A Distributed Signaling Scheme for Provisioning Dynamic Traffic in Wavelength-Routed Networks

Kejie Lu[a], Jason P. Jue[a], Gaoxi Xiao[b], Imrich Chlamtac[a], and Timucin Ozugur[c]

[a]The Center for Advanced Telecommunications Systems and Services
The University of Texas at Dallas, Richardson, TX 75083

[b]School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore 639798

[c]Alcatel Research and Innovation Center, Plano, TX 75075

ABSTRACT

Provisioning dynamic traffic is a major challenge in wavelength-routed networks. While the routes of connections are mainly determined by using global state information, different connections that share the same link may still compete for the same resources. These conflicts can cause significant blocking, a problem that becomes more serious as traffic becomes more dynamic and as the state information changes more frequently. Therefore, it is increasingly important to design appropriate signaling schemes to avoid blocking due to contention between different simultaneous connection requests. In this paper, we propose a new distributed signaling scheme, *Intermediate-Node Initiated Reservation* (IIR), for establishing dynamic lightpaths in wavelength-routed networks. In the framework of IIR, reservations may be initiated at any set of nodes along the path of a connection, and multiple wavelengths may be reserved. Two IIR implementations are designed for networks with no wavelength conversion and with sparse wavelength conversion. Extensive simulation results show that the IIR scheme outperforms the original schemes under various network and traffic conditions. Simulation results also show that the IIR scheme performs better in networks where number of wavelength per fiber is large, or in networks with sparse wavelength conversion.

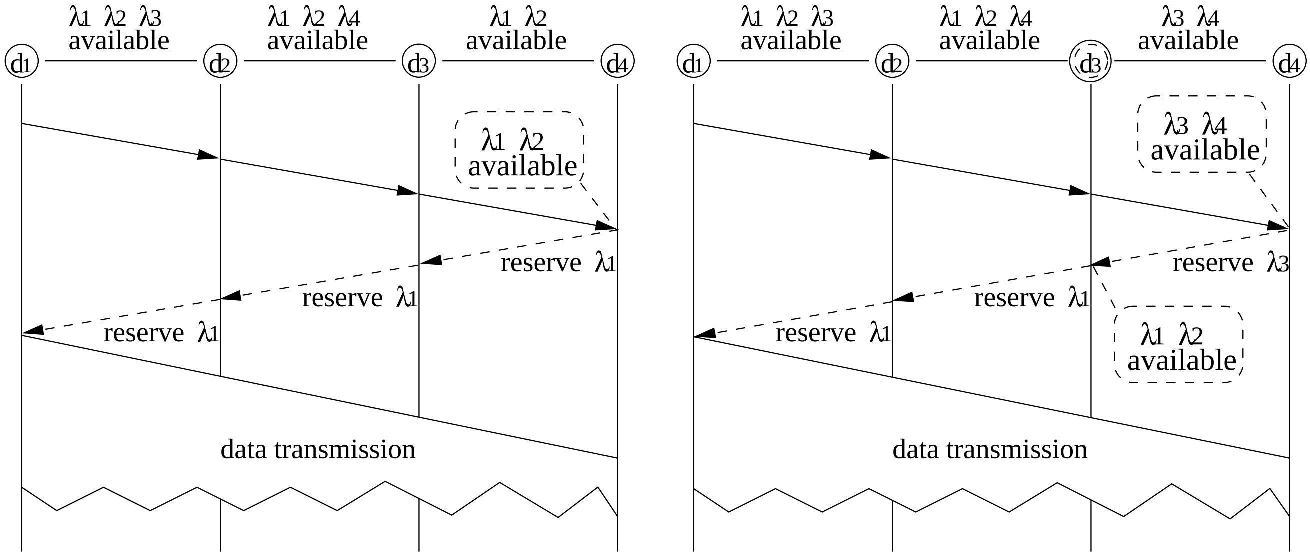
1. INTRODUCTION

Wavelength division multiplexing (WDM) technology has been progressing steadily, with existing systems capable of providing large amounts of bandwidth in a single fiber. While existing WDM networks are mainly point-to-point networks which use electronic switching, next generation networks are evolving toward more flexible, all-optical networks by exploiting advances in optical switching. To fully utilize the high bandwidth in optical networks, all-optical connections, or *lightpaths*,[1] can be established between source and destination nodes. Lightpath-based optical networks are generally referred to as *wavelength-routed networks*.

In legacy backbone networks, traffic is generally static, in which case connections are known in advance and remain in the network semi-permanently. However, in next generation optical networks, especially in the optical Internet, data traffic is expected to be more dynamic, or even highly bursty. To cope with the dynamic traffic loads, dynamic wavelength provisioning is under extensive research (e.g.,[1]-[3]). In this work, we consider the case in which data traffic is rather bursty and requires the establishment of lightpaths for short periods of time.

To accommodate connection requests dynamically, a lightpath provisioning scheme is required to find a route and assign a wavelength for the given connection request. This scheme can be either *centralized* or *distributed*. A centralized scheme may perform more efficiently when the network is small and the traffic is not bursty. However, a distributed scheme may be more appropriate for large optical networks and bursty Internet traffic. Distributed schemes have been proposed and are now being standardized within the framework of *generalized multi-protocol label switching* (GMPLS).[4]

In a GMPLS-based network, routing protocols such as *Open Shortest Path First with Traffic Engineering* (OSPF-TE) are used to exchange state information, including topology and resource availability information. When a connection request is received, a route is calculated based on the available state information by using a constraint-based routing algorithm (CSPF). Once the route is determined, a signaling scheme is responsible



(a) networks with no wavelength conversion (b) networks with sparse wavelength conversion

Figure 1. Examples of the DIR scheme.

for establishing the lightpath. Candidates for the signaling protocol within the GMPLS framework include the *Constraint-based Routing Label Distribution Protocol* (CR-LDP)[5] and the *Resource reSerVation Protocol with TE* (RSVP-TE).[6] Although the routes of connections can be determined by using global state information, different connections that share the same link may still compete for the same resources, which can cause significant contention. This problem becomes more serious as traffic becomes more dynamic and as the state information changes more frequently. Therefore, it is increasingly important to design appropriate signaling schemes to avoid contention between different simultaneous connection requests.

Several signaling schemes have been studied before. A well-known scheme is the *destination-initiated reservation* (DIR) method.[7] In the DIR method, a connection request is forwarded from the source to the destination, collecting the wavelength availability information of every link along the route*. Based on this information, the destination node will select an available wavelength along the path (if such is available) and send a *reservation request* back to the source node to reserve the selected wavelength. Fig. 1 (a) shows an example of the classic DIR method for networks with no wavelength conversion. In a network without wavelength conversion, a connection request will be rejected if a common wavelength cannot be found on the route between the source and destination. This constraint is known as the *wavelength continuity constraint*.[1] From Fig. 1 (a) we can also observe that, if the wavelength continuity constraint does not exist, a connection may have a greater chance of being successfully established. This can be realized by using wavelength converters on all nodes. However, from a practical point of view, this approach is difficult to implement due to the high cost of converters, which are expected to remain expensive in the near future.[8] Another solution is to use wavelength converters only at a subset of nodes. This approach is called *sparse conversion*.[11] Figure 1 (b) shows an example of the DIR method for networks with sparse wavelength conversion, where only node d_3 has full wavelength conversion capability while all other nodes do not have wavelength conversion capabilities.

Another possible signaling candidate is the *source-initiated reservation* (SIR) method,[7] where wavelength resources are reserved as a control messages traverses along the forward path to the destination. In SIR schemes, the detailed method of reserving wavelengths depends on how much information is available to the source node and to individual nodes along the route. When the source node has complete state information, it may send a

*In GMPLS,[4] ingress or any upstream node can restrict the labels that may be selected by downstream node by using the *suggested label* object. This feature is designed for the lightpath establishment in optical domain where wavelengths may be used as labels.

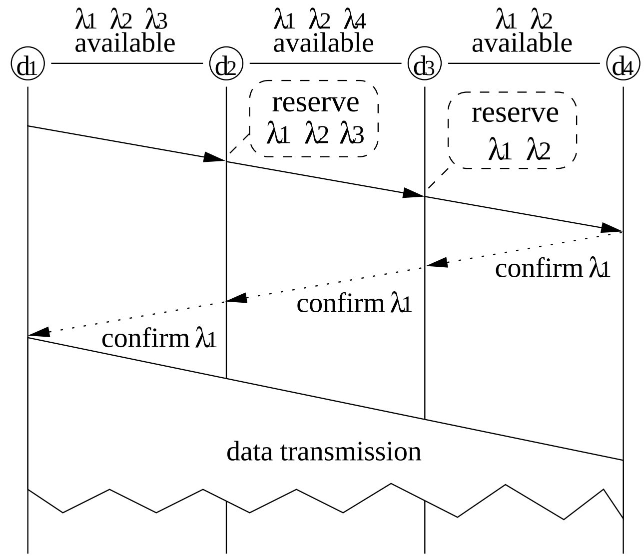


Figure 2. An example of the SIR scheme.

connection setup message along the forward path, reserving only one wavelength that is available along the path. However, under bursty traffic conditions, it is possible that up-to-date global information is not available. In this case, the source node may reserve all possible available wavelengths from the source node,[7] or a subset of the available wavelengths.[9] Figure 2 shows an example of the greedy SIR method in which all possible wavelengths are reserved along the path. It has been shown in[7] that, in general, the DIR scheme outperforms the greedy SIR scheme in networks with no wavelength conversion.

A key measure of performance in dynamic lightpath establishment is the connection blocking probability, i.e. the probability that an arriving connection request will be rejected. Blocking probability in wavelength-routed optical networks has been studied analytically in a number of previous works. While most early studies[10]-[12] considered centralized cases, distributed schemes are studied in recent works[13]-.[15] In,[13] analytical models are first developed to evaluate the blocking probability characteristics of various SIR and DIR schemes. This model considered blocking of connections due to insufficient resources as well as blocking due to contention. In[14] a more accurate analytical model for the DIR scheme was developed to measure the blocking probability in networks with no wavelength conversion. This model was further extended to evaluate the performance in networks with sparse wavelength conversion.[15]

The blocking due to insufficient resource may be reduced by applying more efficient routing algorithms. However, as the traffic becomes more dynamic, the blocking due to contention becomes more serious. In the DIR scheme, when a reservation message arrives at a node without conversion, a connection may be blocked if the wavelength is reserved by other connections after the link state information is collected. This is referred to as the *outdated information* problem. For a certain connection, we denote the *vulnerable period* at a node as the time between the moment that the link state information is collected and the moment that the reservation request arrives. It has been shown that, in the DIR scheme, connection blocking due to outdated information may dominate the overall performance under very dynamic traffic conditions[13]-.[15] Moreover, this kind of blocking increases significantly with respect to the vulnerable period. In the greedy SIR scheme, on the other hand, reserving a greater amount of resources for the current connection request can increase the probability that the current request will be accepted; however, the request may reserve too much network capacity, and block other connection requests. This is referred to as the *over-reservation* problem.

To deal with the outdated information problem of the DIR scheme and the over-reservation problem of the SIR scheme, we present a new signaling scheme, termed *Intermediate-Node Initiated Reservation* (IIR), for establishing lightpaths in a wavelength-routed network. The main idea is to allow the reservation to be initialized by intermediate nodes, so that the over-reservation is reduced and the outdated information is less likely to

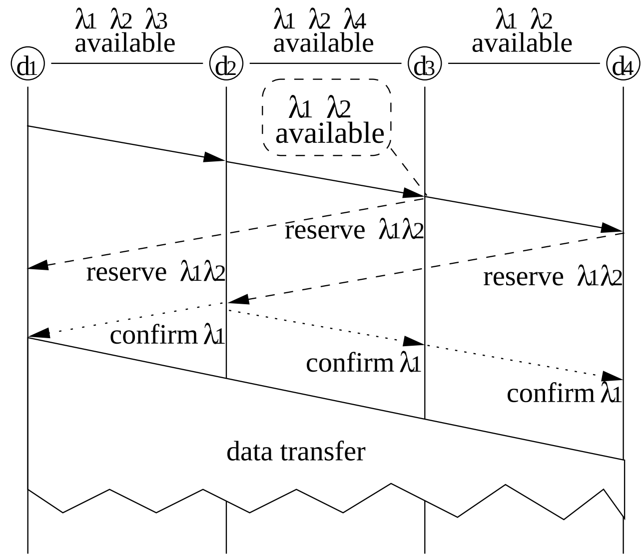


Figure 3. An example of the IIR scheme for networks with no wavelength conversion.

occur due to the shorter propagation delay. Another aspect of our scheme is to allow multiple wavelengths to be reserved. We evaluate the performance of the new scheme by extensive simulations. The simulation results show that the proposed signaling scheme can significantly improve system performance in terms of blocking probability.

The rest of this paper is organized as follows. In Section 2, we provide a generalized framework of the IIR scheme and discuss some specific implementations for two different network scenarios: networks with no wavelength conversion and networks with sparse conversion. Numerical results and analysis are presented in Section 3. Section 4 concludes the paper.

2. INTERMEDIATE-NODE INITIATED RESERVATION SCHEME

In this section, we describe the IIR scheme in which reservations may be initiated at any set of nodes along the path, and in which multiple wavelength channels may be reserved at each node in the set. With this definition, the classic DIR and SIR schemes can also be included in the same framework.

Figure 3 shows an example of the IIR scheme for networks with no wavelength conversion. In this example, similar to the DIR scheme, the source node first sends out a connection request message collecting the wavelength availability information along the path. However, unlike the example in Fig. 1 (a), in which the reservation message is initiated at the destination node, the reservation is issued at node d_3, which is the upstream node of the last hop. Two reservation messages are sent out on opposite directions to reserve two available wavelength channels (λ_1 and λ_2) in each direction. At the destination node, a message is sent back to the source node indicating that two wavelengths have already been reserved. When this message arrives at the downstream node of the first link, † one wavelength (λ_1) is chosen and two confirmation messages are then sent to the source and destination. In the forward direction, when a node receives a confirmation message, the unused channel (λ_2) is released.

Comparing the example in Fig. 3 with examples in Fig. 1 and Fig. 2, we can observe that:

- The vulnerable periods at nodes d_2 and d_3 have been reduced; thus, the blocking due to outdated information may be reduced at these two nodes.

†The reason that we select the second node in the path to issue confirmation is that, in GMPLS, the downstream node of a link determines the label assignment of the link.

- Two wavelength channels are reserved based on the network state information. Therefore, the over-reservation problem still exists. However, less over-reservation occurs in comparison with the greedy SIR scheme.
- Since there are two alternative wavelengths, the blocking due to outdated information may be further reduced.

By carefully selecting the parameters of the IIR schemes, e.g. the node(s) at which the reservation is initiated and the number of wavelength to be reserved, we can reduce the blocking caused by outdated information and better control the over-reservation problem as well. The overall performance improvement will be presented in Section 3.

We now provide a formal definition of the IIR scheme. We define the following parameters:

- S^R: The set of nodes at which reservations can be initiated on route R.

$$S^R = \{s_1^R, s_2^R, \cdots, s_m^R\}, \qquad 1 \leq m \leq N^R,$$

  where N^R denotes the total number of nodes in route R.
- δ_i^R: For each node $s_i^R \in S^R$, we define δ_i^R as the direction of the reservation. δ_i^R can be: forward, backward, and both directions.
- W_i^R: At any node $s_i^R \in S^R$, W_i^R denotes the set of wavelengths to be reserved.

For each route R, the set of nodes S^R and the parameters δ_i^R and W_i^R can be specified either

1. in a static manner off-line,
2. in a dynamic manner by the source node of a connection request, or
3. in a dynamic manner as the forwarded connection request message traverses the selected route of the connection.

The generalized protocols may include algorithms for determining the optimal selection of the nodes for initiating the reservations and algorithms for determining the best number of wavelengths to be reserved. The choice of the parameters in the optimization process could be based on various requirements and properties of the specific connection request, such as quality of service requirements, priorities, hop distance, and other constraints. Therefore, by connection-specific provisioning and proper optimization, the protocol can provide differentiated levels of service and also ensure fairness for connections of different lengths.

It is worth noting that, although the number of signaling messages may increase in the IIR scheme, the setup time of a connection is the same as that of classic DIR and SIR (See Fig. 3). To implement the IIR scheme, current signaling protocols have to be extended to enable the initiation of reservation from an intermediate node. The detailed discussions on such extensions, however, are beyond the scope of this paper.

In the rest of this section, we discuss the implementations of the IIR scheme for two network scenarios: (1) networks with no wavelength conversion, and (2) networks with sparse wavelength conversion, respectively.

2.1. IIR for Networks With No Wavelength Conversion

The first step in defining the IIR scheme is to determine the S^R for each route statically. Moreover, for networks with no wavelength conversion, we assume that only *one node* is in S^R. Therefore, $S^R = \{s_1^R\}$. Note that the classic DIR and SIR schemes can also be included in this framework. For the SIR scheme, the only node in S^R is the source node, and the direction, or δ_1^R, is forward, which means that a reservation message will be sent in the forward direction from the source node. For the DIR case, however, the only node in S^R is the destination node, and the direction δ_1^R is backward. Thus, the proposed IIR method will always perform at least as well as the SIR and DIR if s_1^R is allowed to vary from the source node to the destination.

To determine the S^R for the IIR scheme, we can first study the example in Fig. 1 (a). From this example we can observe that at node d_3, which is the upstream node of the last link, the wavelength usage information of the last link is available. Although this information is not accurate because the downstream node maintains the exact information and there still exists propagation delay between the two end nodes of the link. Consequently, when a forward message arrives at the upstream node of the last link, the wavelength availability information of the path is available.

Based on the observations above, we propose an IIR scheme for networks without wavelength conversion. For any route R, we let

$$s_1^R = \begin{cases} d_2, & N^R = 2 \\ d_{N^R-1}, & N^R > 2 \end{cases}$$

where d_i denotes the ith node in the path (d_1 is the source node and d_{N^R} is the destination node).

Based on this definition, if the route has only one link, then the direction factor δ_1^R will be backward. Otherwise, since the reservation-initiating point is not the source or destination node, the direction factor δ_1^R has to be both backward and forward, which means that reservation message must be sent in each direction. Note that the information of W_1 can be forwarded to d_L in the GMPLS context, since GMPLS allows a set of labels to be suggested by an upstream node.

After the decision of S^R, the next problem becomes the decision of W_1^R. Obviously, if one route contains a single link, then only one wavelength is enough to ensure that the connection will be successful. However, for multi-hop connections, the selection of W_1^R may be tricky. To simplify the discussion, we introduce a reservation ratio, denoted as w ($0 \le w \le 1$) for all multi-hop connections. The usage of w is as follows:

$$W_1^R = \max(1, \lfloor A \times w \rfloor), \qquad 0 \le w \le 1 \tag{1}$$

where A denotes the total number of available wavelengths along the path, indicating by the forwarded message, at the time when the request message arrives at node s_1^R.

Since the reservation ratio is independent of the position of the reservation-initiating point, the ratio can also be used with the original DIR and SIR schemes. For instance, we can see that w is 0 for the classic DIR scheme and is equal to 1 for the greedy SIR scheme. In the example of the IIR scheme demonstrated in Fig. 3, the reservation ratio is also set to 1. In Section 3, we will discuss the impact of the reservation ratio for all schemes.

2.2. IIR for Networks With Sparse Wavelength Conversion

As we discussed in Section 1, the sparse conversion can improve the performance by relax the wavelength continuity constraint. However, the outdated information problem still exists in a distributed environment. For example, on the route shown in Fig. 1 (b), it is possible that when the reservation request reaches node d_2, it is found that λ_1 has been reserved by another reservation request which arrived earlier. Observe from Fig. 1 (b) that we can separate every route into several *segments* such that the end nodes of each segment are the source node, the destination node, and a node with wavelength conversion capability. One important result of the sparse conversion is that two different wavelengths can be reserved on two different segments. For example, in Fig. 1 (b), different wavelengths are reserved on two consecutive segments on the route because node d_3 has full wavelength conversion capability.

Since the wavelength continuity constraint only holds within one segment, we proposed the IIR scheme for networks with sparse conversion as follows:

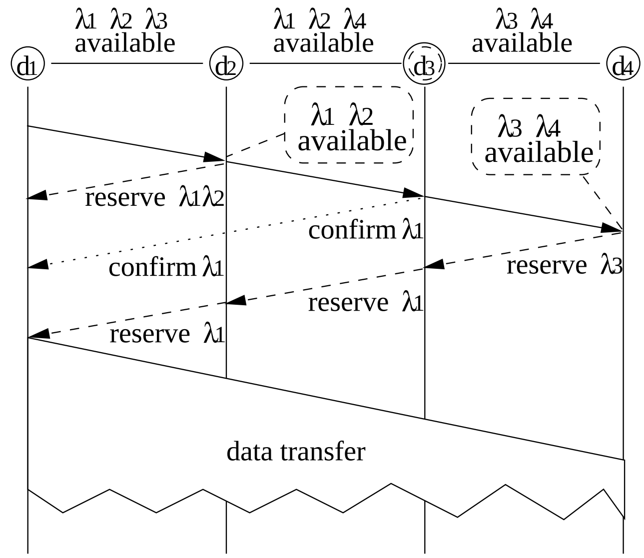


Figure 4. An example of the IIR scheme for networks with sparse wavelength conversion.

- Let L^R ($L^R \geq 1$) be the number of segments in route R.
- Let $S^R = \{s_1^R, \cdots, s_{L^R}^R\}$
- If segment i ($1 \leq i \leq L^R$) contains only one link, then the s_i^R is set to the egress node of segment i, and $W_i^R = 1$.
- If segment i ($1 \leq i \leq L^R$) contains two or more links, then the s_i^R is set to the upstream node of the last link on segment i. Similar to the case for networks without conversion, the W_i^R can be determined by Eq. (1) as well.
- The reservation on each segment may end at the egress node of the segment. If this segment is not the last segment on the route, another connection request must continue on toward downstream nodes with a new label set.

Figure 4 illustrates the proposed IIR scheme for networks with sparse wavelength conversion. We can observe that, by exploiting the sparse conversion capability, the IIR scheme can significantly reduce the vulnerable period. For example, comparing Fig. 1 (b) with Fig. 4, we can observe that the vulnerable period at node d_2 is reduced from the round trip propagation delay between d_2 and d_4 to zero. Consequently, the blocking due to outdated information can be significantly reduced.

3. NUMERICAL RESULTS

In this section, we discuss the blocking performance of the IIR scheme by extensive simulation results. We present the simulation results for the following Poisson traffic model:

- The traffic pattern is uniform, i.e., the arrival rate of connection requests between each pair of source-destination nodes is identical.
- Fixed shortest path routing is used between each pair of source-destination nodes.
- Blocked connection requests are dropped and are not retried.

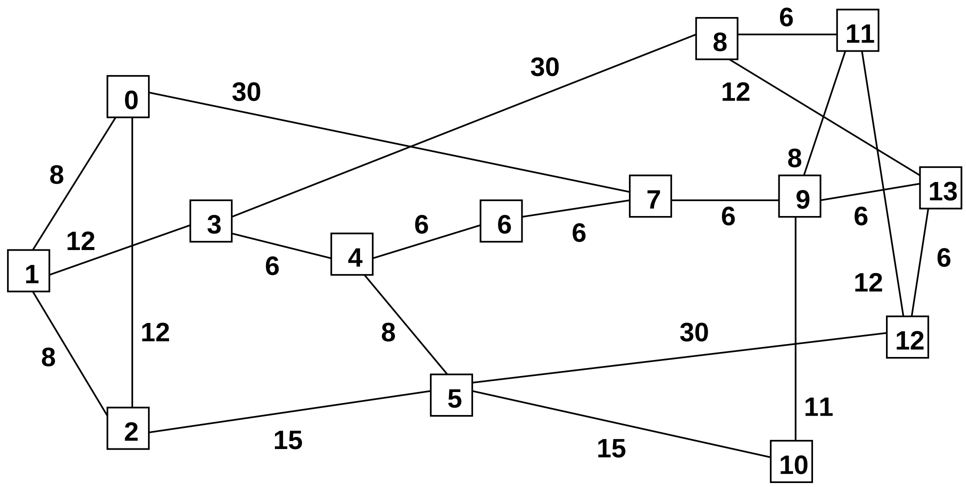


Figure 5. Network topology of NSFNet.

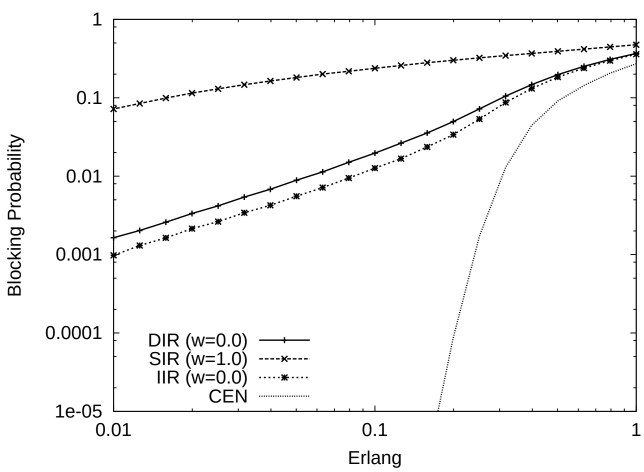


Figure 6. Blocking probability of different schemes ($C = 32,\ D = 100$ ms).

Our experiments are conducted on different topologies: (1) the NSFNet, shown in Fig. 5, where the numbers on each link denote the physical length in 100s of kilometers; (2) a 36-node torus mesh network, where the length of each link is 200 kilometers. For both networks, we assume that each link consists of two directional fibers with opposite directions, with the same number of wavelength channels per fiber.

In all of the following experiments, C denotes the number of wavelength channels per fiber; D denotes the average holding time of all connections; and the traffic load, measured in Erlang, denotes the normalized traffic load originating from each node.

Figure 6 shows the blocking probability for three different signaling schemes as well as a centralized scheme, where $C = 32$ and $D = 100$ ms. To evaluate the performance of the classic DIR and SIR schemes, we let the reservation ratio be 0 for DIR and 1 for SIR. The reservation ratio of the IIR scheme is set to 0 so that we can compare the performance of the IIR scheme with that of the classic DIR scheme in a fair manner. We can see that the blocking probability of distributed schemes is much higher than the blocking of the centralized scheme due to unavailable accurate global state information. For the three signaling schemes, we can observe that: (1) the IIR scheme outperforms the DIR and SIR schemes when traffic load is low or moderate; (2) the classic DIR scheme performs much better than the SIR scheme, as has been shown in some previous works; and (3) with the traffic load increasing, the performance of all schemes, including the centralized scheme, converges.

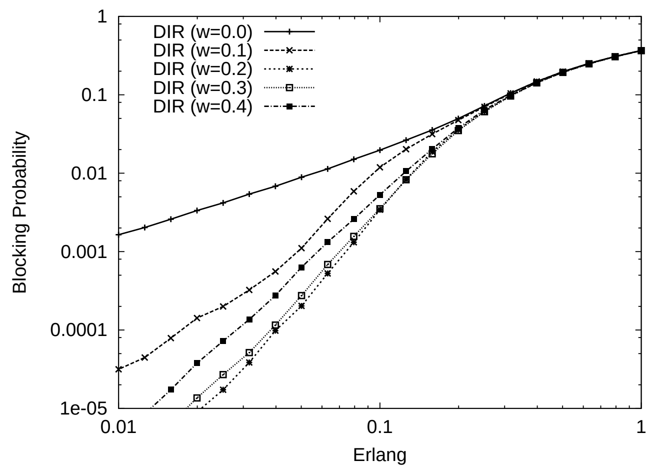
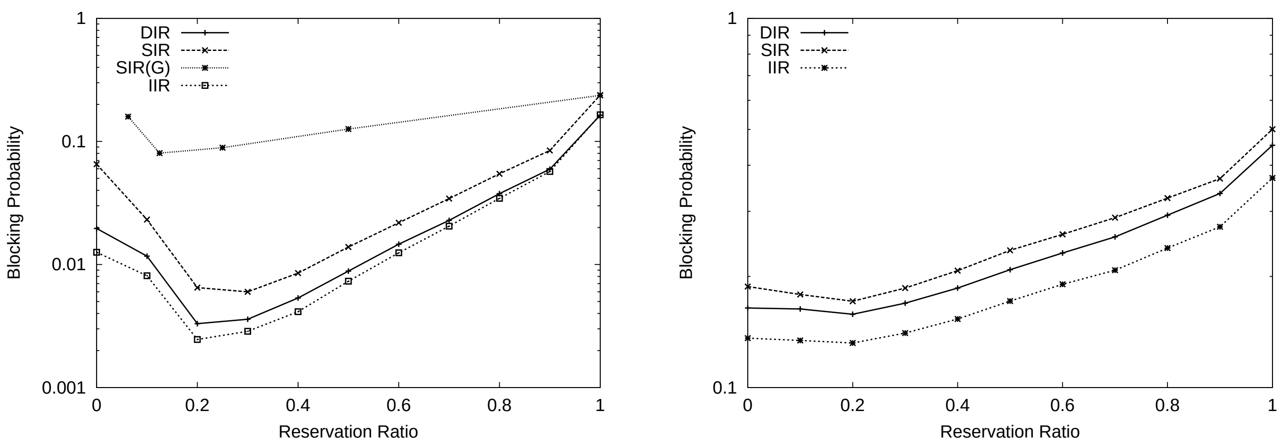


Figure 7. Blocking probabilities of the DIR scheme with different reservation ratios ($C = 32,\ D = 100$ ms).



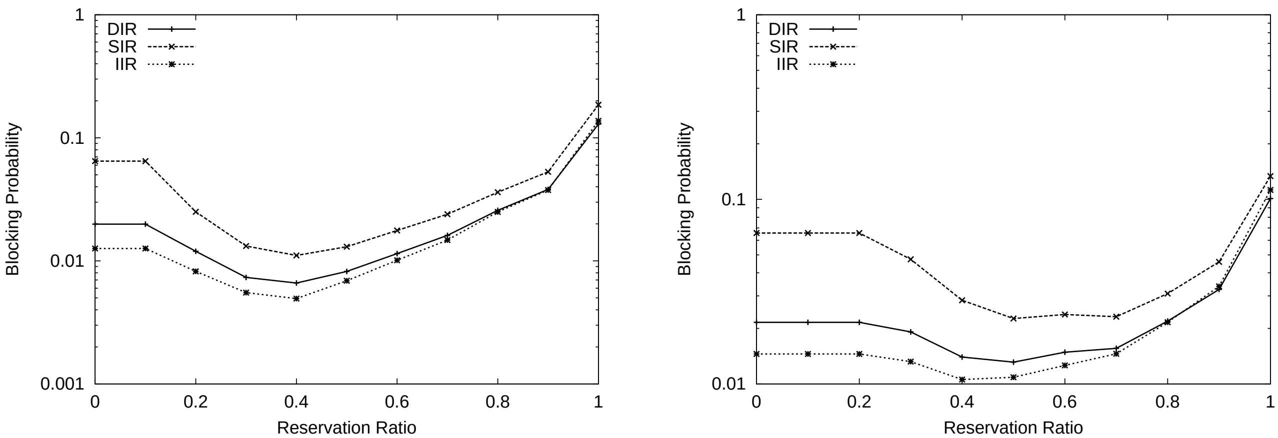
(a) $D = 100$ ms

(b) $D = 10$ ms

Figure 8. Optimum reservation ratio ($\rho = 0.1$ Erlang) under different average connection holding times ($C = 32$).

We now use the DIR scheme to illustrate the influence of different reservation ratios in Fig. 7. We can observe from this figure that, under low and modest traffic load, the blocking probability decreases dramatically when w is increased from 0 to 0.1 and 0.2; however, the blocking probability increases if w is greater than 0.2. The reason for these results is that, when w is small, the dominant effect is blocking due to outdated information; thus increasing w will improve the overall blocking performance. On the other hand, when w is too large, the over-reservation problem becomes prevalent; thus increasing w will lead to higher blocking. Under higher traffic load, the performance of different values of w becomes similar. This is because, under higher traffic load, the blocking is mainly due to insufficient resources instead of conflicts. In other words, the probability that more than one wavelength is available throughout the route becomes smaller under high traffic load. Consequently, the benefit from multiple reservations is smaller, since the number of available channels that can be selected is reduced. From Fig. 7 we can see that the optimum results may be achieved by appropriate value of w.

In Fig. 8, we show the effects of the reservation ratio by varying w under a given traffic load ($\rho = 0.1$ Erlang). Figure 8 (a) compares the performance of different schemes when traffic is dynamic, i.e. $D = 100$ ms. We also demonstrate the performance of SIR with group reservation,[9] where we let $\frac{1}{w}$ be the number of groups. We observe that, for the DIR and IIR schemes, the optimum w is 0.2; and with this setting, the blocking probabilities are almost ten times smaller than that of $w = 0$. For the SIR scheme, the best performance occurs when w is



(a) $C = 16$ (b) $C = 8$

Figure 9. Optimum reservation ratio ($\rho = 0.1$ Erlang, $D = 100$ ms) under different number of wavelength per fiber.

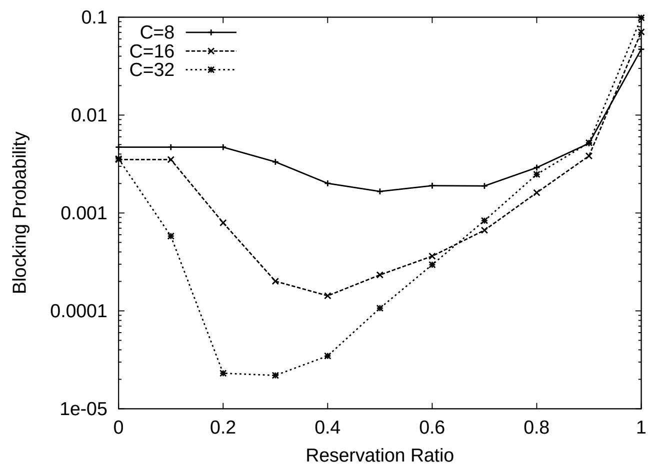


Figure 10. Optimum reservation ratio ($\rho = 0.1$ Erlang, $D = 100$ ms) in network with sparse conversion.

0.3; and with this setting, the benefit by applying reservation ratio is even more significant. We can also see that, although SIR with group reservation can somehow reduce overall blocking, it can not achieve the same performance as the reservation ratio scheme. It can be observed that, among all schemes, the IIR scheme has the best performance in terms of blocking probabilities. In Fig. 8 (b), we demonstrate how blocking varies with respect to w when the traffic is extremely dynamic, i.e. $D = 10$ ms. We see that the optimum w is 0.2 for all three schemes, and that the IIR scheme again outperforms the others. However, the benefit from adjusting w is less significant.

Figure 9 (a) and Fig. 9 (b) show the effects of w when the number of wavelengths per fiber is 16 and 8, respectively. We can observe that the optimum w becomes larger if the total number of channels per fiber is smaller. In Fig. 9 (a), the optimum w is 0.4 for all three schemes; in Fig. 9 (b), the optimum w is 0.4 of IIR and is 0.5 for both DIR and SIR. We can also see from these two figures that the benefit from setting the reservation ratio w is less significant in these two cases than that of $C = 32$. The main reason for these effects is that the total number of available channels at the destination node decreases when C is smaller; thus the effect of multiple reservation is limited.

In Fig. 10, we illustrate the performance of the IIR scheme in the network with sparse wavelength conversion where we assume that wavelength conversion is available at nodes 3, 5, 7, and 9. It can be observed that the

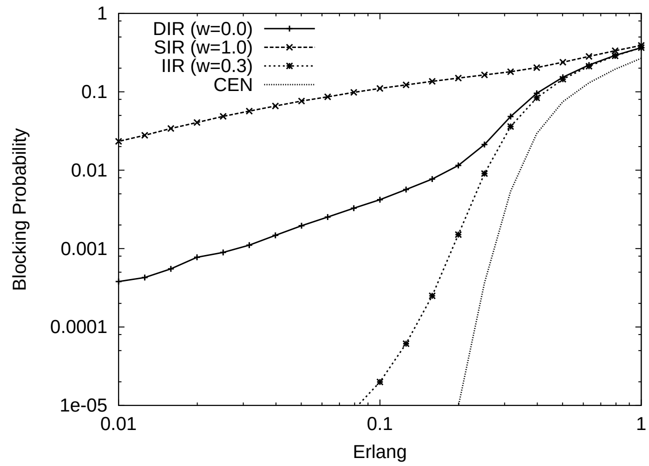
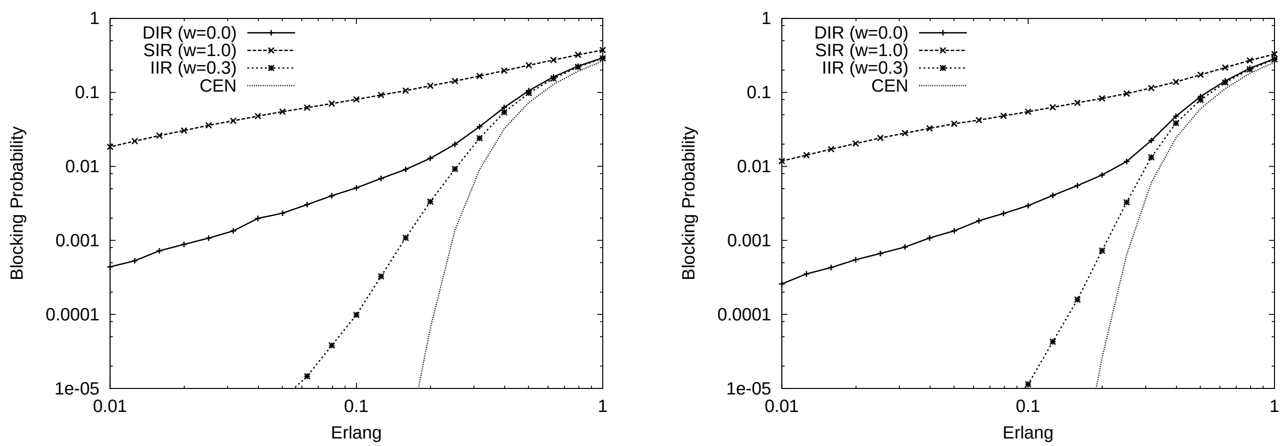


Figure 11. Blocking probabilities for different schemes in the network with sparse conversion ($C = 32,\ D = 100$ ms).



(a) No conversion

(b) Sparse conversion (available in 8 nodes)

Figure 12. Blocking probabilities for different schemes in a 36-node torus mesh network ($C = 32,\ D = 100$ ms).

improvement of multiple reservations is more significant than the improvement in the network without wavelength conversion. For example, when $C = 32$, we can see from Fig. 10 that the blocking when $w = 0.3$ is more than 100 times lower than that of $w = 0$. Similar results are also shown when $C = 16$ and $C = 8$. We compare the blocking performance of the IIR scheme with optimum reservation ratio (0.3) to the original DIR and SIR schemes in Fig. 11. The results show that, with the appropriate reservation ratio, the IIR scheme can significantly improve the blocking performance.

We compare the performance of different schemes in the 36-node torus mesh topology in Fig. 12. For the sparse conversion case, we randomly assign eight nodes with converters. We can see that the IIR scheme significantly outperforms the classic SIR and DIR in both network scenarios. And similar to NSFNet, in this topology, IIR can reduce more blocking in network with sparse conversion than in network with no conversion.

4. CONCLUSION

In this work, we proposed a new signaling framework for dynamic lightpath provisioning in wavelength-routed networks. In this framework, reservation may be initiated at any set of nodes along the path of a connection, and multiple channels may be reserved. Two implementations were developed for networks with no wavelength conversion and for networks with sparse conversion. The simulation results show that: (1) the new signaling scheme can significantly improve the network performance in comparison with the classic DIR and SIR methods; (2) the proposed IIR scheme performs better when the number of wavelengths per fiber increases; and (3) the proposed IIR scheme performs better in networks with sparse wavelength conversion than in networks without wavelength conversion.

REFERENCES

1. I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications: A Novel Approach to High Bandwidth Optical WANs," *IEEE Trans. Commun.*, vol. 40, no. 7, pp. 1171-1182, July 1992.
2. J. M. H. Elmirghani and H. T. Mouftah, "Technologies and Architectures for Scalable Dynamic Dense WDM networks," *IEEE Commun. Mag.*, Feb. 2000, pp. 58-66.
3. J. Strand, A. L. Chiu, and R. Tkach, "Issues for Routing in the Optical Layer," *IEEE Commun. Mag.*, Feb. 2001, pp. 81-87.
4. L. Berger, "Generalized Multi-Protocol Label Switching (GMPLS) Signaling Functional Description," *IETF*, *RFC 3471*, Jan. 2003.
5. P. Ashwood-Smith, *et al.*, "Generalized Multi-Protocol Label Switching (GMPLS) Signaling Constraint-based Routed Label Distribution Protocol (CR-LDP) Extensions," *IETF*, *RFC 3472*, Jan. 2003.
6. L. Berger, "Generalized Multi-Protocol Label Switching (GMPLS) Signaling Resource ReserVation Protocol-Traffic Engineering (RSVP-TE) Extensions," *IETF*, *RFC 3473*, Jan. 2003.
7. X. Yuan, R. Melhem, R. Gupta, Y. Mei, and C. Qiao, "Distributed Control Protocols for Wavelength Reservation and Their Performance Evaluation," *Photonic Network Commun.*, vol. 1, no. 3, pp. 207-218, 1999.
8. J. M. H. Elmirghani and H. T. Mouftah, "All-Optical Wavelength Conversion: Technologies and Applications in DWDM Networks," *IEEE Commun. Mag.*, March 2000, pp. 86-92.
9. A. G. Stoica, A. Sengupta, "On a Dynamic Wavelength Assignment Algorithm for Wavelength-Routed All-Optical Networks," *Proc. SPIE/IEEE/ACM OptiComm 2000*, Dallas, TX, pp. 211-222, Oct. 2000.
10. A. Birman, "Computing Approximate Blocking Probability for a Class of All-Optical Networks," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 852-857, June 1996.
11. S. Subramaniam, M. Azizoglu, and A. K. Somani, "All-Optical Networks with Sparse Wavelength Conversion," *IEEE/ACM Trans. Network.*, vol. 4, no. 4, pp. 544-557, August 1996.
12. A. Sridharan and K. N. Sivarajan, "Blocking in All-Optical Networks," *Proc. IEEE Infocom'00*, Tel Aviv, Israel, vol. 2, pp. 990-999, Mar. 2000.
13. J. P. Jue and G. Xiao, "Analysis of Blocking Probability for Connection Management Schemes in Optical Networks," *Proc. IEEE Globecom '01*, San Antonio, TX, vol. 3, pp. 1546-1550, November 2001.
14. K. Lu, G. Xiao, and I. Chlamtac, "Blocking Analysis of Dynamic Lightpath Establishment in Wavelength-Routed Networks," *Proc. IEEE ICC '02*, New York, NY, vol. 5, pp. 2912-2916, April 2002.
15. K. Lu, G. Xiao, and I. Chlamtac, "Behavior of distributed wavelength provisioning in wavelength-routed networks with partial wavelength conversion," *Proc. IEEE INFOCOM'03*, San Francisco, CA, April 2003.