Wavelength Assignment for Dynamic Traffic in Multi-fiber WDM Networks *

Xijun Zhang
Department of ECE
SUNY at Buffalo
Buffalo, NY 14260

Chunming Qiao
Department of CSE
SUNY at Buffalo
Buffalo, NY 14260

Abstract

We propose an on-line wavelength assignment algorithm for multi-fiber WDM networks, in which lightpaths are established and released dynamically. For a given number of fibers per link and number of wavelengths per fiber, the algorithm aims to minimize the blocking probability. It may also be used to reduce the number of wavelengths required for a given tolerable blocking probability. Simulation results show that our wavelength assignment algorithm performs better than other previously proposed algorithms (in the cases we studied). As the number of fibers per link increases, the benefit of having wavelength converters decreases dramatically, and the performance improvement of our algorithm over others increases. Our results also show that in case a preferred path is not available, rerouting along a node-disjoint backup path can significantly reduce the blocking probability.

1. Introduction

All-optical networks are considered as the transport networks for the future. In such systems, each node has a dynamically configurable photonic switch which supports fiber switching, wavelength switching, and possibly, wavelength conversion. Two adjacent nodes are connected by one or multiple full-duplex fibers (or fiber pairs), and on each fiber, several wavelengths are multiplexed to exploit the fiber's huge bandwidth. A signal is maintained in the optical form from a source to a destination, thereby providing end-to-end transparency.

An all-optical connection between two nodes in wavelength-routed optical networks is called a *lightpath*. Two different ways can be used to establish a lightpath. In the first method, which is called path-multiplexing (PM) [10, 12] (or wavelength-path routing [15], or wavelength-selective routing [5]), the same wavelength has to be assigned on all the links along the path from the source to the destination. Hence, it is possible for a lightpath request (e.g., from node 5 to node 1 in Figure 1) to be blocked although there is a wavelength available on every link along the path (e.g., λ_1 on the link 5 → 2 and λ_2 on the link 2 → 1). This is called *wavelength blocking* which can occur due to the *wavelength continuity* constraint in PM. In the second method, which is called link-multiplexing (LM) [10, 12] (or virtual-wavelength-path routing, or wavelength-interchanging routing), different wavelengths can be assigned on different links. Although wavelength converters can be used at intermediate nodes (e.g., node 2 in Figure 1) to eliminate wavelength blocking, they significantly increase the total system cost.

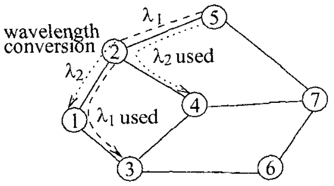


Figure 1. PM and LM in a single fiber WDM network.

Several routing and wavelength assignment (RWA) algorithms have been proposed and evaluated based on different traffic assumptions and performance metrics. Specifically, for *static traffic* with which a set of connection requests known a priori needs to be satisfied simultaneously, RWA algorithms are used to optimize a certain metric (e.g. the total number of wavelengths required) [1, 3, 4, 15, 16]. These RWA algorithms normally use shortest path (in terms of number of hops) routing as a starting point in an iterative improvement procedure. The optimization is then performed through recursively rerouting of some connections (which may end up using longer paths). The procedure stops when no further improvement is possible. For networks with simple topology, such as rings, optimal wavelength assignment may be obtained through analysis [13, 14].

In this paper, we focus on the RWA problem in networks

---

*This research is supported in part by a grant from NSF under contract number MIP-9409864

using PM, and in particular, on on-line wavelength assignment algorithms for *dynamic traffic* with which connection requests arrive randomly. Previous work used blocking probability for a given bandwidth (i.e. the product of the number of fibers per link, F, and the number of wavelengths per fiber, W) and a *proportional* traffic load as a performance metric [2,5–7,9] when comparing different algorithms. In our study, the bandwidth required for a given tolerable blocking probability and a *fixed* traffic load will also be used as a performance metric. We will use the performance achieved by an arbitrary wavelength assignment algorithm in a LM network as the yardstick since it is at least as good as that achievable by the best wavelength assignment algorithm in a corresponding PM network.

Although some wavelength assignment heuristics have been proposed in the literature for dynamic traffic, our proposed wavelength assignment algorithm provides a better performance. In addition, to our best knowledge, this is the first paper that analyzes the effect of using multiple fibers on the blocking performance of a network with a fixed bandwidth, that considers deterministic backup path rerouting for dynamic traffic, and that determines wavelength requirement for dynamic traffic with a fixed load. The paper is organized as follows. In Section 2, we describe the system model and introduce algorithms previously proposed. In Section 3, we describe the new wavelength assignment algorithm and discuss its implementation. Simulation results are presented in Section 4, and we conclude the paper in Section 5.

2. Dynamic Wavelength Assignment in PM

Consider a PM network at a certain state in which a set of connections has already been established and wavelengths are assigned to those connections. When a new connection request arrives, the problem is to determine a path and then assign a wavelength to the new connection without disturbing those existing ones (in terms of both their paths and wavelengths used) so that the average blocking probability is minimized. This is an NP-complete problem, and therefore, heuristics are necessary.

Assume that for each potential connection, deterministic routing is used. In other words, for a given source and destination node pair, a fixed path is pre-selected from the source to the destination. Traffic (if any) on the reverse direction may take a different path. In what follows, we will use p to denote either a connection request or the corresponding path, and concentrate on wavelength assignment. Note that it is possible to have multiple, concurrent sessions between a source-destination pair, and they may all take the same path, i.e., multiple lightpaths (one for each session) may be established along the same path.

In real networks, blocking may be caused by not only a limited bandwidth, but also a limited I/O capacity, i.e., the number of transceivers at each node. Since the main purpose of this paper is to study wavelength assignment algorithms, we will not model the effect of having a limited number of transceivers at each node by assuming that there are enough transceivers to prevent source/destination blocking. Hence, blocking will refer to bandwidth blocking hereafter.

Since it is very difficult to calculate the blocking probability of a network in an arbitrary state, other measures are often used to indicate the value of the blocking probability and based on such indications, the wavelengths are assigned accordingly. For instance, the *link capacity* of a link l on a wavelength λ, denoted by $L_c(l, \lambda)$, is defined to be the number of fibers on which λ is available on link l. Let $L(p)$ denote the set of links along path p. Then, the *wavelength path capacity (WPC)* of path p on wavelength λ, denoted by $P_c(p, \lambda)$, can be defined as $\min_{l \in L(p)} L_c(l, \lambda)$, or in other words, the link capacity of the most congested link along path p. If the number of fibers per link is F, it is clear that $L_c(l, \lambda) \leq F$ and $P_c(p, \lambda) \leq F$ for any l, p and λ. When a new connection request (requesting path) p^* arrives, $P_c(p^*, \lambda)$ is calculated for every λ. Obviously, a lightpath can be established for this request only if there is at least one wavelength λ such that $P_c(p^*, \lambda) > 0$. Let $\Lambda(p^*)$ denote the set of wavelengths on which WPC of path p^* is larger than zero. As long as $\Lambda(p^*)$ is not empty (ϕ), the requested lightpath will be established. The question is on which $\lambda^* \in \Lambda(p^*) \neq \phi$ the lightpath should be established so that the blocking probability is minimized for a given bandwidth (this is the wavelength assignment problem).

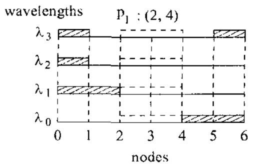
Several heuristic wavelength assignment algorithms have been proposed [2, 5–7, 9]. Among these heuristics, First-Fit (FF) [7, 9] which assigns the λ^* ($\in \Lambda(p^*)$) having the lowest index is the simplest. Let $P'_c(p, \lambda)$ be the WPC of p on wavelength λ after the new lightpath is established. The MaxSum (MS) algorithm [2], which assigns a λ^* that maximizes $\sum_p \sum_\lambda P'_c(p, \lambda)$ for all potential paths p and all wavelengths λ, is shown to be the best for rings and tori. Note that if we denote by $P_c(p, \lambda)$ the WPC of p on wavelength λ *before* the new lightpath is established, then MS can also be considered as a way to choose a λ^* so as to minimize the total WPC loss, which is $\sum_p [P_c(p, \lambda^*) - P'_C(p, \lambda^*)]$. This is because for every path p, only its WPC on the wavelength λ^* (on which the new lightpath is established) will change.

3. Proposed Wavelength Assignment

In this section, we propose a new wavelength assignment algorithm, which models the effect of establishing a lightpath on other potential lightpaths more accurately, and thereby improving the performance. The algorithm proposed is independent of both network topology and traffic pattern. In other words, it can be applied to any network with an arbitrary topology and an arbitrary traffic pattern.

3.1. The Relative Capacity Loss Algorithm

Note that when a new lightpath is assigned wavelength λ^*, WPC of path p on λ^*, $P_c(p, \lambda^*)$, may decrease by at most 1. Although the total WPC loss of all potential paths on λ^* can be used to represent the effect of establishing the new lightpath as in MS, it may not always result in the best choice. This is because decreasing WPC by 1 does not have the same significance for two potential paths when the WPC of one is only 1 and that of the other is more than 1 before the establishment of the new lightpath.



	WPC loss of each path p_2 : (1, 5)	p_3 : (3, 6)	p_4 : (0, 3)	Total WPC loss on each λ
λ_3	1	0	0	1
λ_2	1	1	0	2
λ_1	0	1	0	1
λ_0	0	0	1	1

Figure 2. An example of wavelength assignment (with single fiber of four wavelengths).

As an example, Figure 2 shows a segment of a network with a single fiber and four wavelengths. Suppose a request for connection p_1 (which is from node 2 to node 4) arrives and that the wavelength channels marked by the shaded bars are already used by other connections which do not share common links with p_1, and thus will not be *directly* affected by the establishment of p_1. Three potential paths which share common links with p_1 are p_2 (from node 1 to node 5), p_3 (from node 3 to node 6) and p_4 (from node 0 to node 3). The WPC loss of these three paths on each of the four wavelengths is given in the figure for each possible wavelength assignment of p_1. For example, if p_1 is established on λ_3, WPC of p_2 on λ_3 is 1 before and is 0 after the establishment of p_1. Therefore, the WPC loss of p_2 on λ_3 is 1. Similarly, the WPC loss of other two paths on other wavelengths can be obtained. According to MS, establishing p_1 on λ_0, λ_1 or λ_3 has the same effect (or cost) since the total WPC loss is only 1 in all three cases. However, if λ_0 is chosen, connection p_4 will be blocked, which is not as good as choosing any other wavelength (including λ_2) because all three potential paths may still be established.

Based on the above observation, we define *Relative Capacity Loss (RCL)* of path p on wavelength λ^*, denoted by $R_c(p, \lambda^*)$, as the ratio of WPC loss of path p on λ^* over the current total WPC of path p on *all* wavelengths, i.e., $R_c(p, \lambda^*) = \frac{P_c(p,\lambda^*) - P'_c(p,\lambda^*)}{\sum_\lambda P_c(p,\lambda)}$. The corresponding algorithm, also referred to as RCL, chooses a wavelength λ^* such that $\sum_{p \in G(p^*)} R_c(p, \lambda^*)$ is minimized, where $G(p^*)$ is the set of "neighbors" of p^*, or in other words, the set of paths which have common links with p^* (i.e. $p \in G(p^*)$ if $L(p) \cap L(p^*) \neq \phi$). We only consider the neighbors of p^* when evaluating the effect of establishing the new lightpath because only the WPC of these paths may decrease.

In the above example, $G(p_1) = \{p_2, p_3, p_4\}$. To calculate RCL of p_2 on λ_3, we note that $P_c(p_2, \lambda_3) = 1$, $P'_c(p_2, \lambda_3) = 0$, and $\sum_\lambda P_c(p_2, \lambda) = 2$. Hence, $R_c(p_2, \lambda_3) = \frac{P_c(p_2,\lambda_3) - P'_c(p_2,\lambda_3)}{\sum_\lambda P_c(p_2,\lambda)} = 0.5$. Similarly, RCL of p_2 on other three wavelengths can be calculated, so can RCL of p_3 and p_4 on all four wavelengths. Finally, the value of $\sum_{p \in G(p_1)} R_c(p, \lambda) = R_c(p_2, \lambda) + R_c(p_3, \lambda) + R_c(p_4, \lambda)$ can be determined as 1, 0.5, 1, and 0.5, respectively, on λ_0, λ_1, λ_2 and λ_3. Therefore, λ_1 (or λ_3) will be assigned to p_1. In this way, none of the three potential paths is blocked after connection p_1 is established.

The computational time complexity of RCL algorithm can be analyzed as follows. First, we may ignore all initialization which can be carried out off-line. In addition, assume that the link capacity of any link l on any wavelength is stored in an array of registers (or memory), and can be accessed and updated (e.g. decreased by 1) in $O(1)$ (i.e. constant number of) time units. Let H be the maximal number of links along a path over all possible paths. For a given new request p^* and λ^*, the the path capacity of any path p on λ^* before and after p^* is established (on λ^*) can be determined in $O(H)$ time units. Hence, the time needed to calculate the total WPC of p over all wavelengths (i.e. the denominator in the formula) is $O(W \cdot H)$. Note that for any given p, once this denominator is determined, it can be re-used when calculating the RCL of p on all other wavelengths in $\Lambda(p^*)$, which contains fewer than W wavelengths. Accordingly, the number of time units needed to calculate $R_c(p, \lambda)$ for the given p and all wavelengths in $\Lambda(p^*)$ is also $O(W \cdot H)$. Accordingly, let M be the maximal number of paths in $G(p^*)$ over any given p^*, then the total number of time units needed by the RCL algorithm for any given p^* is $O(W \cdot H \cdot M)$. We also note that, in a network of N nodes, $H < N$ and $M < N^2$, and accordingly, the worst case time complexity of RCL is $O(W \cdot N^3)$. The above analysis also indicates that RCL has the same worst case time complexity of MS (at least asymptotically).

3.2. Nonuniform Traffic and Back-up Path

In a network with an arbitrary topology of N nodes and an arbitrary traffic pattern, let T_{ij} denote the average traffic intensity (in Erlangs) from node i to node j, where $1 \leq i, j \leq N$. When the traffic pattern is not uniform (i.e. T_{ij} may vary for different i and j), weighted RCL can be used. Specifically, let $w(p) = T_{ij}$ denote the weight of the preferred path p from source node i to destination node j, we will minimize $\sum_{p \in G(p^*)} R_c(p, \lambda) \cdot w(p)$ instead.

In our study, a fixed load means that T_{ij} is fixed with respect to the network bandwidth $F \cdot W$, while a proportional load means T_{ij} is proportional to $F \cdot W$. As long as $T_{ij} > 0$, there will be potential transmissions from node i to node j, and a shortest path with the least number of hops is used as the preferred path for this source-destination pair. Note that alternately, one may treat the traffic as if it is static (with the same traffic pattern), and apply the heuristics for static traffic mentioned in the third paragraph of Section 1 to determine a preferred path. Using this alternative, the traffic load may be distributed uniformly and thus the bandwidth requirement for dynamic traffic may be reduced. In either case, after the preferred path p is determined for each source-destination pair, a node-disjoint backup path p' will be determined. Such a backup path is useful not only when there is blocking along the preferred path, but also when there is an intermediate node failure or link failure.

4. Simulation Results

As mentioned earlier, the proposed RCL algorithms can be applied to any network with arbitrary topology and arbitrary traffic pattern. We have simulated a practical network called NSFNET, which has an irregular topology. However, in order to compare RCL with MS, the majority of the results reported here is for a regular 4×4 torus (similar results are also obtained for unidirectional rings). By default, uniform traffic (i.e., $T_{ij} = T$) is assumed but non-uniform traffic is also simulated.

In a torus, the simple row-column shortest path routing is used to find the preferred path for each source-destination pair. The backup path, which is node-disjoint to the preferred path, is selected in the way shown in Figure 3.

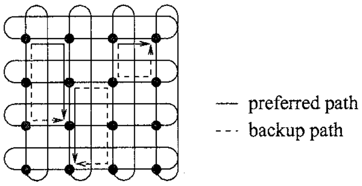


Figure 3. Routing for both preferred path and backup path in a torus.

Specifically, if the source node and the destination node are neither at the same row nor at the same column, the column-row shortest path routing will be used for the backup path. If they are at the same row, the backup path first goes through the node at the next row (cyclic) and then follows the row-column shortest path routing. Similarly, if they are at the same column, the backup path first goes through the node at the next column and then follows the column-row shortest path routing. Note that the backup path selected is the shortest node-disjoint path available in most cases.

We present the following sets of simulation results. The first is the blocking performance with a fixed load and a fixed bandwidth $F \cdot W$, but for different combinations of F and W to show the effect of having multiple fibers (i.e. space division multiplexing). The second is the effect of increasing bandwidth with a proportional load. The third is the effect of rerouting using a pre-determined backup path for each source-destination pair in case blocking occurs on the preferred path. The fourth is the benefit of wavelength conversion with a fixed load. Finally, the fifth is the bandwidth requirement when using different wavelength assignment algorithms to achieve a given blocking probability for a given fixed load. To make comparisons, we run simulations for networks using (1) the simplest wavelength assignment algorithm (FF); (2) the best heuristic previously proposed (MS); (3) our new heuristic (RCL); and (4) wavelength conversion (LM). In most cases, we compare the performance of RCL with that of MS.

Networks with a fixed load and a fixed bandwidth

To asses the optimality (or non-optimality) of a wavelength assignment algorithm, α, let the blocking probability be denoted by $B(\alpha)$, and the blocking probability in LM be denoted by B_0. The difference in blocking probabilities (DBP) between a PM network using the wavelength assignment algorithm and a LM network using any wavelength assignment is $B(\alpha) - B_0$. The non-optimality factor (NOF) of α is then defined to be the ratio of DBP and the blocking probability in the LM network, i.e., $NOF(\alpha) = \frac{B(\alpha)-B_0}{B_0}$. Note that the blocking probability in a PM network using the best possible wavelength assignment algorithm, B'_0, is no less than B_0. Hence, the "real" $NOF(\alpha)$ should be smaller. To compare two different wavelength assignment algorithms α and β, where $NOF(\beta) > NOF(\alpha)$, we define the improvement ratio of NOF of algorithm α over algorithm β as $\frac{NOF(\beta)-NOF(\alpha)}{NOF(\beta)}$.

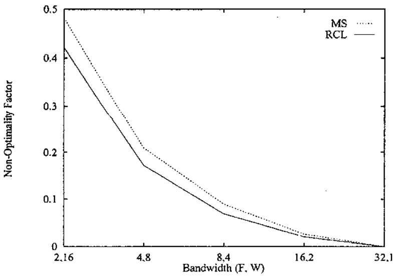


Figure 4. NOF of RCL vs that of MS with a fixed bandwidth ($F \cdot W = 32$).

Figure 4 plot the NOF of the MS and RCL algorithms under a fixed load with uniform traffic when $F \cdot W = 32$ and F varies from 2 to 32, and the improvement ratio of the latter over the former is plotted in Figure 5. As can be seen, the NOF decreases dramatically as F increases, and when $F = 8$ and $W = 4$, the improvement ratio of NOF of RCL over MS reaches its maximal of 23%. In general, increasing F (and decreasing W) increases the improvement ratio of NOF except that in the extreme case of $W = 1$, where all algorithms achieve the same performance (since both DBP and the improvement ratio of NOF are zero).

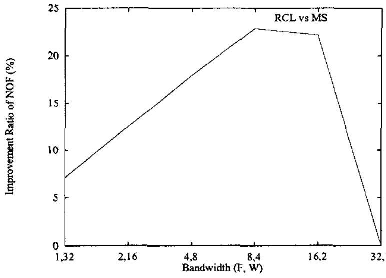


Figure 5. Improvement ratio of NOF with a fixed bandwidth ($F \cdot W = 32$).

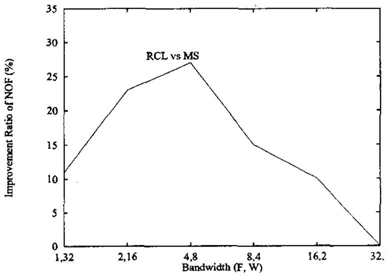


Figure 6. Improvement ratio of NOF with non-uniform traffic ($F \cdot W = 32$).

Similar results have also been obtained with non-uniform traffic, and the improvement ratio of NOF is shown in Figure 6. In non-uniform traffic, we assume that T_{ij} has uniform distribution between $T_{max} = max\{T_{ij}\}$ and $T_{min} = min\{T_{ij}\}$, and $\frac{T_{max}}{T_{min}} = 10$. Compared with Figure 5, a slightly higher maximum improvement ratio is achieved with non-uniform traffic.

The improvement ratio of NOF with uniform traffic and a larger bandwidth, $F \cdot W = 64$, is shown in Figure 7. As can be seen, the results are similar to those shown in Figure 5 with a smaller bandwidth. But with a larger bandwidth, the improvement ratio of RCL over MS is slightly higher.

In addition, Figure 8 shows the results for non-uniform traffic on NSFNET and 4x4 torus when $F \cdot W = 64$. As can be seen, both networks exhibit similar improvement ratio except when F is small, the improvement ratio for the NSFNET is much higher than that for the torus. This indicates that RCL can be especially attractive in practice when a network has an irregular topology and traffic is non-uniform.

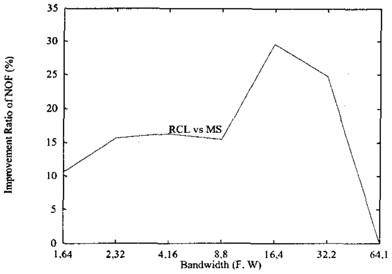


Figure 7. Improvement ratio of NOF with a fixed bandwidth ($F \cdot W = 64$).

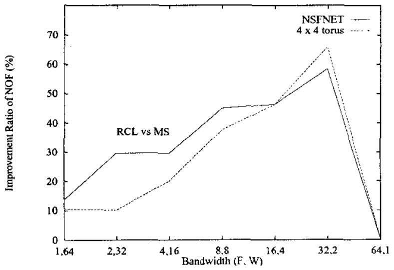


Figure 8. Improvement ratio of NOF with non-uniform traffic ($F \cdot W = 64$)

By comparing Figure 8 with Figure 6, and also Figure 7 with Figure 5, we observe that the increase in the improvement ratio (for the torus) due to the increase in bandwidth (from $FW = 32$ to $FW = 64$) is much higher with non-uniform traffic (where the maximum increases from about 28% to about 65%) than that with uniform traffic (where the maximum increases from about 24% to about 30%). This also explains why the improvement ratio shown in Figure 8 with $FW = 64$ and non-uniform traffic is much higher than that shown in Figure 7 with $FW = 32$ and uniform traffic.

Effect of Applying a Proportional Load

The improvement ratio of NOF when F increases and $W = 8$ is shown in Figure 9, and that when W increases and $F = 1$ is shown in Figure 10. In both cases, a traffic load proportional to the network bandwidth is applied. As can be seen from Figures 9 and 10, the improvement ratio increases with the bandwidth, especially the number of fibers.

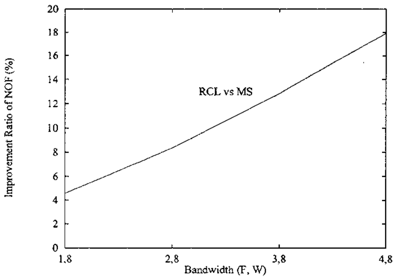


Figure 9. Improvement ratio of NOF with a increasing F ($W = 8$).

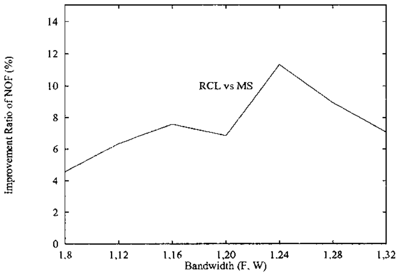


Figure 10. Improvement ratio of NOF with a increasing W ($F = 1$).

Effect of Back-up Path Rerouting

In order to improve the blocking performance, one may use backup path p' in case blocking occurs on the preferred path p. Since the tolerable blocking probability in a real network should be very low, which wavelength assignment algorithm to use on the backup path may not be significant. In our simulation, the same RCL algorithm is used for both preferred path and backup path. As shown in Figure 11, using rerouting, blocking probability is reduced dramatically especially in multi-fiber networks (more than one order of magnitude).

Effect of Wavelength Conversion

The benefit of wavelength conversion is indicated by DBP. For a given bandwidth, we can compensate for the lack of wavelength conversion in several ways. First, using multiple fibers on each link can reduce the DBP from 1.87×10^{-2} to 3.9×10^{-3} (by 79%) as shown in Table 1, which is compiled from various simulation results. Second, by using intelligent wavelength assignment algorithms such as RCL, the DBP can be further reduced from 3.9×10^{-3} to 1.7×10^{-3} (by 56%). Finally, when backup path is used, the DBP can be reduced again to 1.02×10^{-4} (by 94%). Note that in this case, although NOF is the same as the original one (185%), the blocking probabilities in both PM and LM networks are well below the tolerable value, which makes a large NOF less significant. In short, by using multiple fibers on each link and an intelligent wavelength assignment heuristic (RCL), and allowing backup rerouting, the DBP due to the lack of wavelength conversion can be reduced dramatically for dynamic traffic. This result is consistent with previous findings that benefit of wavelength conversion is in general limited for both static traffic and dynamic traffic under centralized control, although it was shown that the benefit of wavelength conversion can be significant for dynamic traffic under distributed control [8, 11].

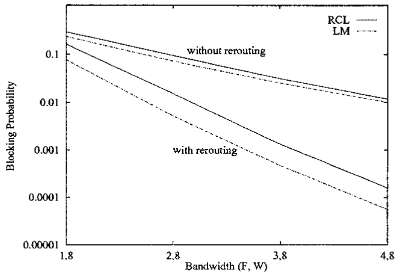


Figure 11. The effect of backup path on blocking probability in networks with proportional load.

$F \times W$	PM	LM	DBP	NOF
1×32 (FF)	2.88×10^{-2}	1.01×10^{-2}	1.87×10^{-2}	185%
4×8 (FF)	1.40×10^{-2}	1.01×10^{-2}	3.9×10^{-3}	39%
4×8 (RCL)	1.18×10^{-2}	1.01×10^{-2}	1.7×10^{-3}	17%
4×8 (RCL+rerouting)	1.57×10^{-4}	0.55×10^{-4}	1.02×10^{-4}	185%

Table 1. Reduce the difference of blocking probability between PM and LM networks.

Wavelength Requirement with a Fixed Load

So far, we have focused on how the proposed intelligent wavelength assignment (RCL) can reduce the blocking probability. The results obtained so far are the blocking probability (or improvement ratio of NOF) either for the same bandwidth but different combinations of F and W under the same load (Figure 5), or like in other previous works, for different bandwidth under a proportional load. Here, we obtain the blocking probability for different bandwidth under the same load, and accordingly, show how RCL can also be used to determine (and reduce) the bandwidth requirement for a given tolerable blocking probability. Figure 12 gives the bandwidth needed for different blocking probability requirements. In general, to achieve the same blocking probability, a single fiber PM network needs two more wavelengths than a single fiber LM network if FF is used. However, if the proposed RCL is used, the difference becomes only one in most cases. Under the same load, our simulations (the results are not shown here) also indicate that in a multi-fiber network with $W = 8$, the blocking probability is around 10^{-2} when $F = 4$, but drops to between 3×10^{-4} and 5×10^{-4} when $F = 5$ using any wavelength assignment algorithm. This means that to achieve reasonable blocking probabilities in a multi-fiber network, there is no significant difference in fiber-count among different wavelength assignment algorithms.

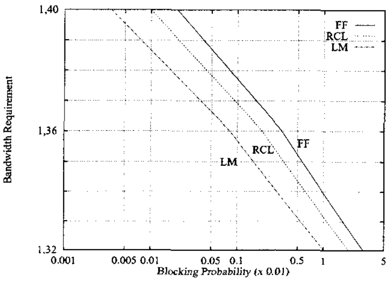


Figure 12. Determine the bandwidth requirement for a network with a fixed load.

5. Conclusion

In this paper, we have proposed a new on-line RWA algorithm called Relative Capacity Loss, which constantly results in a better performance than algorithms previously proposed. Simulation results have shown that with uniform traffic, the performance improvement of RCL over other algorithms increases with both the number of fibers under a fixed load and the bandwidth under either a fixed load or a proportional load. In addition, the improvement becomes more significant with non-uniform traffic in a network having irregular topology and a large bandwidth.

We have also studies the effect of backup path rerouting and shown that it can improve the blocking performance especially in multi-fiber networks. Finally, we have determined the bandwidth (and in particular, the number of wavelengths) required to achieve a tolerable blocking probability under a fixed load, and shown that the DBP due to the lack of wavelength conversion for dynamic traffic can be greatly reduced by using the proposed intelligent wavelength assignment algorithm combined with backup path rerouting in multi-fiber networks.

References

[1] S. Baroni and P. Bayvel. Wavelength requirements in arbitrarily connected wavelength-routed optical networks. *IEEE/OSA Journal of Lightwave Technology*, 15(2):242–251, Feb. 1997.

[2] R. A. Barry and S. Subramaniam. The MAX_SUM wavelength assignment algorithm for WDM ring networks. In *Proc. OFC'97*, Feb. 1997.

[3] I. Chlamtac, A. Ganz, and G. Karmi. Lightpath communications: An approach to high bandwidth optical WAN's. *IEEE Transactions on Communications*, 40(7), July 1992.

[4] M. Garnot, F. Masetti, L. Nederlof, G. Eilenberger, S. Bunse, and A. Aguilar. Dimensioning and optimization of the wavelength-division-multiplexed optical layer of future transport networks. In *Proc. Int'l Conference on Communication*, 1997.

[5] G. Jeong and E. Ayanoglu. Comparison of wavelength-interchanging and wavelength-selective cross-connects in multiwavelength all-optical networks. In *Proc. INFOCOM'96*, pages 156–163, March 1996.

[6] E. Karasan and E. Ayanoglu. Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks. In *IEEE/LEOS Broadband Optical Networks*, Aug. 1996.

[7] M. Kovacevic and A. S. Acampora. Benefits of wavelength translation in all-optical clear channel networks. *IEEE J. on Sel. Areas in Comm.*, 14(5):868–880, June 1996.

[8] Y. Mei and C. Qiao. Effcient distributed control protocols for wdm optical networks. In *IC3N'97*, pages 150–153, Sept. 1997.

[9] A. Mokhtar and M. Azizoglu. Adaptive wavelength routing in all-optical networks. *submitted to IEEE/ACM Transactions on Networking.*

[10] C. Qiao and Y. Mei. On the multiplexing degree required to embed permutations in a class of interconnection networks. In *Proceedings of the IEEE Symp. High Performance Computer Architecture*, pages 118–129, Feb. 1996. (A comprehensive version has been submitted to IEEE/ACM Trans. on Networking).

[11] C. Qiao and Y. Mei. Wavelength reservation under distributed control. In *IEEE/LEOS Broadband Optical Networks*, Aug. 1996. (a comprehensive version has been submitted to IEEE/ACM Trans. on Networking).

[12] C. Qiao and R. Melhem. Reducing communication latency with path multiplexing in optically interconnected multiprocessor systems. *IEEE Transactions on Parallel and Distributed Systems*, 8(2):97–108, 1997. (A preliminary version appeared in HPCA'96).

[13] C. Qiao and X. Zhang. Optimal design of WDM ring networks via resource-balance. In *IEEE/LEOS Broadband Optical Networks*, August 1996.

[14] C. Qiao, X. Zhang, and L. Zhou. Scheduling all-to-all connections in WDM rings. In *SPIE Proceedings, All Optical Communication Systems: Architecture, Control and Network Issues*, pages 218–229, November 1996. (A comprehensive version has been submitted to IEEE/ACM Trans. on Networking).

[15] N. Wauters and P. Demeester. Wavelength requirements and survivability in WDM cross-connected networks. In *Proc. ECOC'94*, pages 589–592, 1994.

[16] Z. Zhang and A. S. Acampora. A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength reuse. *IEEE/ACM Transactions on Networking*, 3(5):281–288, June 1995.