Evaluation of Routing Algorithms for Distributed Lightpath Establishment in Wavelength–Routed Networks

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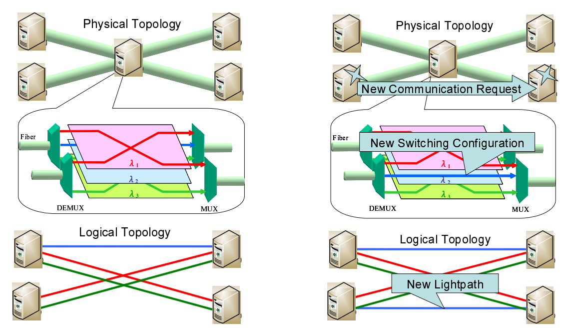
***Abstract*— Optical networks, where all–optical wavelength channels (called lightpaths) convey traffic, have been considered to effectively utilize WDM technology. In distributed lightpath networks, each node sets up and tears down the lightpath between a pair of communicating nodes. Therefore, conflicts about wavelength reservations during signaling operations may occur because of a lack of precise link–state information. In this paper, we evaluate effects of delayed link–state information on reservation protocols and routing algorithms through some simulations. More specifically, we evaluated the average path setup time for routing algorithms in distributed networks, and found how the frequency of link–state information exchange affects the precision of collected link–state information. From simulation results, we conclusively confirmed that a backward reservation–protocol lessens the effect delayed link–state information has. The effect is less than 0.2% increase of blocking probability with the backward reservation protocol, while the forward reservation protocol increases the blocking probability more than 15%. We also confirm the proposed alternate routing algorithm shortens lightpath setup time about 20% than the least loaded routing algorithm assuming ideal conditions.**

I. Introduction

Wavelength division multiplexing (WDM) provides multiplex wavelength channels on a single fiber, enables high–capacity parallel transmission, and is expected to provide capacity for backbone networks.

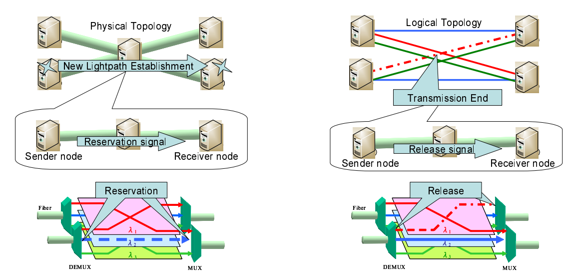
One way of using the WDM technology is to establish wavelength channels (called *lightpaths*) on a demand basis (Fig. 1(a)). A lightpath network consists of nodes with switching devices and links to optical fibers in a physical network. OXC is a switching device that binds an input wavelength channel to a specified output wavelength channel on the same wavelength. Lightpaths are formed through this switching process in intermediate nodes. When a new lightpath request arrives, the intermediate node switches specified fibers on a wavelength (Fig. 1(b)). When a data transfer request arrives at the sender node in a lightpath network on a demand basis, one wavelength is reserved along the route between the sender and the receiver nodes (Fig. 2(a)) [1], [2]. After data have been transferred along the lightpath, the wavelength is immediately released (Fig. 2(b)). As two or more lightpaths cannot share a wavelength on a fiber, some method is necessary to control the process of assigning routes and wavelengths in lightpath networks.



(a) Lightpath network

(b) New lightpath establishment

Fig. 1. Lightpath network: physical topology, logical topology, and switching



(a) Wavelength reservation to establish a lightpath

(b) Wavelength release for tear down a lightpath

Fig. 2. Lightpath establishment and release

There are two approaches to establishing lightpaths. The first is the centralized approach, in which a special node sets up and tears down lightpaths. The special node manages all the lightpath requests, and therefore can select appropriate routes and wavelengths for lightpath requests. The disadvantage of this network is scalability, the network scale more grow, the lightpath set–up request more frequently arrives to the special node, which cannot process all of requests. The second is the distributed approach, in which each node can set up and tear down lightpaths. Because nodes do not know whether the other nodes are trying to reserve wavelengths in the distributed approach, conflicts about wavelength reservations may occur. To minimize the probability of such conflicts in establishing lightpaths, the sender node must select the appropriate route and wavelength for the lightpath. The nodes should know the state of wavelength utilization within the network to find and select which route is appropriate.

Each node needs precise information about the use of wavelength resources so that the routing algorithm can find the best route. In a distributed network, however, each node only knows about the states of adjacent links, so they must exchange link–state information to efficiently select the appropriate route. There are two types of link–state information exchange. The first is frequent exchanges where nodes distribute link–state information immediately if the states of wavelength utilization change. The second is infrequent exchanges where nodes distribute link–state information periodically or when the states change over a given threshold. When nodes periodically exchange information, the amount of exchanged data is much smaller than with frequent exchange. However, the blocking probability may increase because of the discrepancy between the current status of wavelength use and the exchanged link state information [1]. Even if nodes exchange link state information every time the link state changes, propagation delays prevent this information from arriving at all the nodes at the same time, which affects route and wavelength selection at the sender node [3]–[5]. Furthermore, traffic for link–state information exchange much increases.

In [6], [7], a destination–node–oriented reservation protocol (backward reservation protocol) is described. The backward reservation protocol collects information about available wavelength resources during wavelength reservation, and the sender node only needs to select the route. Therefore, because the necessary information for all nodes is about route selection, there is no need for frequent link–state information exchange and detailed link state information. For example, link–state information only about the use of wavelength resources is sufficient to select a route.

Many routing algorithms have been studied for lightpath networks [1], [2], [8]–[11]. Two main algorithms have previously been proposed for routing lightpaths: adaptive–routing and alternate–routing algorithms. With the first, a sender node, at which a lightpath–setup request has arrived, evaluates all available routes in the network, according to the current status of wavelength utilization, and selects the one that will provide the best route for the lightpath. With the second, each node has a route–list in which a set of pre–defined routes is described. The routes in the list are ordered by hop–counts, for example, and the sender node selects a route from the list. If the lightpath setup on the selected route fails, the sender node tries the next route. Although adaptive routing has better performance than alternate routing [12], it requires additional overheads to calculate appropriate routes from link–state information. Alternate routing requires less computational complexity than adaptive routing since the set of routes is pre–defined and no routes need to be calculated when the lightpath–setup request arrives at sender nodes. However, the discrepancies between the current status of wavelength use and the exchanged link–state information have not been considered in these studies. These discrepancies make sender nodes select the “worse” route, which increases the probability of requests being blocked. Routing with the discrepancy is worse than that without it. Therefore, the adaptive routing algorithms do not perform well since periodic information exchanges and the above–mentioned propagation delays prevent link–state information from being precise. If sender nodes select a route adaptively, the blocking probability is considered to increase because of the delayed link–state information. With the alternate routing algorithm, on the other hand, the sender node selects the next route from pre–defined routes if the path setup fails. We found the degradation in performance is small with alternate routing. In this paper, we discuss our evaluation of the average path setup time for routing algorithms to clarify the effect delayed link state information has.

This paper is organized as follows. In Section II, we explain the existing routing and wavelength selection methods and wavelength reservation protocols. In Section III, we discuss how the frequency of link–state–information exchange affects the establishment of lightpaths using computer simulations. The conclusion is in Section IV.

II. Routing and Wavelength Assignment in Optical Networks

There are two elements involved in establishing lightpaths: route and wavelength selection and the reservation protocol. One of the most important issues facing routing in distributed networks are the intervals between link–state–information exchanges. If nodes exchange link–state–information every time the link status changes, huge amounts of information spread throughout the network and the routing table is frequently calculated making increasing the loads of CPUs in nodes. To reduce these processing overheads, some method is needed that enables less frequent link–state exchanges using less detailed link–state information.

We will first explain the wavelength reservation protocol in Subsections II-A. We will then discuss the routing algorithms, i.e., fixed–routing, adaptive–routing and alternate–routing algorithms, in Subsection II-B.1, II-B.2 and II-B.3.

A. Wavelength reservation protocols

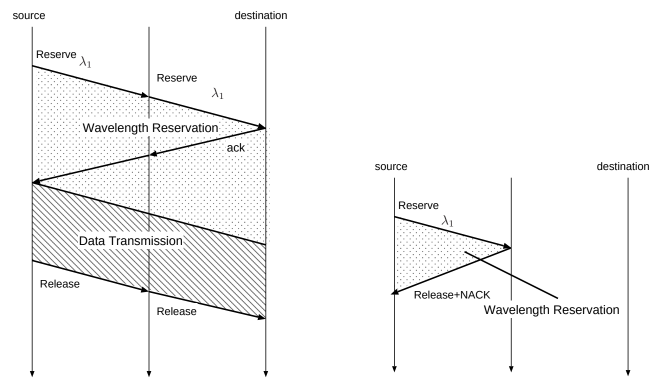
There are two reservation protocols; forward–reservation (II-A.1) and backward–reservation (II-A.2). Table I summarizes the operations of nodes on the lightpath set–up.

1) Forward reservation: When a request to establish a lightpath arrives at the sender node, it selects the route and wavelength for the lightpath. The sender node then transmits a RESERVE signal and reserves the wavelength along the selected route. When an intermediate node receives the signal, it obtains the wavelength from the signal, and reserves the wavelength on the next link. When the RESERVE signal arrives at the receiver node, a lightpath is established and

TABLE I

RESERVATION PROTOCOLS: OPERATIONS AT NODES

Node	Forward reservation	Backward reservation
Sender node	route and wavelength selection, reservation	route selection, PROBE signaling
Intermediates (up)	reservation	update PROBE signal
Receiver node	return ACK	wavelength selection and reservation
Intermediates (down)	forward ACK signal	reservation



(a) A successful case of a lightpath establishment

(b) A failure case of a lightpath establishment

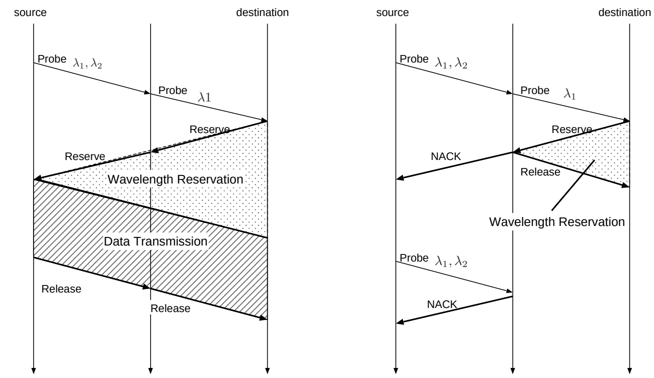
Fig. 3. Forward reservation protocol

the receiver node transmits an ACK signal to the sender node (Fig. 3(a)). The sender node transfers the data upon receiving the ACK signal, and transmits a RELEASE signal to the receiver node at the end of the data. The RELEASE signal releases the wavelength used for the lightpath. Figure 3(b) illustrates a case where lightpath establishment has failed. The RESERVE signal has arrived at the intermediate node, but the wavelength is already reserved or is being used by another lightpath. Here, the request to establish a lightpath has been rejected, and the intermediate node transmits a NACK signal to the sender node.

The forward reservation protocol needs to select a route as well as a wavelength at the sender node; the link state information should include information about the use of each wavelength on each link. We can use the number of available wavelengths as link state information. However, the sender node may select the wrong wavelength because of this less–detailed link state information, and blocking probability will increase.

2) Backward reservation: When a lightpath request arrives at the sender node, it only selects the route for the lightpath. The sender node then generates a PROBE signal containing a set of available wavelengths on the next link, and transmits this to the receiver node. When an intermediate node receives the PROBE signal, it intersects the sets of available wavelengths on the next link that are contained in the PROBE signal, and writes in the PROBE signal.

After updating the PROBE signal, the node transmits the



(a) A successful case of lightpath establishment

(b) A failure case of lightpath establishment

Fig. 4. Backward reservation protocol

signal to the next node. The set of wavelengths in the PROBE signal contains available wavelengths on the route along which the PROBE signal arrived at the receiver node. The receiver node selects a wavelength from the available wavelengths in the PROBE signal, and transmits a RESERVE signal to reserve the wavelength on the route. On receiving the RESERVE signal at the sender node, the sender node acknowledges that a lightpath has successfully been established, and starts transferring the data. After the data have been transferred, the reserved wavelength is released via a RELEASE signal. Figure 4(a) illustrates a case of successful wavelength reservation. There are two instances when a request to reserve wavelength can be rejected with the backward reservation protocol (Fig. 4(b)). The first is when the available wavelengths are being probed (PROBE sequence), and the second is when the wavelength has already been reserved (RESERVE sequence).

Rejection on receiving a PROBE sequence occurs when the set intersected by the intermediate node is empty. When this happens, there are no available wavelengths on the route, and the intermediate node sends a NACK signal to the sender node. Rejection on the receipt of a RESERVE sequence occurs when wavelength reservation conflicts with the establishment of another lightpath. When wavelength reservation fails, a NACK signal is transmitted to the sender node, and a RELEASE signal is transmitted from the intermediate node to the receiver node to release the reserved wavelength.

B. Routing algorithms

Routing algorithms select routes for path setup. They use link–state information and candidate routes. In this subsection, we explain three typical routing algorithms, and their advantages and disadvantages. Table II briefly outlines routing algorithms.

1) Fixed routing: The fixed routing algorithm uses a predetermined route for all node pairs each time a connection is established [11], [13]. On the arrival of a lightpath request, the fixed routing algorithm chooses a predetermined route.

TABLE II

COMPARISON OF ROUTING ALGORITHMS: ADVANTAGES AND DISADVANTAGES

Routing Algorithm	Advantages	Disadvantages
Fixed routing	No CPU consumption of route selection	Blocking increase because of convergence
Adaptive Routing	avoid highly–loaded route selection	need link state information exchange
Alternate Routing	can retry other routes if establishment fails	may result in wrong route selection

Route selection does not depend on the actual dynamic link–state change. A typical fixed routing algorithm is minimum hop routing (for instance, Dijkstra's shortest path algorithm). When lightpath establishments are congested on certain links, this algorithm cannot reroute the link, and the lightpath request may be blocked.

In this paper, we discuss our use of a minimum hop routing algorithm, where the sender node selects the shortest route to connect a node pair.

2) Adaptive routing: With adaptive routing, sender nodes dynamically select a route to the receiver node when a lightpath setup request arrives ([1], [10], [11], [14]). Route selection depends on network–state information, i.e., both the connectivity of each adjacent node and the wavelength utilization of each link. The advantage with this algorithm is that the sender node evaluates all available routes in the network, which is expected to result in less blocking. The disadvantage with this algorithm is that the discrepancy between the current status of wavelength utilization and exchanged link–state information greatly affects blocking. With this algorithm, it is necessary to efficiently select the proper route that current link–state information can use.

In this research, we used a least loaded routing algorithm, where the sender node selects the route that has the minimum number of reserved wavelengths along it. Note that the least loaded routing algorithm requires the number of reserved wavelengths in each link as the link state information.

3) Alternate routing: There are two types of alternate routing; fixed–alternate and adaptive–alternate routing [12], [15]–[17]. With fixed–alternate routing, each node has a route–list for a set of pre–determined routes. This list contains an ordered list of routes to each destination node, and the routes are not changed dynamically. When a lightpath setup request arrives at the sender node, the node selects a route (primary route) according to its order on the list. If the lightpath cannot be established along the primary route, the sender node then selects the next route. This continues until all the routes in the list have been examined. An advantage of fixed–alternate routing is that since the list has been determined in advance, the route does not have to be calculated before the lightpath has been set up. Furthermore, even if some links fails, the sender node can easily select other routes. With adaptive routing, the sender node must calculate another route to avoid failed links.

With adaptive–alternate routing, each node also has a route list, but the order of routes changes dynamically according to wavelength utilization in the network. This is a hybrid approach to adaptive routing and fixed–alternate routing to balance the number of wavelengths used in each link while providing less computational complexity in selecting routes. If the sender node is aware of congestion on links based on link–state–information exchange, it establishes an order to load–balance the network. If the lightpath setup along the route fails, the sender node selects another route by considering whether the link load on the route would be lower. As the order of routes can be changed by the sender node with adaptive routing, the degradation in performance due to delayed information was considered low using adaptive routing with an appropriate routing algorithm.

In following sections, we discuss our evaluation of the routing algorithms and reservation protocols from the viewpoint of degradation in performance due to delayed link–state information.

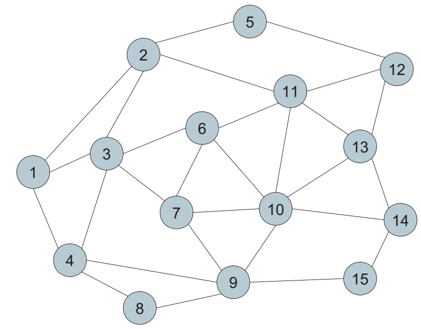


Fig. 5. Random network model

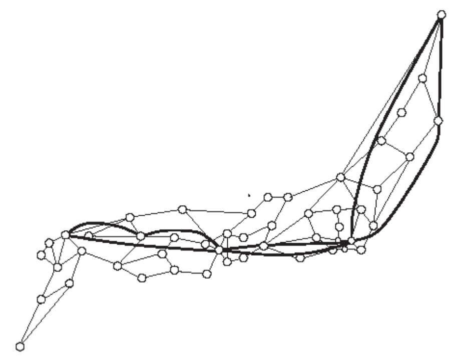


Fig. 6. Japan backbone network

III. PERFORMANCE EVALUATION

This section discusses our evaluation of reservation protocols and routing algorithms in distributed environments using computer simulations.

A. Simulation model

Figures 5–6 have the two network topologies we used to evaluate performance. Figure. 5 has a random network

TABLE III

ALTERNATE ROUTING ALGORITHMS: ROUTING TYPE AND BRIEF SUMMARY OF SELECTED ROUTE

Algorithm name	Routing Type	Selected route
Shortest Path	Fixed	minimum hop count
FAR	Alternate	By order of hop count
Least Loaded	Adaptive Alternate	Least loaded route
FAR with LL	Adaptive Alternate	By order of load
FAR with 1SP and LL	Adaptive Alternate	Shortest primary route others in order of load.

consisting of 15 nodes and 28 duplex links. There is an average number of 2.50 minimum hop–counts between node pairs, and the mean propagation delay for each link was set by multiplying the length of each link in Fig. 5 by scale factor α. Figure 6 shows the Japan backbone network, which consists of 49 nodes and 91 duplex links. The average number of minimum hop–counts is 6.06 in this network, and the mean propagation delay is 0.59 ms.

We did simulations on computer with the following parameters.

- Requests arriving at each node follow with the Poisson arrival with a mean of P. The arrival rate to each node pair is even.
- The service time for a lightpath has an exponential distribution with a mean of $1/\mu$.
- The number of multiplexed channels in each optical fiber is $W + 1$. One channel is used as a control channel on which the nodes exchange control signals and link–state information. The other W channels are used to establish lightpaths.
- Link–state information is updated at T intervals.

We assumed that there would be no processing delays in the routing, wavelength–selection, or wavelength-reservation processes at each node. Every control signal is delayed due to the effect of link propagation delay. The signals are not affected by either node processing delays or queueing delays.

B. Routing algorithms

Let us next discuss our evaluation of adaptive routing and alternate routing performed. We used the backward reservation protocol to select an available wavelength on the route. We also used the k–shortest path algorithm to select a route for the lightpath ([18]). With adaptive routing, the best route (i.e., the least loaded route of the k–shortest routes) is selected by the sender node. In alternate routing, the sender nodes decide the order the routes will be selected from the k–shortest paths. If a lightpath is set up k–times, the sender node re-determines the order routes will be selected from the k–shortest paths.

Table III summarizes the routing algorithms we used in our simulations. With the shortest path (SP) algorithm, the sender node repeatedly selects the shortest path that has the minimum hop counts. With FAR (: Fixed Alternate Routing), the sender node only selects routes according to their defined order. Each node selects a route from the route–list in ascending sequence with regards to the number of hop–counts. With the least loaded algorithm, the sender node selects the least loaded route according to defined routes and collected link–state information that has been dynamically updated. If path setup fails, the sender node selects the least loaded route using link–state information that has been collected at that time. As this algorithm balances the number of reserved wavelengths on the links, the blocking probability is low in highly–loaded networks.

The "FAR with LL" is a fixed alternate routing algorithm with adaptive (least loaded) selection. The sender node selects a primary route as with the least loaded algorithm and the other defined routes are sorted by order of load. If path setup fails, the sender node selects the next route from the left of the sorted routes. This algorithm also balances the number of reserved wavelengths on the links. Routes are always selected using delayed link–state information with the least–loaded algorithm, which degrades performance. However, with the "FAR with LL" algorithm, as the sender node can select other routes from candidate routes, the degraded performance of delayed link–state information is expected to be low.

Finally, let us introduce our new algorithm: "FAR with 1SP and LL" algorithm. With this algorithm, the sender node selects the less loaded route from candidate routes the same as the "FAR with LL" algorithm, except that the primary route is fixed to the shortest path. "FAR with 1SP and LL" algorithm has the advantages of "Shortest Path and FAR with LL" algorithm. The primary route selection with this algorithm consumes fewer wavelength resources, and if the setup fails, the next route is selected to achieves load–balancing.

C. Policies for link–state–information exchange

Routing algorithms use link–state information to select the proper route depending on the network actual state of the network. The initial exchange of link state information allows routers to build an incremental view of the network topology. The routers then monitor adjacent links, and exchange link attributes to neighbor node on some triggers of flooding. These triggers have been considered in [19].

(1) frequent exchange: flooding every time the state changes,
(2) periodic exchange: flooding every a few seconds.

Frequent exchange improves preciseness of exchanged link–state information. Therefore, routes can be properly selected depending on how accurate this information is. However, there is a huge amount of traffic from this link–state–information exchange because frequent link–state updates cause control channel congestion and heavy CPU calculations on flood the information. Therefore, we need to consider the trade–off with this triggering method between the control–channel and degradation routing granularity. Periodic exchange, on the other hand, degrades the accuracy of exchanged link–state information. How well route selection works depends on how much information has deteriorated. If the route has been selected adaptively, it needs to avoid congested links, but in this case the delayed link–state information prevents the route from being properly selected. However, the traffic from OSPF of periodic exchange is much smaller than that of frequent exchange. Therefore, we need to consider the trade–off between the frequency of link–state–information exchange and route selection accuracy. Ref [3] clarified the issues with this problem and proposed new link–state triggering methods. The nodes have a certain constant threshold for triggering and flood whenever the triggering value exceeds the given threshold. One of triggering value is the difference of current link state and previously flooded link state information and the other is relative proportion of current and previous link state. Flooding traffic and the effect of delayed link–state information depends on the threshold, and they found through evaluation that new methods provide better routing accuracy with less flooding than periodical link state exchange. However the OSPF standard does not support the new method. Therefore, we evaluated the periodic link–state exchange and frequent link–state exchange using computer simulation.

D. Evaluation of wavelength reservation protocols

The performance measurement for the reservation protocols is blocking probability. The blocking probability is the probability of lightpath establishment will fail. We used a model for this evaluation where the nodes terminated a lightpath establishment request if the lightpath could not be established. On the other hand, the performance measurement for the routing algorithms is lightpath setup delay. Lightpath setup delay is defined as the time from when a lightpath setup request was received at the sender node to when the lightpath was successfully established. We used a model where the nodes continued to establish a lightpath even if lightpath establishment had failed.

Route and wavelength selection algorithms for the forward and backward reservation protocols will now be described. With both forward and backward reservation protocols, the least loaded route is selected from the k–shortest paths. The least loaded route is defined as a route such that the maximum number of wavelengths used in each link on the route is minimal among k-shortest paths.

With the forward reservation protocol, the sender node selects a route with at least one available wavelength. If there are two or more available wavelengths, one is randomly selected. Note that information about wavelength use in each link is distributed as link state information. With the backward reservation protocol, the sender node selects the least loaded route from k–shortest paths. The receiver node then randomly selects a wavelength from the set of available wavelengths in the PROBE signal as described in Sec. II-A.2. Note that information about the number of wavelengths used in each link is distributed as link state information with this protocol.

From Figs. 7 through 10, we can see the blocking probability for a lightpath request for different link state update intervals with both forward and backward reservation protocols. The x–axis is the arrival rate for a lightpath request and the y–axis is the blocking probability for a lightpath request. Both the x–axis and y–axis are log–scale. "Global" means that the sender nodes obtain global link state information, assuming that all nodes exchange link–state information with no propagation delay, which is an ideal case. Here, "T=0" means that the link state information is exchanged immediately after there has been a change in the link state, "T=15sec" means that link state information is exchanged every 15 seconds.

Figure 7 plots the blocking probability at arrival rate P. The number of multiplexed channels (W) was set to 8 and the average service time ($1/\mu$) was set to 1.0ms. The average link propagation delay was 0.1ms (α = 0.0557 ms). The results of blocking probability for "global" are almost the same as for "T=0" with both forward and backward reservation protocols. This is because the average link propagation delay is short, and the link–state information is transmitted with smaller delays. If we compare the results for "T=15sec" and those for "T=0", the blocking probability increases with both forward and backward reservation protocols. The results for the backward reservation protocol have a smaller increase than for the forward reservation protocol. The reason is that when link–state information is exchanged periodically with the forward reservation protocol, the probability that the route and wavelength selected by the sender node have already been reserved increases because the wavelength is selected based on the old link–state information. With the backward reservation protocol, the difference in blocking probability between link–state information and with the actual link state is small because the PROBE signal dynamically collects information about the available wavelengths on the route. Therefore, the blocking probability slightly decreases with the backward reservation protocol. Note that when the arrival rate is low (lower than 0.004), there are no significant differences between the results for "T=0" and "T=15sec" due to less frequent link–state–information exchanges.

Figure 8 plots the blocking probability when the average service time is 100ms. We can see that a longer service time significantly increases the blocking probability based on the difference between "T=0" and "T=15sec" with both forward and backward reservation protocols. When this occurs, lightpaths are held longer than in other situations, but the link–state information intervals are longer than the mean service time. Because the received link–state information often fails to reflect the actual link state, the selected wavelength is likely to have already been reserved for other lightpaths with the forward reservation protocol. With the backward reservation protocol, a long service time affects the PROBE sequence because the available wavelengths do not change often. Discrepancies between wavelengths available in the PROBE signal and actually available wavelengths do not occur frequently and RESERVE sequence are rejected less frequently. Therefore, rejection with PROBE sequence are dominant in blocking under these conditions. Rejection when a PROBE signal is received occurs when there is a discrepancy between the selected route and actual available wavelengths in routing at the sender node. Therefore periodic link–state exchanges affects blocking probability. Thus, both forward and backward reservation protocols need precise link–state

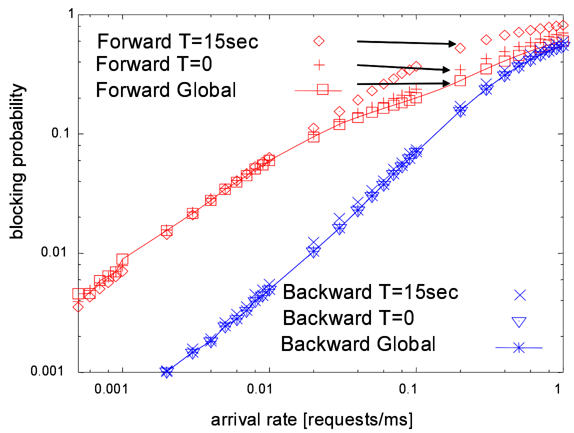


Fig. 7. Blocking probability and link state update interval in random network : $W = 8$, $1/\mu$ = 1.0ms, average link propagation delay of 0.1ms (α = 0.0557ms)

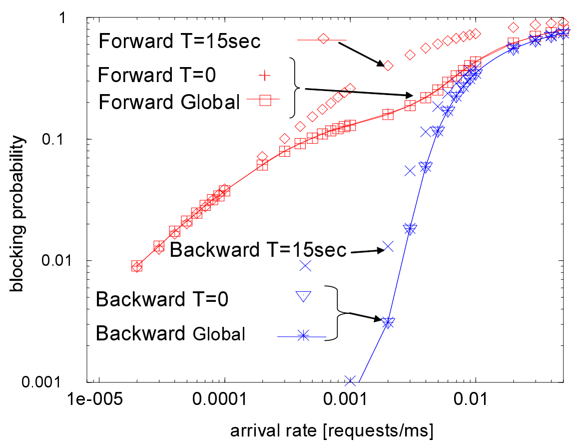


Fig. 8. Blocking probability and link state update interval in random network : $W = 8$, $1/\mu$ = 100ms, average link propagation delay of 0.1 ms (α = 0.0557ms)

information when the service time is long. However, blocking probability with the backward reservation protocol is small because the available wavelength collected based on the PROBE sequence works well.

We next examine both forward and backward reservation protocols on the Japan backbone network. Figure 9 plots blocking probability depending on the arrival rate. The advantage of frequent link–state exchange decreases both for forward and backward reservation protocols, compared with Figure 7. That is, the difference between the results for "T=0/15sec" and "Global" is not as great. This is because the minimum number of hop–counts between nodes for the Japan backbone network is larger than that for the random network. Lightpath establishment with larger hop–counts frequently causes conflicts. Here, the available wavelengths the sender node receives from link–state information tend to be reserved by other lightpath requests. Therefore, the advantage of routing with accurate link–state information is reduced, and blocking probability cannot be improved with frequent link–state exchanges.

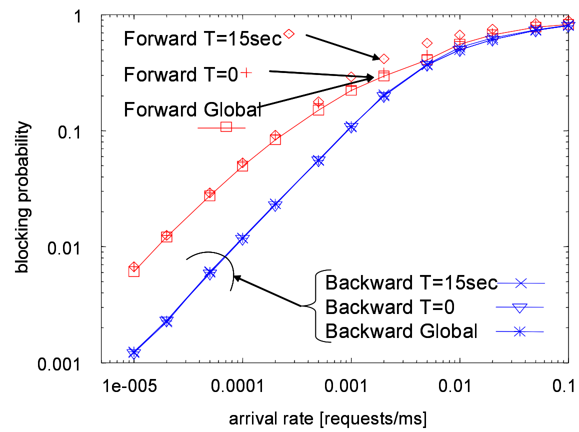


Fig. 9. Blocking probability and link state update interval in Japan backbone network: $W = 8$, $1/\mu$ = 1ms, average link propagation delay of 0.59 ms

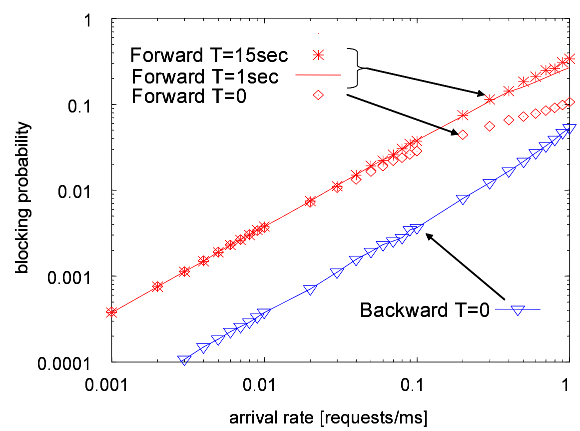


Fig. 10. Blocking probability in three node tandem network $W = 8$, $1/\mu$ = 1.0ms, average link propagation delay of 0.1ms

We now explain how the link–state information interval affects wavelength selection by using a three–node tandem network for the simulation topology. The route for the lightpath is fixed, so we can only see the effect of discrepancy between the actual utilization of wavelength resources and the link–state information exchanged in wavelength selection. Figure 10 plots blocking probability dependent on the arrival rate. Interval T was set to 0 for this simulation because the backward reservation protocol does not use link–state information at the sender node to select wavelengths We can see that as the link–state–information–update interval increases, so too does the blocking probability. A shorter link–state update interval is needed with forward reservation protocol to select wavelengths. In contrast, with the backward reservation protocol, wavelength selection depends on the link state information, and a shorter interval is not necessary.

E. Evaluation of routing algorithms

From Figs. 11 through 14, we can see the average setup time for lightpath requests for different alternate routing algorithms with the backward reservation protocol. The x–axis is the arrival rate, and the y–axis is the average path setup time for a lightpath request. Both x– and y–axes are linear–scale. "Global" means that the sender nodes can use global link–state information without any propagation delay, which is an ideal case. Here, "T=0" means that link–state information is exchanged immediately after there has been a change in the link state ;"T=15sec" means that link–state information is exchanged every 15 seconds.

Figure 11 plots the average path setup time for algorithms with a random network topology (Fig. 5). We can see that the average path setup time with the "Shortest Path", with "FAR with 1 SP", and with "Least–Loaded Global" is shorter than that with the "Least–Loaded and FAR with LL" algorithm when the arrival rate is low. We can also see the slope for the average path setup time with the "Shortest Path" increases more steeply than with the other algorithms when the arrival rate is high. This is because when the arrival rate is low and the number of hop–counts of established lightpaths is small, more available wavelengths are left in the network than when the least–loaded route is selected. However, when the arrival rate is high, some links are over–loaded with the Shortest Path algorithm. Consequently the network is not load–balanced by the Shortest Path, so the average path setup time increases sharply as the arrival rate increases. However, the load for all links are balanced with the other algorithms, so that the slope for the average path setup time does not exhibit the sharp increase.

Figure 12 compares the performance of algorithms with immediate link–state–information exchange and periodic link–state–information exchange. We can see that the difference between the results with "T=0" and "T=15sec" is small. That is, the discrepancy does not affect blocking. The main reason is that the backward reservation protocol determines the lightpath's wavelength based on information collected from available wavelengths on the route.

Figures 13–14 plot the performance of routing algorithms with the Japan backbone network topology. The differences in performance for each algorithm have a similar tendency to those in the random network. However, Fig. 14 does not plot the same as in Fig. 12; the performance of the least loaded algorithm is much more degraded than that of the "FAR with 1SP and LL" algorithm. This is because the average distance between nodes in the Japan backbone network is longer than that in the random network. That is, the inaccuracy of link–state information increases. In all the figures, "FAR with 1SP and LL algorithm" performs better than the other algorithms. It is important that routing algorithms select the route that uses the lowest amount of wavelength resources as well as one that balances the number of wavelengths used in each link. The "FAR with 1SP and LL" algorithm does both. Furthermore, its selecting of alternate routes reduces performance degradation due to imprecise link state information.

IV. Conclusion

We investigated the effect of frequency of link state information exchange on reservation protocols. We evaluated them with three network topologies, i.e., a random mesh network,

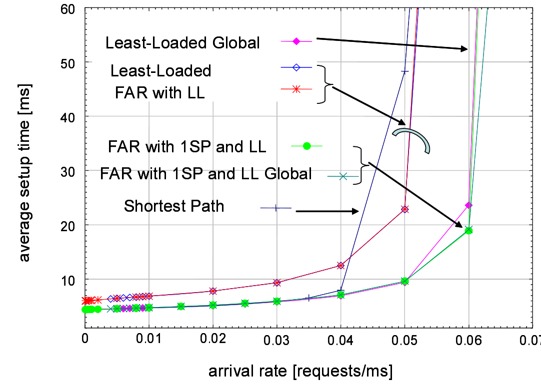


Fig. 11. Average path setup time for random network with dynamic link use information: $W = 8$, $1/\mu$ = 1.0ms, average link propagation delay of 0.1 ms

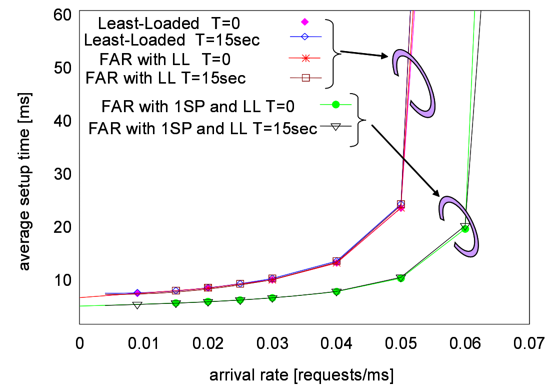


Fig. 12. Average path setup time for random network with periodic link use information: $W = 8$, $1/\mu$ = 1.0ms, average link propagation delay of 0.1ms

realistic mesh network, and three–node tandem network in computer simulations. The results revealed that when the backward reservation protocol was used, routing could be done with less frequent link–state information exchange using less detailed information than when the forward reservation protocol was used. We then evaluated alternate routing algorithms in terms of routing and delayed link–state information. The results revealed that when the primary route was fixed to the shortest path and the other routes were less loaded it performed with the save average lightpath establishment time as the least loaded algorithm with global link–state information. Furthermore, as the topology grew larger, the performance of the least loaded algorithm degraded because of imprecise link–state information, while that of the alternate routing algorithms did not.

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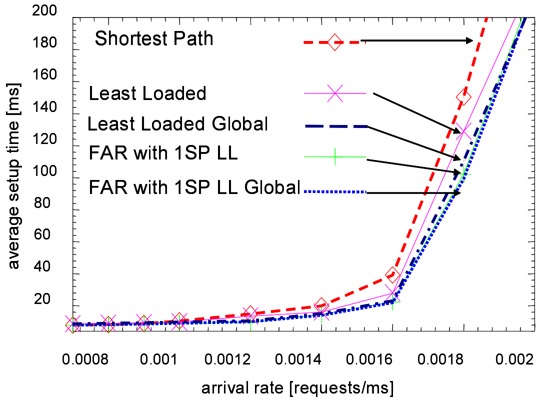

Fig. 13. Average path setup time for Japan backbone network with dynamic link use information: $W = 8$, $1/\mu$ = 1.0ms

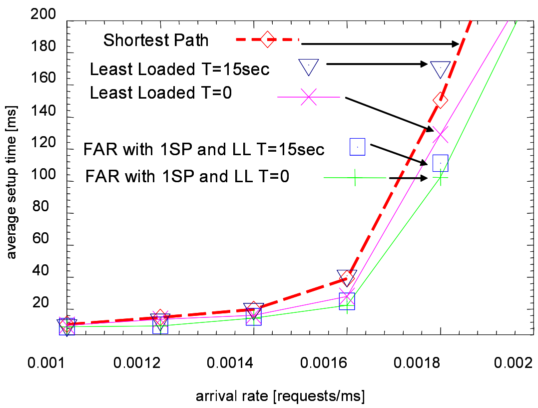

Fig. 14. Average path setup time for Japan backbone network with periodic link use information: $W = 8$, $1/\mu$ = 1.0ms.

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