. The lightpath is configured by reserving wavelengths in every fiber links along the source–destination path. The lightpath enables data transfer to be high speed and low cost communication since the absence of the expensive O-E-O converters. On the other hand, bursty nature of the Internet traffic reduces the bandwidth utilization even if we can perform all optical communication. It is a big research topic in all-optical WDM networks.

A promising approach to the effective utilization of WDM networks is to transfer the data on an on-demand basis. That is, when a data request arises at a source node, a wavelength is dynamically reserved between the source and destination nodes, and a wavelength channel (called a *lightpath*) is configured. After the data transmission using the lightpath, the lightpath is immediately torn down (i.e., the wavelength is released). These dynamic lightpath setup or tear down will be adapted for the bursty nature of the Internet traffic and utilize the bandwidth efficiently.

Two methods have previously been presented to set up lightpaths in a distributed manner [2]. In both methods, the lightpaths are established by exchanging control packets between the 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., forward direction), or from the destination node to the source node (i.e., backward direction). There have been several studies on reservation schemes aimed at reducing the blocking probability for lightpath requests [2–6]. However, a more important measure for these reservation models is *lightpath setup delay*, which is defined as the time from when the lightpath request arrives at the source node to when a lightpath is successfully configured between the source and destination nodes. Only in [6], lightpath setup delay with the retrial is evaluated but this retrial just employs existing method repeatedly and an improvement method of lightpath setup delay including the retrial is not considered. However, in order to transfer the data, the source node must keep trying to setup a lightpath until the lightpath is successfully configured. Consequently, lightpath setup delay is increased by such retrials due to the link propagation delay along the path. Thus, it is important to improve lightpath setup delay with consideration of retrials.

In this paper, we propose a new wavelength reservation method aimed at reducing lightpath setup delay by increasing the trials of wavelength reservation. More specifically, by integrating two existing reservation method, our method reserve a wavelength in both forward and backward direction, while existing reservation methods reserve a wavelength in *either* forward or backward direction.

The rest of the paper is organized as follows. Section 2 outlines wavelength–routed networks and related work, Section 3 presents our proposed method, Section 4 presents the simulation results, and Section 5 includes a brief summary.

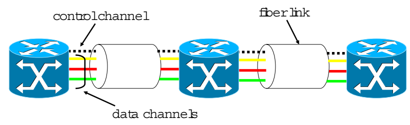

Fig. 1. Wavelength routed network

II. Related Work

First, we will describe the structure of our focused wavelength–routed network. A model of the network is shown in Figure 1. It consists of OXCs and optical fibers. Configuring OXCs enables data to be transferred in all optical domain. It increases cost–effectiveness of data transfer in WDM networks because of the absence of O-E-O converters which take high cost and furthermore, which delay the data transmission. Each fiber carries a certain set of wavelengths. Within these sets, one wavelength carries control packets and the other wavelengths are used for data transfer. The control packet controls the setup and/or tear down of lightpaths, in other words, control channel or control packet behaves as the control plane of wavelength–routed networks. For control plane, it is necessary to determine a route for a lightpath and assign a wavelength to a lightpath. This problem is known as the *routing and wavelength assignment* (RWA) problem. The RWA problem is major research topic in wavelength–routed networks and extensive research efforts have been done in this problem [7–9]. The objective of the RWA problem is to minimize the amount of network resources which is consumed for lightpath establishment, and at the same time to ensure that each lightpath in the same link is assigned the different wavelength.

In a wavelength–routed network, the lightpath establishment can be either static or dynamic:

- In a static lightpath establishment, a set of lightpaths are set up all at once and remain in the network for a long period. In this situation, the RWA problem is formulated by using integer linear problem (ILP)

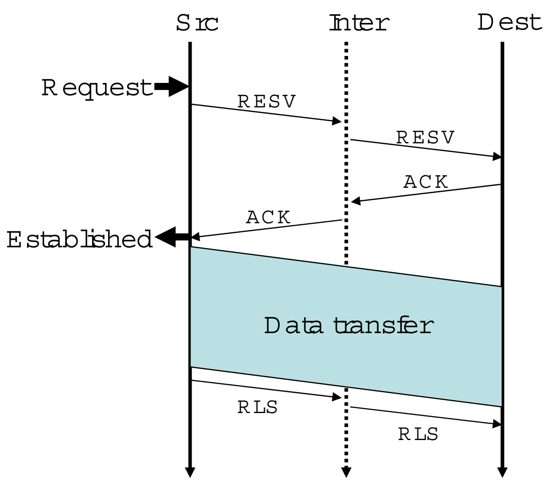

Fig. 2. Forward Reservation (successful case)

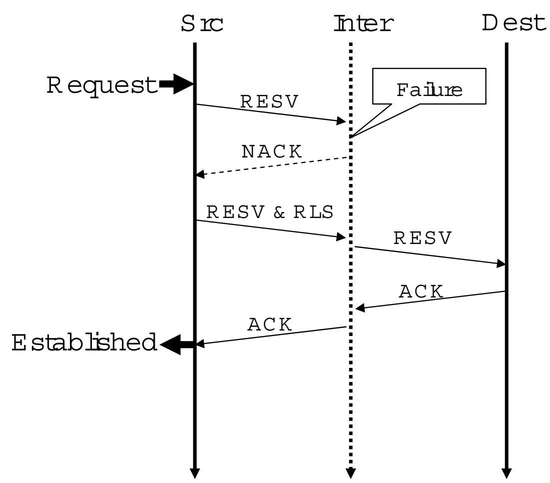

Fig. 3. Forward Reservation (retrial case)

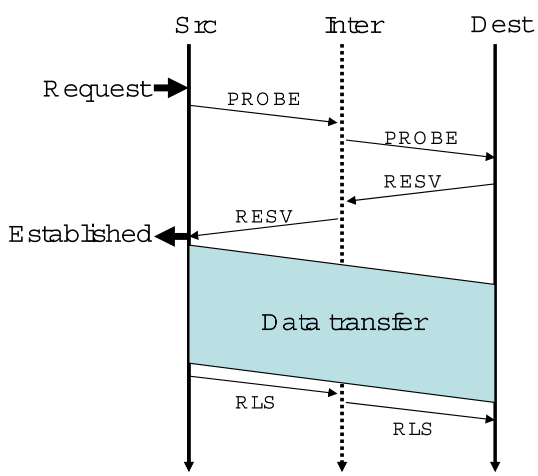

Fig. 4. Backward Reservation (successful case)

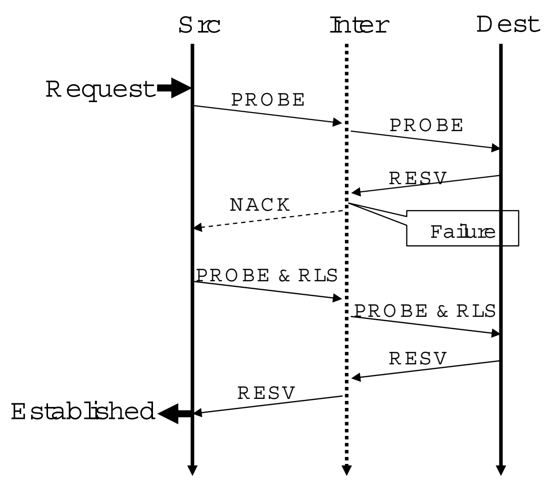

Fig. 5. Backward Reservation (retrial case)

formulations or heuristic methods.

- In a dynamic lightpath establishment, a lightpath is set up for each connection request as it arrives, and the lightpath is released after some finite amount of time, i.e., connection holding time. In this situation, the main objective of the RWA problem is to maximize the probability of lightpath setup and consequently to minimize the lightpath setup delay [10].

In the aspect of wavelength utilization, it is believed that the dynamic or on–demand lightpath establishment is more preferable because of the bursty nature of the Internet traffic, so that our paper focuses on the dynamic lightpath establishment.

The lightpath control mechanisms in dynamic WDM networks can be either centralized or distributed [11]:

- In a centralized control, a central controller is needed which keeps the information of the current network state and processes all lightpath setup requests. This method can allocate network resources more efficiently because the central controller knows all the information about link failure, the number of wavelength in each link, wavelength availability and so on. But there are two disadvantages. The first one is its low scalability. The central node has to process too much information and consequently becomes the bottleneck of the network. The second one is its poor survivability. If the central node fails, the entire network will be out of control. Therefore centralized control mechanism is suitable for small–scale networks.
- In a distributed control, a central controller does not exist and each node controls routing and wavelength assignment in cooperation with the other neighbor nodes. There are two advantages. The first one is that a distributed method has high scalability since the processing congestion caused by central controller does not occur any more. The second one is its high survivability. In contrast to a centralized one, a single node failure will not affect other parts of the network. Therefore distributed control mechanism is suitable for large–scale networks.

In this paper, we focus on distributed lightpath establishment in dynamic wavelength–routed networks.

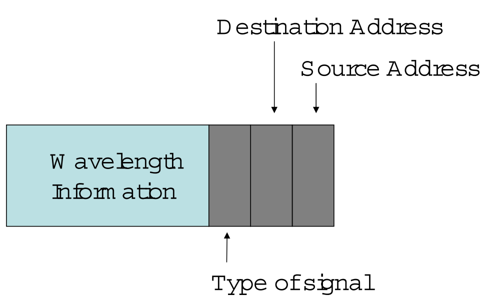

Fig. 6. The control packet format

Conventional lightpath setup methods in above mentioned distributed dynamic WDM networks are mainly based on two reservation schemes: *forward reservation* and *backward reservation*. Figure 2 and 4 illustrate *forward reservation* and *backward reservation* respectively. Figure 6 is a brief model of the control packet format. It has *the routing information*: source address and destination address, *type of the signal*: reserve packet(RESV), release packet (RLS), acknowledgment packet (ACK), negative ACK packet (NACK) and especially in *backward reservation*, probe packet (PROBE). The part of *wavelength information* is used for reserving and releasing a wavelength or probing wavelengths group that is available along the entire path. The lightpath setup mechanisms in existing two methods are described as follow.

- *Forward reservation*
  In *forward reservation*, the source node sends a RESV packet when a lightpath setup request arises. The RESV packet reserves a wavelength from the source node to the destination node. More specifically, the reservation is performed at every intermediate node which exists in the source–destination route. In the first place, the source node selects a wavelength for reservation from an available wavelength group in next link and sends a RESV packet toward the destination node. When an intermediate node receives a RESV packet, it extracts the candidate wavelength for lightpath from the wavelength information part of the control packet. Then, it checks the next link state whether the candidate wavelength is available or unavailable. If the wavelength is available in the next link, the intermediate node reserves the wavelength and forwards the RESV packet to the next node. The lightpath establishment is completed as soon as a RESV packet reaches the destination node. Since the source node only knows that which wavelength is now available in the neighbor link, there is no guarantee that the selected wavelength will be also available in each link which is distant from the source node. When the reservation fails, an intermediate node discards a RESV packet and sends back a NACK packet immediately. This packet informs the source node that reservation fails at an intermediate node. In this case, the source node must send a RLS packet to tear down the half–finished lightpath. At the same time it chooses a wavelength and sends a RESV packet again. These series of the exchange of the control packets will be repeated until the lightpath is successfully established. The retrial case is illustrated in Figure 3.
- *Backward reservation*
  In *backward reservation*, the reservation of the network resource is performed more accurately. That is, the source node sends a PROBE packet before a wavelength reservation. A PROBE packet collects the information on usage of wavelengths along the forward path, but no wavelengths are reserved at this time. Every intermediate node which receives a PROBE packet examines that each wavelengths written in a PROBE packet is available or unavailable in the next link. If a wavelength is unavailable or in use, the wavelength is

removed from the available–list in a PROBE packet (It is written in the wavelength information part in Figure 6.). When the destination node receives a PROBE packet, it will know that which wavelengths are now available between 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.

Although the reservation in backward scheme is more precisely due to PROBE–based reservation policy, the reservation failure is still unavoidable. There are two cases where the reservation failure occurs in backward scheme. The first one is the PROBE–failure. If there are no wavelength which is available through the entire path, a PROBE packet carries an empty set and the destination node can't find a wavelength for reservation. In this case, the destination node returns a NACK packet and then, the source node re–sends a PROBE packet. At this time, back–off time may be required. The wavelength converter will be a powerful solution of this problem. But, applying the wavelength converters will produce another issue, i.e., facility cost. Note that, in this paper, we do not consider the wavelength conversion facilities. That is, a lightpath uses the same wavelength along the entire path, which is known as *the wavelength continuity constraint* [12]. The second one is the 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 which was free until 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 the outdated information, the reservation may be failure because the wavelength has been already reserved by the other source–destination pair. Figure 5 shows this case of reservation failure. In order to keep the accuracy of the wavelength information and avoid the congestion, it is important to exchange the control packets as quickly as possible. Our proposed Optical–Code label processing is effective in this problem [13].

III. Our Proposal

In both these existing reservation methods, there is only one trial for lightpath establishment during the round–trip propagation time. We therefore propose a new method for lightpath setup, based on integrating the *forward* and *backward reservation schemes*, which tries to establish a lightpath twice during the round–trip propagation time. Figures 7 and 8 illustrate our proposed scheme. And with Figure 6, there are five types of signal in proposed scheme: PROBE, RESV_PROBE, RLS, ACK and NACK_PROBE. A RESV (or NACK)_PROBE packet performs just like sending a RESV (or NACK) packet and a PEOBE packet simultaneously. In our scheme, when a lightpath setup request arises at a source node, the source node sends a PROBE packet toward the destination node, just like in backward reservation. However, in contrast to backward reservation, when the destination node receives a PROBE packet, it sends a RESV_PROBE packet (or NACK_PROBE packet) toward the source node. The RESV_PROBE packet reserves a wavelength and collects the information on wavelength usage from the destination node to the source node. If the reservation failed, a RESV_PROBE packet is changed into a NACK_PROBE packet. A NACK_PROBE packet does not reserve a wavelength but still collects the wavelength information. When the source node receives a NACK_PROBE packet, it selects a wavelength based on this information. This retrial scenario is illustrated in Figure 8. The main feature of the proposed scheme is that the PROBE packets are transmitted in both forward and backward direction. Below we explain the details of our proposed reservation scheme.

1. Behavior of the source node
   - (S1) When a data transfer request arrives from a terminal, the source node creates a PROBE packet and sends it toward the destination node. Before it sends a PROBE packet, it examines which wavelength is available in the next link, and writes it in the wavelength information area (See Figure 6).
   - (S2) When a RESV_PROBE (or ACK) packet arrives, the source node informs the terminal that a lightpath has been established. And the data transmission will start.
   - (S3) When a NACK_PROBE packet arrives, the source node sends a RESV_PROBE packet. This is the case where the reservation failure occurs in the backward direction; the original features of our proposal relate to this behavior. Although a NACK packet only informs the reservation failure, a NACK_PROBE packet additionally has the same function as a PROBE packet. Therefore the source node always can perform the lightpath setup based on probed information. Since a NACK_PROBE packet informs the reservation failure, the source node may have to send a RLS packet if the reservation is blocked halfway.
   - (S4) When the data transmission is completed, the source node sends a RLS packet to tear down the lightpath.
2. Behavior of the intermediate node
   - (I1) When the intermediate node receives a PROBE packet or a NACK_PROBE packet, it calculates the intersection between the wavelength list carried by the packet and the wavelength list which is available in the next link. Then, it renews the wavelength information in the packet and forwards the packet to the next node.
   - (I2) When a RESV_PROBE packet arrives, the intermediate node extracts the candidate wavelength from the wavelength information area of a RESV_PROBE packet. If the wavelength is available in the next

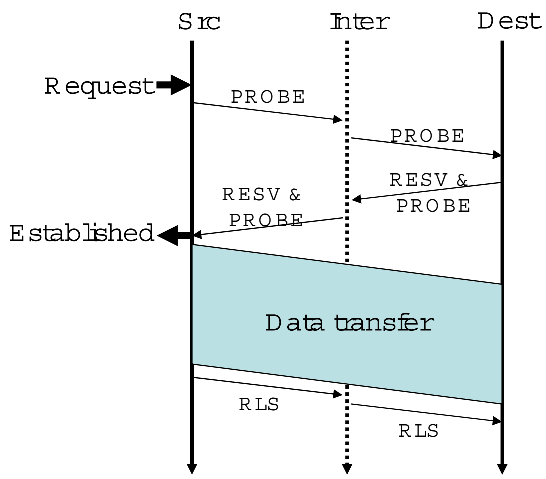

Fig. 7. Proposed Method (successful case)

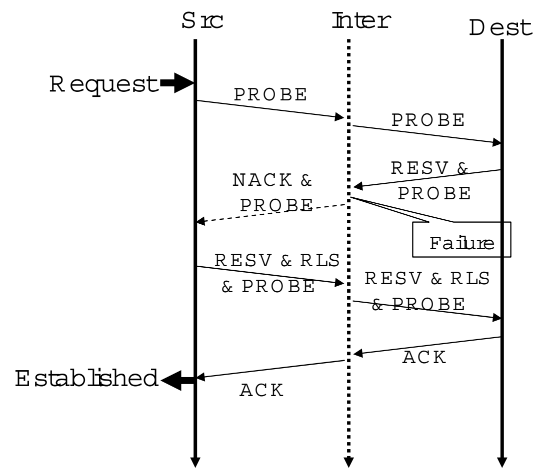

Fig. 8. Proposed Method (retrial case)

link, the intermediate node reserves the wavelength. If the wavelength is unavailable or in–use, the intermediate node changes a RESV_PROBE packet into NACK_PROBE packet. A RESV_PROBE packet has the same information area as a PROBE packet and it is processed in the same way in (I1) regardless of whether the reservation succeeds or fails.

(I3) When a RLS packet arrives, the intermediate node releases the wavelength immediately.

(I4) An ACK packet is forwarded to the next node without any processing.

3. Behavior of the destination node
   - (D1) Basically, the behavior of the destination node is similar to that of the source node. When a PROBE packet or a NACK_PROBE packet arrives, the destination node sends a RESV_PROBE packet. If the packet carries an empty set and no wavelength is found, the destination node sends a PROBE packet toward the source node. Especially in the case of a NACK_PROBE packet, the destination node may have to send a RLS packet to tear down the half–finished lightpath.
   - (D2) When a RESV_PROBE packet arrives, the destination node sends an ACK packet toward the source node to notify that a lightpath has been established in forward direction.
   - (D3) When a RLS packet arrives, the destination node discards it.

Integrating *forward reservation* and *backward reservation* is also proposed in [4]. The reservation method proposed in [4] is named *adaptive hybrid reservation protocol* (AHRP). AHRP is oriented to increase the number of sending a RESV packet. The source node sends a RESV packet and a PROBE packet. In contrast to our proposal, the destination node sends either an ACK packet: the case where the reservation in forward direction succeeded, or a RESV packet: the case where the reservation in forward direction failed. The destination node doesn't send a PROBE packet in both cases. Note that, in AHRP the reservation in forward direction is the same way as *forward reservation* and not based on a PROBE packet. Consequently, if the reservation in forward direction failed and in backward direction also failed, the source node must re–send a RESV packet without any network state information. This retry will increase the congestion between RESV packets and reduce the capability of the network. To avoid such a case, the reservation in our proposed method is always based on PROBE packets.

IV. Simulation Result

A. *Simulation model*

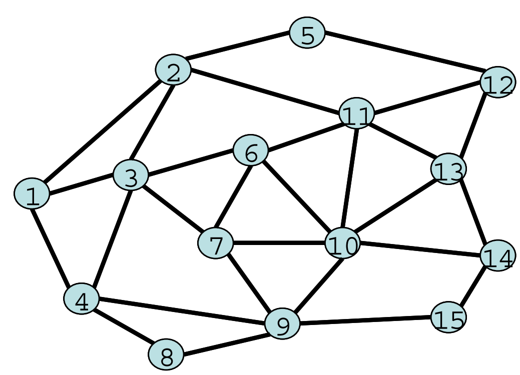

Fig. 9. Random Network

We evaluate the mean lightpath setup delay of the proposed method through the computer simulation. For the performance comparison, we employ the *backward reservation* since it generally outperforms the *forward reservation*. We use a random network as the simulation topology. Figure 9 shows the topology, which has 15 nodes and 28 links. Each source–destination pair has inconsistent hop–counts.

The average number of the hop–counts is 2.2. Other simulation parameters are briefly described below.

- All links have the same number of wavelengths and it is set to 32.
- Each link has a random propagation delay with mean 1.77 [ms].
- Data-transfer requests for each source–destination pair were assumed to arrive at the network in accordance with the Poisson process. The lightpaths are held for a connection-holding period that is assumed to be exponentially distributed with mean $1/\mu$ [ms].
- For each source–destination pair, the routes are predetermined using *shortest–path–first* algorithm.
- The wavelength selection for the RESV packet is assumed to be random selection.

We define the load ρ in Figures 10 and 11 as the offered load for a source–destination node pair.

B. Evaluation of Lightpath Setup Delay

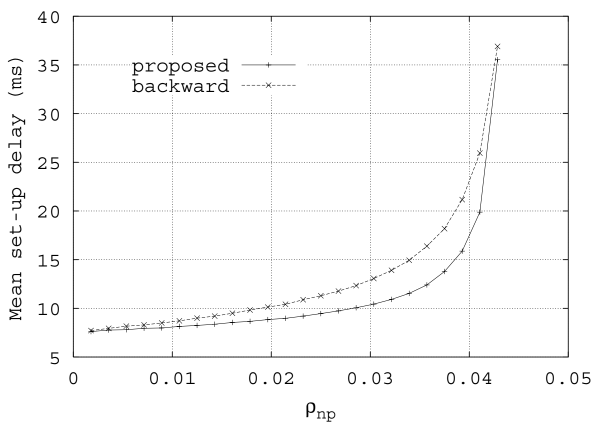

Fig. 10. Lightpath setup delay ($1/\mu = 100ms$)

In Figures 10 and 11, we present the mean setup delay dependent on the load ρ. Figure 10 and Figure 11 show the results when the average of holding time $1/\mu$ is set to 100 [ms] and 10 [ms], respectively. The results show that

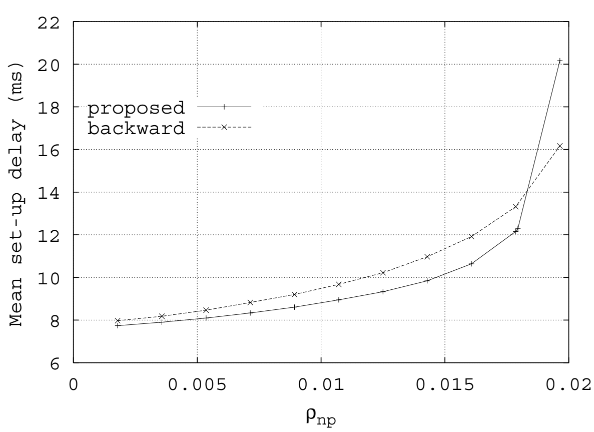

Fig. 11. Lightpath setup delay ($1/\mu = 10ms$)

our proposed scheme outperforms the *backward reservation* at almost every range of ρ. In our proposal, the PROBE packet travels between source–destination pair in both forward and backward direction. Consequently, the source node (or destination node) can find the available wavelength faster than the *backward reservation.* Moreover in contrast to the *backward reservation*, the reservation can be performed twice in a round–trip time in our proposal. In other words, the granularity of the wavelength reservation is twice as that of the *backward reservation.* When the load ρ is not so high, small granularity of the reservation can improve the mean lightpath setup delay. When we assume that the congestion of the RESV packet arises based on a certain probability, the number of reservation trials increases a success rate and improves the lightpath setup delay (Though only when the blocking probability is not so high.).

In Figure 11, the lines cross each other near the $\rho = 0.018$. At a high load, small granularity of the reservation increases the mean setup delay. The reason why the proposed scheme was inferior to the *backward reservation* under a high load is the inaccuracy of the probed information. When the information collected by a PROBE packet is not accurate due to link propagation delay, the information becomes out-of-date. If the information is too old, the edge node may select a wavelength that has already been reserved by another source–destination pair. Then, it results in a rise of the half–finished lightpath. The half–finished lightpath is caused by reserving a wavelength not through the entire path but halfway and, it will be an obstacle to the other source–destination pair. When the half–finished lightpath arises much in the network, it will be hard to reserve a wavelength through the entire path. In the proposed scheme, the edge nodes can make several attempts to send PROBE packets compared with the *backward reservation*, so the accuracy of the information is more important to avoid the half–finished lightpath. When the connection–holding period $1/\mu$ is relatively short compared to the link propagation delay (as in Figure 11), the information tends to be less accurate.

C. Variation in Lightpath Setup Delay

In a wavelength–routed network, it is preferable to establish a lightpath with little variation or jitter in setup delay. If a wavelength reservation method has large variation, it is difficult to achieve the stable data transmission. Therefore, it is important to consider the variations in the lightpath setup delay. In this section, we use the 99.9-percentile delay as an indication of delay jitter. The 99.9-percentile delay is defined as follow: 99.9-percentile of the all connection requests finishes the lightpath setup within the time.

Figures 12–15 plot the 99.9-percentile delay dependent on the number of hop–counts "H" of each source–destination node pair. Figure 12 shows the 99.9-percentile delay of 1-hop connection. In 1-hop connection, proposed method outperforms the *backward reservation* and, a difference between the proposed method and the *backward reservation* becomes bigger and bigger when ρ increases.

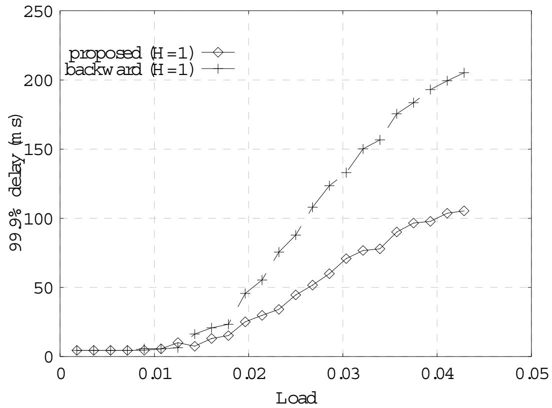

Fig. 12. 99.9-percentile delay (H=1)

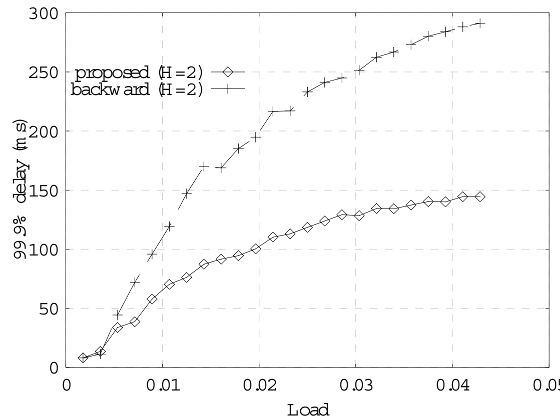

Fig. 13. 99.9-percentile delay (H=2)

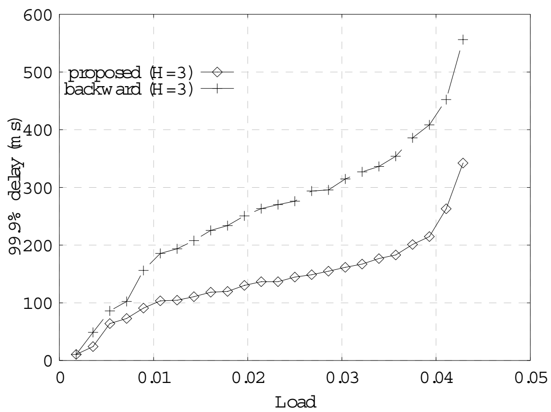

Fig. 14. 99.9-percentile delay (H=3)

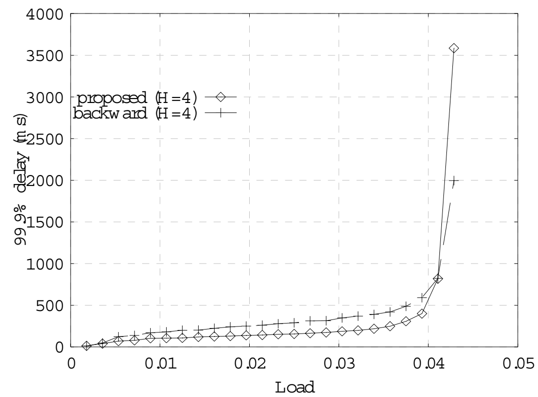

Fig. 15. 99.9-percentile delay (H=4)

The similar tendency is appear in Figure 13, but the difference of the 99.9-percentile delay are stopped increasing at a high load ($\rho \sim 0.04$). Figure 14 shows the result of 3-hop connection. Although proposed method shows better performance as well as in Figure 12–13, the 99.9-percentile delay raises rapidly at a high load ($\rho \geq 0.04$) unlike in previous figures. Such tendency is much clearer in Figure 15, besides, the lines cross each other. From these results, we can find an unfairness between the small-hop connection (e.g., $H = 1, 2$) and the large-hop connection (e.g., $H = 3, 4$). The reservation on the large-hop connection is harder than on the small-connection because the control packet travels more links. When the control packet travels many links, it is hard for the PROBE packet to find available wavelengths through the entire path. Moreover for the RESV packet, it is hard to reserve the wavelength successfully because the round–trip propagation delay is larger. This unfairness between the number of hop–counts seems to be more remarkable in proposed method from Figure 15. In our proposed method, the small-hop connection can reserve the wavelength quite quickly due to its bi-directional reservation. The wavelengths are finite resources of the network. Consequently, the large-hop connection can't make the reservation easily since the small-connection snatches the greater part of the wavelengths.

V. Conclusion

In this paper, we presented a new lightpath setup method that reserves wavelengths in both forward and backward directions. The main objective of our method is to reduce lightpath setup delay. Our proposed method, which integrates features of two existing methods, performs lightpath establishment twice within a round–trip, while the previous methods perform it only once. The simulation results indicate that the proposed method performs better except under high traffic loads. We also evaluated other statistical property of the methods. The results show that although there is an unfairness between the number of hop–counts, our proposed method can improve the 99.9-percentile delay which is defined as the time in which 99.9 percentile of the all requests finished the lightpath establishment. We have mainly two future works. First, we develop a numerical analysis of lightpath setup delay. Second, we consider to avoid the unfairness between the hop–counts.

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