On the Use of Adaptive Weight Functions in Wavelength-Continuous WDM Multi-Fiber Networks under Dynamic Traffic

Konstantinos V. Miliotis, Georgios I. Papadimitriou, and Andreas S. Pomportsis

Abstract: **In this paper, we address the problem of efficient routing and wavelength assignment (RWA) in multi-fiber wavelength division multiplexing (WDM) networks without wavelength translation, under dynamic traffic. We couple Dijkstra's shortest path algorithm with a suitable weight function which chooses optical paths based both on wavelength availability and multi-fiber segments. We compare our approach with other RWA schemes both for regular and irregular WDM multi-fiber network topologies in terms of blocking probability and overall link utilization.**

Index Terms: **Dynamic traffic, multi-fiber wavelength division multiplexing (WDM) networks, routing and wavelength assignment (RWA) algorithm, wavelength continuity, weighted graph.**

I. INTRODUCTION

Optical networks in any form are increasingly replacing copper in the telecommunication infrastructure as the only medium able to support the current and the foreseeable demand in network resources. *Wavelength division multiplexing* (WDM) is the current favorite mechanism of tapping into the existing optical resources in an efficient manner. Although the operating envelope of traditional time division technologies has been pushed even further approaching 100 Gbps the benefits of WDM still lean heavily in its favor. Such benefits include transparency to protocols and data formats to name a few.

In WDM networks which mainly are deployed at the metropolitan and wide area environment certain issues arise when a signal has to reach its destination. First a route has to be found and then an appropriate wavelength has to be assigned. This is formally called the *routing and wavelength assignment problem* (RWA). When the routing nodes are not capable of wavelength translation then the lightpath must use the same wavelength in all the optical segments it uses. In the absence of a free wavelength along the entire route the connection cannot be established and it is blocked. This is formally known as the *wavelength continuity constraint*. Consequently the term *wavelength-continuous network* refers to a network in which a lightpath must occupy the same wavelength along its path from source to destination. On the contrary when wavelength translation is present the problem is similar to connection satisfaction in typical circuit-switched networks, where the only limiting factor is the bandwidth of every link. In such a network a connection is blocked only when no wavelength is available at some segment of an optical path assuming full wavelength translation.

Furthermore, the RWA problem has to take into consideration the nature of the connection requests. When the connections are known beforehand the network has knowledge of all the future events. This is called the *static case* or the *off-line model*. In this case, the optimization procedure tries to minimize the number of wavelengths in order to satisfy all the connections over the physical topology or to maximize the connections honored for a fixed number of wavelengths. Several algorithms have been proposed to cope with this problem.

On the other hand, when no connection matrix is given the network has no information about future connection requests in order to route a lightpath. This is called the *dynamic case* or the *on-line model* where connections arrive to and depart from the network in a random fashion. Our objective here is to maximize the number of requests honored or similarly to minimize the blocking probability. With the rapid growth of the Internet the bandwidth demand for data traffic is exploding. It is believed that dynamic lightpath establishment will enable service providers to respond quickly and economically to customer demands. In this paper, we are going to deal with this sort of communication environment. Related work on this subject is discussed in Section II. In Section III, we present an adaptive weight function coupled with Dijkstra's algorithm and try to solve the RWA problem in multi-fiber WDM networks with no wavelength conversion. The selection of a path between a source-destination node is executed based both on the availability of wavelengths on a given optical path as well as on the existence of multi-fiber optical segments. After the selection of a route a wavelength is assigned in random fashion. The performance of our RWA algorithm is studied under dynamic traffic for different network topologies in Section IV.

II. RELATED WORK

Motivated by the respectable cost of deploying WDM networks a large volume of research has targeted design issues in these networks in the past. In dynamic RWA, lightpath requests between end-nodes arrive at random times and have random holding times. Therefore, each lightpath is setup and torn down individually while the other lightpaths exist in the network [1], [2].

The dynamic RWA algorithms can be classified as *static* or *adaptive*. In static algorithms, the RWA procedure does not change with time. This means that, possible route-wavelength pairs are searched in a predefined order in static algorithms. On

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the other hand, adaptive algorithms use network state information at the time a request arrives to find a route and a wavelength in order to establish a lightpath . Therefore, in dynamic adaptive algorithms, all possible route-wavelength pairs can be searched for optimal routing of the lightpath for an objective function. Most routing algorithms are constrained in the sense that the admissible paths are selected as a predetermined subset of all possible paths. For example the set of admissible paths for a given connection might be limited to those having no more than $d+m$ hops, where d is the source destination distance in optical hops. In most practical cases, path admissibility and ordering is based on path length. The paths typically are listed in increasing order of path lengths, and path length is normally defined as the sum of link weights along the path. The link weights are typically chosen using some desirable routing criterion, and because they can be assigned arbitrarily, they offer a wide range of possibilities for selecting path properties [3]. The *fixed* or *alternate* routing and *first-fit* or *random* wavelength assignment [4] are the most commonly used static algorithms. In [7], a method for obtaining approximate blocking probabilities for fixed and alternate routing with first-fit wavelength assignment is developed. It is shown that alternate routing with only two alternate paths between each source-destination node pair results in a large reduction in the blocking probability compared to fixed routing. In [8], first-fit and random wavelength assignment methods with shortest path (fixed) routing are compared through simulations, and an analytical model is developed for analyzing blocking probability of the first-fit algorithm. It is shown that, first-fit algorithm performs much better than the random algorithm at low loads, and performance difference is marginal at higher loads. In [7], an *asynchronous criticality avoidance* (ACA) protocol is proposed to cooperate with fixed or alternate routing. It was shown that the ACA protocol can improve the network performance especially when the traffic load is light. Also in [8], an adaptive routing strategy called *weighted-shortest-cost-path* (WSCP) was proposed that minimizes the resource cost while simultaneously maintaining the traffic load among the links as balanced as possible.

If information about global wavelength usage is available at the time of routing, it may be possible to reduce further the blocking probability for the future requests (compared to first-fit or random algorithms) by finding a good route-wavelength pair. The *pack (most-used)* and *spread (least-used)* adaptive wavelength assignment algorithms [5] are proposed for this purpose. The pack algorithm tries to assign the most utilized wavelength to the lightpath. On the other hand, in spread algorithm, the least utilized wavelength is assigned to the lightpath. Therefore, the load is uniformly distributed over the wavelength set. In [5], blocking performances of pack, spread, random, and first-fit wavelength assignment algorithms with *adaptive unconstrained routing* (AUR) are compared. In AUR, all possible routes between a source-destination pair are searched in the routing process. The simulations show that, the pack scheme has the best performance followed by random and spread schemes. An extension of the above scheme for multi-fiber networks was made in [9]. The *least-loaded routing* (LLR) algorithm proposed in [6] jointly selects the least-loaded route-wavelength pair over the k alternate routes (shortest paths) between source-destination pairs. Therefore, the residual capacity over all wavelengths and over k shortest routes is maximized. To do this, LLR chooses the route p and wavelength j pair that achieves

$$\max_{\pi\in\Pi}\max_{\lambda_j\in\Lambda}[\min_{l\in\pi}(M_l - A_{lj})] \tag{1}$$

where π denotes the routes in the alternate route set Π, Λ denotes the set of wavelengths available in the network, l denotes the links that constitute a path π, M_l denote the number of fibers on link l, and A_{lj} denotes the number of fibers for which wavelength j is utilized on link l. An alternative approach called *minimum congested route* (MCR) routing is proposed in [10] for dynamic RWA. In MCR, the lightpaths are routed on the least congested path and first-fit wavelength assignment is done.

In [11]–[13], graph based methods for finding optimal routes and wavelengths for lightpaths using shortest path routing are proposed. In [11], an auxiliary graph is created to facilitate the representation of conversion cost and channel cost. Edges are assigned to weights that represent its status (wavelength-link usage information), and wavelength conversion cost (number of remaining converters in a router). In [12], a similar approach is used to construct a graph that facilitates the routing and wavelength assignment by virtually separating the wavelengths into different paths. This approach is called *layered graph approach*. In this model, limited-range wavelength conversion is considered. In [13], a fast and practical algorithm is presented to optimally route lightpaths taking into account both the costs of wavelengths on the links and the cost of wavelength conversion.

While all the works reviewed so far in this section are all *centrally managed*, that is, to assume that a central controller is present and has access to all necessary information for solving the RWA problem, another proposal has introduced a distributed solution [14]. Based on the classical Bellman-Ford algorithm, two realistic algorithms were implemented that achieve minimum congestion and minimum wavelength conversion respectively. And when considering bursty and correlated traffic a learning-automata-based protocol for WDM passive star networks is presented in [15].

III. DYNAMIC RWA IN MULTI-FIBER NETWORKS

In Dijkstra's algorithm every link in the network is associated with a specific weight, describing a metric for that link, e.g., propagation delay. The motivation behind this work is to assign WDM specific information to the links of a multi-fiber-WDM, execute the shortest path routing on random generated backbone topologies and compare the various performances. Earlier work on this subject has studied only the single-fiber case which may not reflect the true state in fiber installation nowadays [21], [23]. There has been an increasing interest in studying the performance improvement due to the deployment of multiple fibers between node pairs [5], [9], [18]. This interest is motivated by the economic advantage of installing bundles of fibers for the purposes of fault tolerance and future network growth. From the telecommunications operator viewpoint, one of the largest costs incurred while deploying an optical network stems from physically trench-digging to bury the optical fibers. Hence, to protect themselves from demand uncertainties and failures, operators usually install many fibers. Although frequently fibers are used independently, the opportunity to exploit this redundancy gives rise to multi-fiber WDM networks (MWNs) [16], [17]. Two kinds of multi-fiber networks are studied in this paper. One is the network with even links, i.e., the number of fibers on each link across the entire network is the same. The other is the network with uneven links, i.e., the number of fibers on different links can vary [26]. In a real network, it is not always true that the number of fibers in any link remains the same. Note that the multi-fiber network has partial wavelength conversion capability. An n-fiber m-wavelength network is functionally equivalent to a nm-wavelength single fiber network with limited wavelength conversion of degree n. The benefits of wavelength conversion at the wavelength routing nodes have been studied extensively. As mentioned in [19], limited wavelength conversion can obtain most of the performance advantage of full wavelength conversion. Multi-fiber links are also found to reduce the gain obtained due to wavelength conversion, and the number of fibers is found more important than the number of wavelengths for a network [20]. Therefore, multi-fiber networks can provide a viable and economical alternative to wavelength conversion.

Some of the notations used:
Λ_{ijk}^A: Available wavelengths in fiber k of link $i-j$.
Λ_{ijk}^T: Total wavelengths in fiber k of link $i-j$.
F_{ij}: Number of fibers on link $i-j$.
W_{ij}: Associated weight (cost) of using link $i-j$.

The network topology is represented by an undirected graph $G(V,E)$, where typically V denotes the set of network nodes and E the set of the links interconnecting them. Each link is associated with a weight which denotes the cost of using that link. We try to couple the shortest path routing of Dijkstra's algorithm with the resulting cost of using such a route (lightpath) for different weight scenarios and see how they affect the overall performance measured by metrics such as blocking probability and network utilization. We use dynamic traffic in which calls arrive and terminate in random. In every weight scheme we shall give the cost value of 1 unit when a link—comprising of one or more fibers—has only one available wavelength for use. When there is no available wavelength—blocked lightpath—then the cost becomes infinite. The other extreme is to have infinite number of wavelengths available which results in zero cost of using that link. Hop-count: This weight scheme takes in account only the hop count for establishing a lightpath between a source-destination node pair. Hence,

$$W_{ij} = \frac{1}{F_{ij}} \quad ,\forall(i,j) \in E. \tag{2}$$

When selecting a route based only on the number of nodes traversed, it is expected to chose those routes which contain as many multi-fiber segments as possible in order to decrease the blocking probability. The resulting cost of setting up a lightpath along a route, r is the sum of the above weight definition along its optical segments. This is a static weight attribute since it can be computed off line.

$$\mathit{fiber-count} = \sum W_{ij} \quad ,\forall(i,j) \in r. \tag{3}$$

Available wavelengths: In this case, dynamic weight calculations are produced since the number of available wavelengths on link $i-j$ is constantly changing. We will try to produce a formula that considers the number of available wavelengths when selecting a shortest path route. The total number of wavelengths on link $i-j$ can be expressed as follows

$$\Lambda_{ij}^T = \sum_{k=1}^{F_{ij}} \Lambda_{ijk}^T. \tag{4}$$

Similarly the number of available wavelengths will be

$$\Lambda_{ij}^A = \sum_{k=1}^{F_{ij}} \Lambda_{ijk}^A. \tag{5}$$

The probability of any wavelength being readily available at a present moment will be

$$p_a = \frac{\Lambda_{ij}^A}{\Lambda_{ij}^T}, \forall(i,j) \in E. \tag{6}$$

The probability that the same wavelength will be available at all fibers of link $i-j$ shall be

$$p_a = \left(\frac{\Lambda_{ij}^A}{\Lambda_{ij}^T}\right)^{F_{ij}}, \forall(i,j) \in E. \tag{7}$$

Hence $p_u = 1 - p_a$ will be the probability that a wavelength will be used on link $i-j$ to satisfy a connection request.

The probability that all wavelengths will be used in a future connection shall be

$$p_{u\_all} = p_u^{\Lambda_{ij}^A}. \tag{8}$$

And finally the probability of finding at least one wavelength to satisfy a future connection will be

$$p = 1 - p_{u\_all}. \tag{9}$$

Therefore, when a path is composed of many links we try to maximize the above probability when selecting the routes.

$$W_{ij} = 1 - \left(1 - \left(\frac{\Lambda_{ij}^A}{\Lambda_{ij}^T}\right)^{F_{ij}}\right)^{\Lambda_{ij}^A}, \forall(i,j) \in E. \tag{10}$$

Due to the additive nature of Dijkstra's algorithm we apply $-\log(W_{ij})$ and consequently try to minimize this value. Again the resulting cost of setting up a lightpath along a route, r is the Sum of the above weight definition along its optical segments. This is a dynamic weight attribute since it is computed on line.

$$w - \mathit{selection} = \sum W_{ij}, \forall(i,j) \in r. \tag{11}$$

When coupling together the above weight schemes (2) and (10) we produce an adaptive weight function which chooses the best next optical segment depending both on the possibility of finding an idle wavelength as well as selecting those segments with the largest free capacity (more fibers).

$$W_{ij} = -\log\left(1 - \left(1 - \left(\frac{\Lambda_{ij}^A}{\Lambda_{ij}^T}\right)^{F_{ij}}\right)^{\Lambda_{ij}^A}\right) * \frac{1}{F_{ij}}, \forall(i,j) \in E. \tag{12}$$

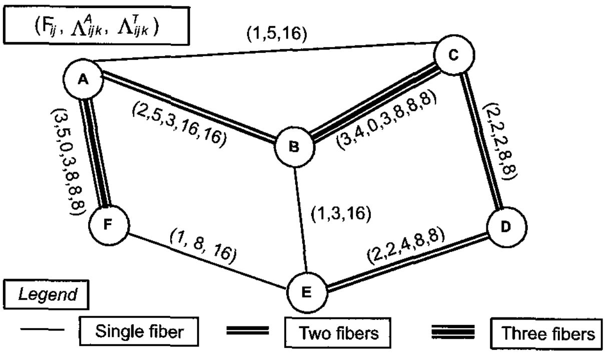

Fig. 1. A sample network demonstrating the path selection depending on the proposed weights.

Again the resulting cost of setting up a lightpath along a route, r is the Sum of the above weight definition along its optical segments. This is a dynamic weight attribute since it is computed on line.

$$combined = \sum W_{ij}, \forall(i,j) \in r. \qquad (13)$$

Then Dijkstra's algorithm is invoked and the "currently-best" path is selected. We do not impose any limit at the selected path's length in hop-counts. The resulting path consists of those optical links which minimize the above weight function. We shall call the above scheme, *weighted selective adaptive routing* (WSAR). After the selection of the route the wavelength is assigned following the random scenario.

In Fig. 1, we present a sample network in which path selection depends upon the different weight schemes used. Considering only fiber-count route A-B-C-D is chosen because it contains the most multi-fiber segments. Looking at the third column, path A-C-D is selected because it has the highest probability of presenting a wavelength to satisfy a future connection. Finally, when combining the above two weights we see that path A-F-E-D is chosen. We observe that path selection is heavily dependent upon the weight scheme used. It is important to note that for our proposed scheme at every call request between a source-destination pair the routing table at the source router must search all the possible paths to the destination router, isolate a path which corresponds to the lowest total weight metric and assign a wavelength in random. This approach is expected to result in higher execution times from having a RWA algorithm which has to choose from a predetermined set of routes. Also wavelength usage information must be updated to the network, in order to have an accurate description of the current network state.

IV. PERFOMANCE ANALYSIS

We use discrete event simulation to test the behavior of the network for the different weight schemes and algorithms. We study the performance of our algorithm on two regular and one irregular topology which are shown in Fig. 2. The first network is a 2×3 mesh topology with 6 nodes and 7 links. The second network is a 4×4 mesh-torus network, which has 16 nodes and 32 links. The last one is the NSFNET T1 backbone network with 14 nodes and 21 links.

Table 1. Path selection based upon different weight schemes.

Path	Cost for each path		
From A to D	F-count	W-selection	Combined
A-C-D	1.5	0.7149	0.3934
A-B-C-D	1.33	1.8296	0.7826
A-B-E-D	2.00	0.9519	0.3093
A-F-E-D	1.83	0.8088	0.3075
A-C-B-E-D	2.83	1.422	0.7818
A-F-E-B-C-D	3.16	2.3543	1.1149

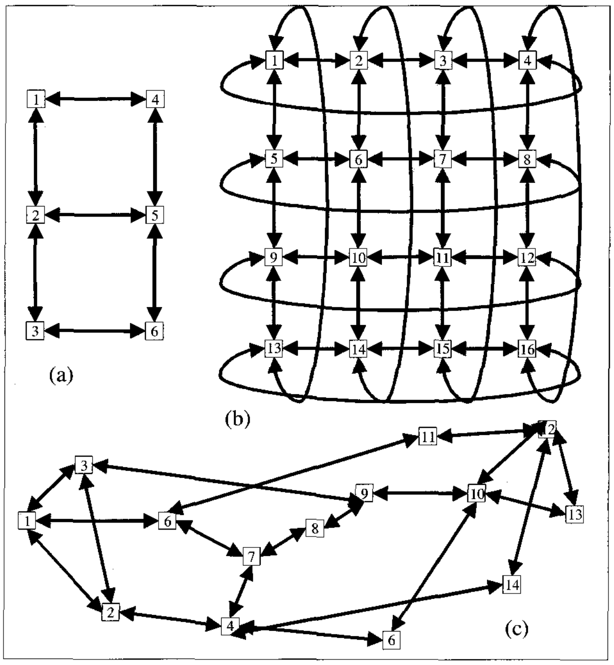

Fig. 2. The hypothetical WDM networks used in our study, (a) 2×3 mesh network, (b) 4x4 mesh-torus network, (c) NSFNET-like network.

Table 2. The matrix of the number of fibers on each link for the uneven 2×3 mesh network.

0	2	0	4	0	0
2	0	4	0	8	0
0	4	0	0	0	2
4	0	0	0	8	0
0	8	0	8	0	2
0	0	2	0	2	0

We examine each of the three networks with two versions. In the first it is assumed to consist of even links, meaning that the number of fibers per link remains constant throughout the network. When this is the case every link in both three networks consists of 4 fibers unless otherwise stated. In the second version each link has a fiber bundle which can vary from having 2,4 or 8 fibers. The following tables describe the way fibers are allocated on each link. Note that the matrices are symmetrical. This occurs because all the links are supposed to be bidirectional. The number of wavelengths on each fiber is also varied ranging from 32 to 64 wavelengths per fiber.

Table 3. The matrix of the number of fibers on each link for the uneven 4×4 mesh-torus network.

0	8	0	2	8	0	0	0	0	0	0	0	4	0	0	0
8	0	8	0	0	2	0	0	0	0	0	0	0	4	0	0
0	8	0	8	0	0	2	0	0	0	0	0	0	0	4	0
2	0	8	0	0	0	0	8	0	0	0	0	0	0	0	4
8	0	0	0	0	2	0	4	8	0	0	0	0	0	0	0
0	2	0	0	2	0	4	0	0	2	0	0	0	0	0	0
0	0	2	0	0	4	0	4	0	0	2	0	0	0	0	0
0	0	0	8	4	0	4	0	0	0	0	8	0	0	0	0
0	0	0	0	8	0	0	0	0	2	0	4	8	0	0	0
0	0	0	0	0	2	0	0	2	0	2	0	0	0	0	0
0	0	0	0	0	0	2	0	0	2	0	8	0	4	2	0
0	0	0	0	0	0	0	8	4	0	8	0	0	0	0	2
4	0	0	0	0	0	0	0	8	0	0	0	0	4	0	8
0	4	0	0	0	0	0	0	0	0	4	0	4	0	4	0
0	0	4	0	0	0	0	0	0	0	2	0	0	4	0	2
0	0	0	4	0	0	0	0	0	0	0	2	8	0	2	0

Table 4. The matrix of the number of fibers on each link for the uneven nsfnet network.

0	2	8	0	0	4	0	0	0	0	0	0	0	0
2	0	4	4	0	0	0	0	0	0	0	0	0	0
8	4	0	0	0	0	0	0	4	0	0	0	0	0
0	4	0	0	4	0	4	0	0	0	0	0	0	2
0	0	0	4	0	0	0	0	0	4	0	0	0	0
4	0	0	0	0	0	2	0	0	0	4	0	0	0
0	0	0	4	0	2	0	8	0	0	0	0	0	0
0	0	0	0	0	0	8	0	4	0	0	0	0	0
0	0	4	0	0	0	0	4	0	2	0	0	0	0
0	0	0	0	4	0	0	0	2	0	0	4	4	0
0	0	0	0	0	4	0	0	0	0	0	8	4	0
0	0	0	0	0	0	0	0	0	4	8	0	8	2
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0	0	0	2	0	0	0	0	0	0	0	2	0	0

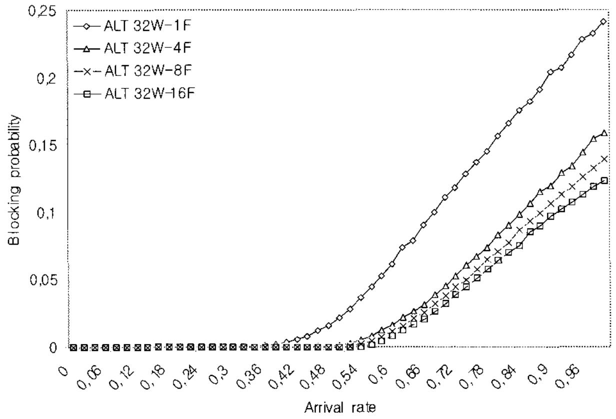


Fig. 3. The benefits of using multiple fibers in terms of blocking probability in an even nsfnet-type network with shortest path routing.

Most investigations of WDM networks reported in literature are based on the assumption of Poisson traffic. However, recent measurements for Internet dial up traffic have shown that traffic on the connection level can be significantly different from Poisson behaviour for various scenarios. In this study we are going to use non-Poisson traffic. Calls—lightpath requests—are assumed to arrive at the network according to an independent hyper-exponential time distribution with arrival rate λ. This type of distribution allows a simple description for bursty behaviour [24], [25]. The source-destination node pairs are randomly chosen according to a uniform distribution. Each call has a duration or call holding time which is negative-exponentially distributed. A sufficient number of calls were generated in order to ensure reliable results. Simulation results are plotted within 95% confidence intervals estimated by the method of replications. The number of replications is 30 with each simulation run having at least 10^5 call arrivals. The parameters varied are the arrival rate λ—in increments of 0.02—, and the number of wavelengths—nominal capacity—on each fiber.

As performance metrics we use overall blocking probability and link utilization. The blocking probability is expressed as the fraction of the overall rejected connection requests due to wavelength unavailability divided by the total number of connection requests at a simulation run. The utilization is expressed as the percentage of total time that all links in the network are active. We compare our proposal with fixed routing, alternate routing (ALT), and LLR. We vary the admissible path list from having 1 or 2 paths and the search parameter for extra hops from having 0 or 1.

In Fig. 3, we present the benefits from using multiple fibers in a network in terms of blocking probability. We plot the call blocking probability for fixed-routing—that is equivalent to saying alternate routing with only one admissible path—as a function of connection requests rate, with 1, 4, 8, and 16 fibers per link and 32 wavelengths per fiber. We see that there is a reduction of almost 100% in blocking probability when comparing the two extreme cases, for the same arrival rate ($\lambda = 0.90$).

In Fig. 4, we demonstrate that when having links with the same nominal capacity it is better to have multiple fibers in a link. Having 32 wavelengths and 4 fibers is superior to having 128 wavelengths in a single fiber. This can be attributed to the fact that multi-fiber links are equivalent to links having limited wavelength-conversion capability with degree the number of fibers. Fig. 5 verifies the increase in utilization as a result of the reduced blocking probability.

A. *Results for the* 2×3 *Mesh Network*

In Fig. 6, we see that when considering only one alternate path, WSAR has significant advantage in decreased blocking probability and increased link utilization over ALT and LLR in the even network case. The same can be said for the uneven scenario as seen in Fig. 8. When we increase the number of alternate paths to 2 we observe in Fig. 7 that the three algorithms come very close, yet our proposal holds a slight advantage. Link utilization is also very similar since the limited search area of the 2×3 mesh network doesn't allow WSAR to select different paths. This advantage becomes more obvious in Fig. 9 where the uneven version is considered. In this example, WSAR per-

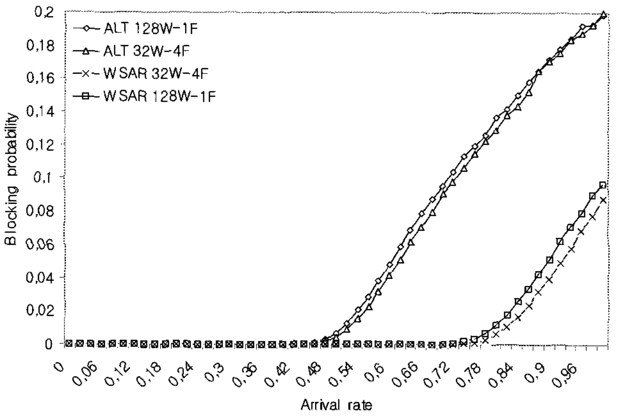


Fig. 4. Reduction in blocking probability as the result of using multiple fibers in links with the same nominal capacity in an even 2 × 3 mesh network, with shortest path routing and WSAR.

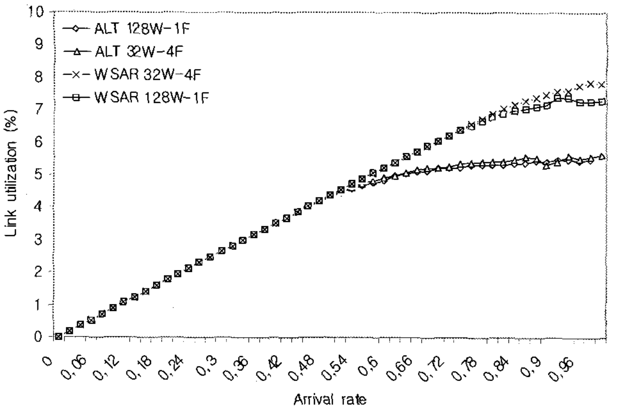


Fig. 5. Increased utilization as a result of using multiple fibers in links with the same nominal capacity in an even 2 × 3 mesh network, with shortest path routing and WSAR.

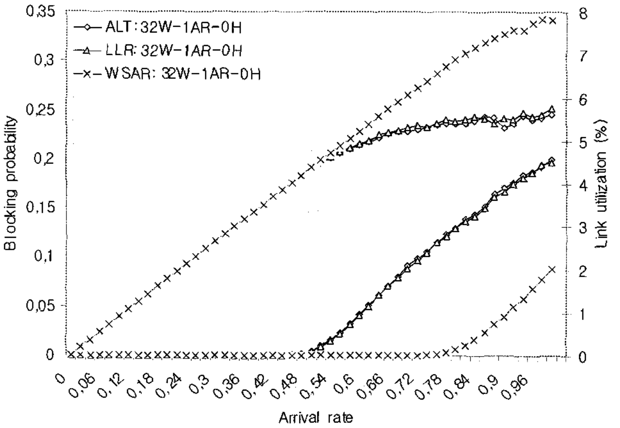


Fig. 6. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even 2 × 3 mesh network with a single alternate path.

forms better since it benefits from the inequality of fibers over the links, to select the best path.

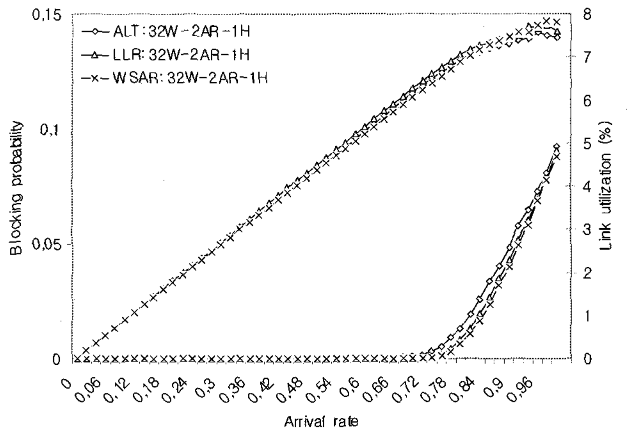


Fig. 7. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even 2 × 3 mesh network with two alternate paths and 1 extra hop as a search parameter.

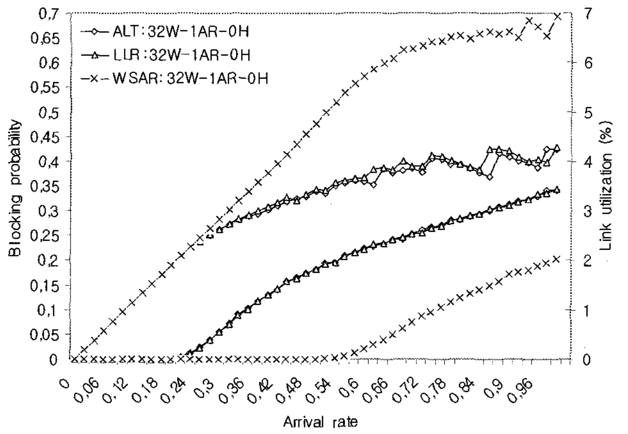


Fig. 8. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an uneven 2 × 3 mesh network with a single alternate path, the shortest one.

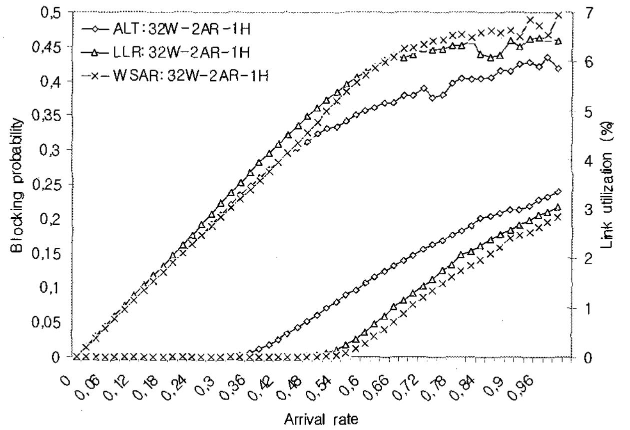


Fig. 9. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an uneven 2 × 3 mesh network with 2 alternate paths and one extra hop as a search parameter.

B. Results for the 4 × 4 *Mesh-Torus Network*

In our second regular topology WSAR outperforms Alternate routing and LLR by a wide margin when only one path

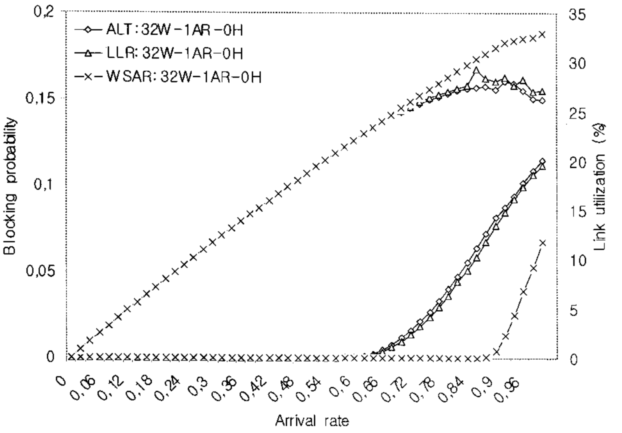


Fig. 10. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even 4 x 4 mesh-torus network with a single alternate path.

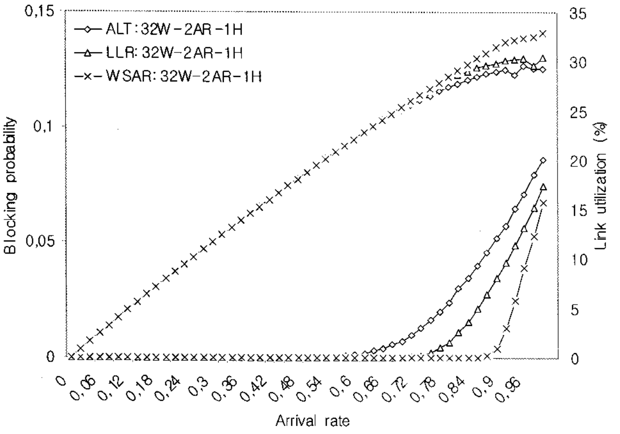


Fig. 11. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even 4×4 mesh-torus network with two alternate paths and one extra hop as a search parameter.

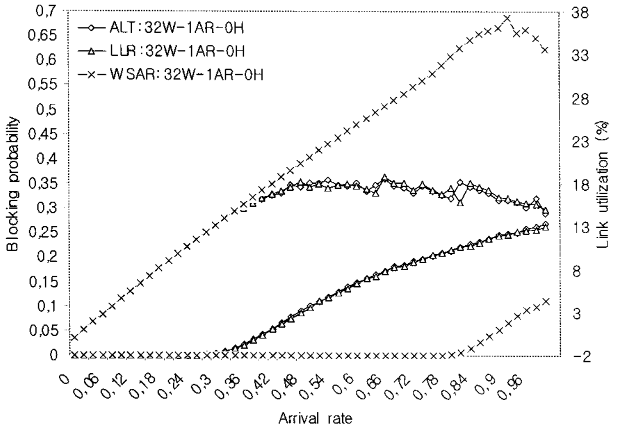


Fig. 12. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an uneven 4×4 mesh-torus network with one alternate path.

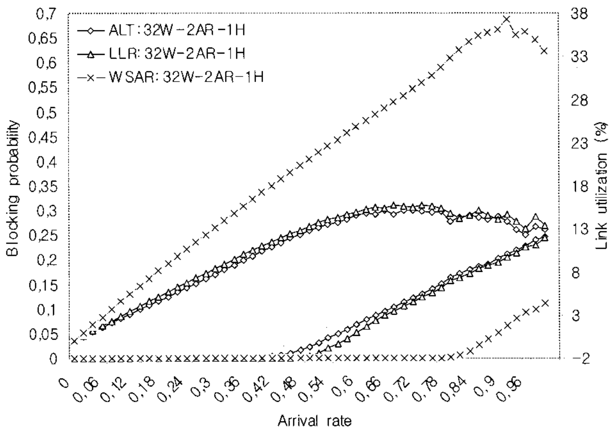


Fig. 13. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an uneven 4×4 mesh-torus network with 2 alternate paths and one extra hop as a search parameter.

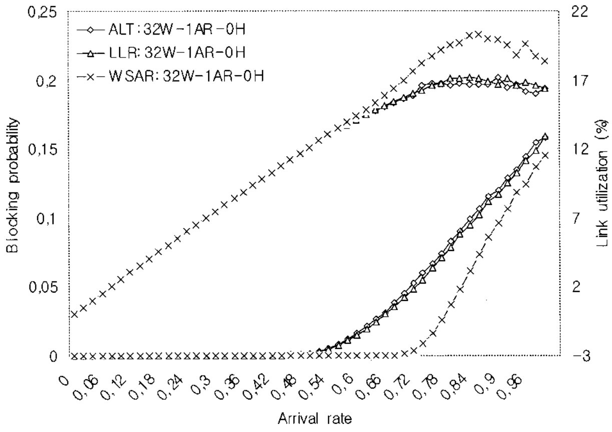


Fig. 14. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even NSFNET-like network with a single alternate path.

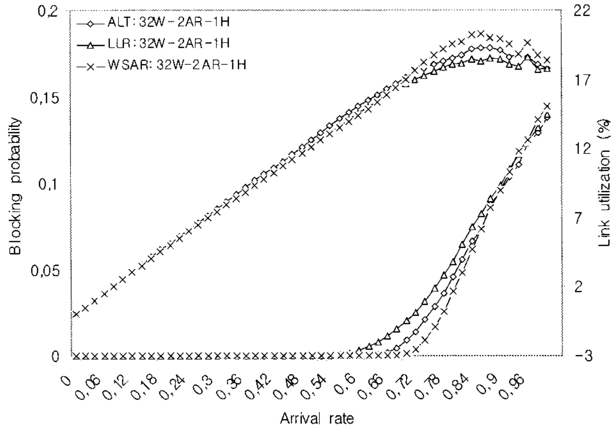


Fig. 15. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an even NSFNET-like network with two alternate paths and one extra hop as a search parameter.

is computed as seen from Figs. 10 and 12. In the second case in the even mesh-torus network we observe that WSAR falls

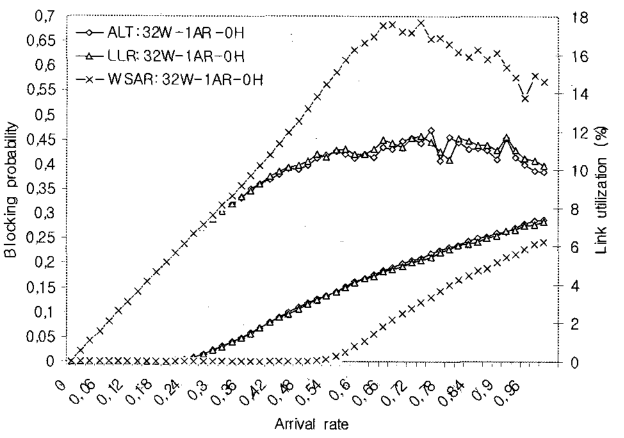


Fig. 16. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves—in an uneven NSFNET-like network with one alternate path.

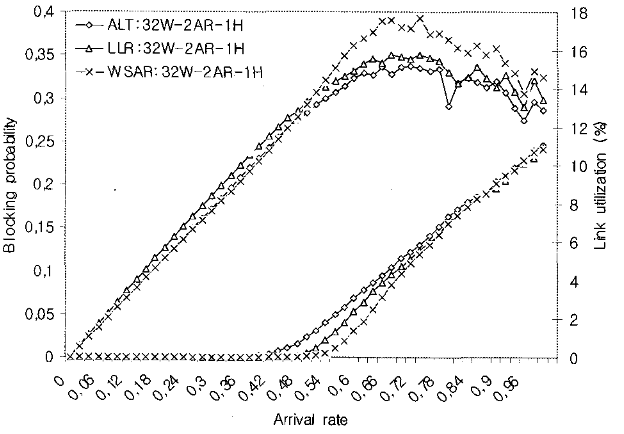


Fig. 17. Comparing the three RWA algorithms in terms of blocking probability—lower set of curves—and link utilization—upper set of curves— in an uneven NSFNET-like network with 2 alternate paths and one extra hop as a search parameter.

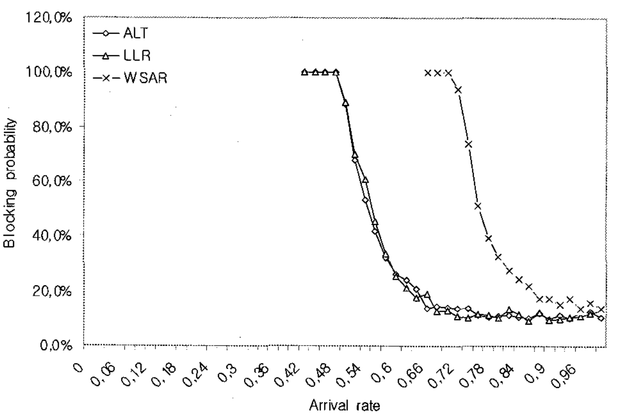


Fig. 18. Reduction of the blocking probability in the even NSFNET network with one alternate path when the wavelength table is increased from 32 to 64.

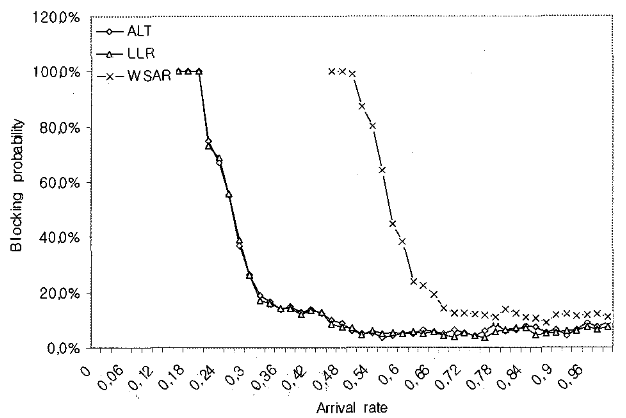


Fig. 19. Reduction of the blocking probability in the uneven NSFNET network with one alternate path when the wavelength table is increased from 32 to 64.

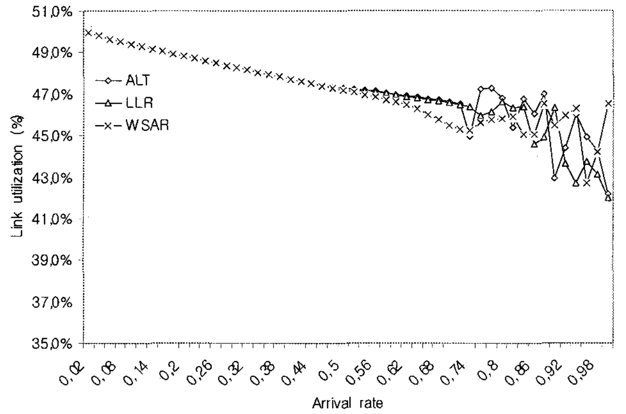


Fig. 20. Increase of link utilization in the even NSFNET network with one alternate path when the wavelength table is increased from 32 to 64.

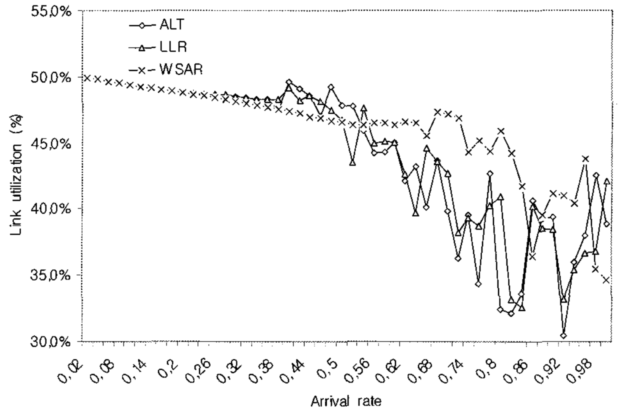


Fig. 21. Increase of link utilization in the uneven NSFNET network with one alternate path when the wavelength table is increased from 32 to 64.

back when the load increases significantly, Fig. 11. This can be attributed to the fact that because of the network's uniformity both in fibers and link placement, WSAR selects similar paths between source-destination pairs resulting in higher blocking. Nevertheless, WSAR demonstrates increased link utilization since it spreads traffic more through the network. But when the uneven version of the mesh-torus network is considered, Fig. 13, WSAR shows better adaptation since it benefits from the varied fiber distribution.

C. Results for the NSFNET Network

When examining an irregular topology in the form of the NSFNET T1 backbone network, the WSAR algorithm performs better when the network has uneven links as seen in Figs. 16 and 17. In any case the link utilization resulting from the WSAR implementation is the highest among the three algorithms, again as a result of WSAR not being constrained to follow a predetermined route, but being able to search an optimal path with unlimited hop-count.

When we increase the wavelength pool from 32 to 64 wavelengths per fiber in the NSFNET network, we expect the blocking probability to be reduced and the link utilization to increase. From our results we observe that WSAR has the greater reduction for blocking probability when considering the even network case Fig. 18. In the even network blocking probabilities for ALT and LLR follow roughly the same reduction curve, Fig. 18. As far as link utilization is concerned in both network cases we observe an increase in the range of 30% to 50% with the even case approaching the upper-portion of the afore mentioned interval, Figs. 20 and 21.

V. CONCLUSION

In this paper, we studied the routing and wavelength assignment problem in wavelength continuous WDM multi-fiber networks under dynamic traffic. We produced an adaptive RWA algorithm which uses Dijkstra's shortest path algorithm suitably modified to incorporate WDM multi-fiber characteristics. The proposed WSAR algorithm selects any route that maximizes the probability of finding an idle wavelength to use along a lightpath as well as maximizing the number of multi-fiber segments it traverses. Our proposal is compared with other RWA schemes in a network topology with fixed or varying number of fibers per optical segment. Simulation results show good performance in terms of blocking probability and link utilization, especially in the uneven network case.

REFERENCES

[1] G. I. Papadimitriou, C. Papazoglou, and A. S. Pomportsis, "Optical switching: Switch fabrics, techniques, and architectures," *IEEE J. Lightwave Technol.*, vol. 21, no. 2, Feb. 2003.

[2] G. I. Papadimitriou, P. Tsimoulas, M. S. Obaidat, and A. S. Pomportsis, *Multiwave-Length Optical LANs*, Wiley, 2003.

[3] T. E. Stern and K. Bala *Multiwavelength Optical Networks: A Layered Approach*, Prentice Hall PTR, 1999.

[4] E. Karasan and E. Ayanoglou, "Performance of WDM transport networks," *IEEE J. Select. Areas Commun.*, vol. 16, no. 7, pp. 1081–1096, Sept. 1998.

[5] A. Mokhtar and M. Azizoglu, "Adaptive wavelength routing in all-optical networks," *IEEE/ACM Trans. Networking*, vol. 6, no. 2, pp. 197–206, Apr. 1998.

[6] E. Karasan and E. Ayanoglou, "Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks," *IEEE/ACM Trans. Networking*, vol. 6, no. 2, pp. 186–195, Apr. 1998.

[7] P.-H. Ho and H. T. Mouftah, "A novel distributed protocol for path selection in dynamic wavelength-routed WDM networks," *Photonic Network Commun.*, vol. 5, no. 1, pp. 23–32, 2003.

[8] C.-F. Hsu, T.-L. Liu, and N.-F. Huang, "Perfomance of adaptive routing in wavelength-routed networks with wavelength conversion capability," *Photonic Network Commun.*, vol. 5, no. 1, pp. 41–57, 2003.

[9] X. Zhang and C. Qiao, "Wavelength assignement for dynamic traffic in multi-fiber WDM networks," in *Proc. ICCCN'98*, 1998, pp. 479–585.

[10] M. Azizoglou, R. A. Barry, and A. Mokhtar, "Impact of tuning delay on the performance of bandwidth-limited optical broadcast networks with uniform traffic," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 935–944, June 1996.

[11] K. C. Lee, O. Vicor, and K. Li, "A wavelength convertible optical network," *J. Lightwave Technol.*, vol. 11, no. 5/6, pp. 962–970, May/June 1993.

[12] H. Harai, M. Murata, and H. Miyahara, "Performance analysis of wavelength assignment policies in all-optical networks with limited-range wavelength conversion," *IEEE J. Select. Areas Commun.*, vol. 16, no. 7, pp. 1051–1060, Sept. 1998.

[13] I. Chlamtac, A. Farago, and T. Zhang, "Lighpath (wavelength) routing in large WDM networks," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 909–913, June 1996.

[14] O. Basbugoglu and S. Bilgen, "A distributed minimal congestion routing algorithm," *ISCIS XIV*, Oct. 1999.

[15] G. I. Papadimitriou and A. S. Pomportsis, "Self-adaptive TDMA protocols for WDM star networks: A learning-automata-based approach," *IEEE Photonics Technol. Lett.*, vol. 11, no. 10, Oct. 1999.

[16] A. Ferreira, S. Perennes, and H. Rivano, "Models, complexity, and algorithms for the design of multi-fiber WDM networks," *Telecommun. Syst.*, vol. 24, no. 2–4, pp. 123–138, 2003.

[17] Y. Luo and N. Ansari, "A computational model for estimating blocking probabilities of multi-fiber WDM optical networks," *IEEE Commun. Lett.*, vol. 8, no. 1, Jan. 2004.

[18] L. Li and A. K. Sonami, "Blocking performance analysis of fixed paths least-congestion routing in multi-fiber wdm networks," in *Proc. SPIE Photonics East'99*, Boston, MA, 1999.

[19] V. Sharma and E. A. Varvarigos, "Limited wavelength translation in all-optical WDM mesh networks," in *Proc. INFOCM'98*, pp. 893–901.

[20] G. Jeong and E. Ayanoglu, "Comparison of wavelength-interchanging and wavelength-selective cross-connects in multiwavelength all optical networks," in *Proc. INFOCOM'96*, pp. 156–163.

[21] N. M. Bhide, K. M. Sivalingam, and T. Fabry-Asztalos, "Routing mechanisms employing adaptive weight functions for shortest path rounting in optical WDM networks," *J. Photonic Network Commun.*, vol. 3, pp. 227–236, 2001.

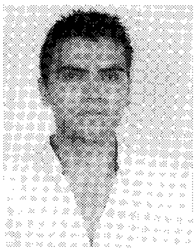
[22] T. Fabry-Asztalos, N. Bhide, and K. M. Sivalingam, "Adaptive weight functions for shortest path routing algorithms for multi-wavelength optical WDM networks," in *Proc. IEEE ICC 2000*, 2000.

[23] C.-F. Hsu, T.-L. Liu, and N.-F. Huang, "On adaptive routing in wavelength-routed networks," *Optical Network Mag.*, vol. 3, no. 1, pp. 15–24, 2002.

[24] A. Feldmann and W. Whitt, "Fitting mixtures of exponentials to long tail distributions to analyze network performance models," *Perfomance Evaluation*, pp. 245–279, 1998.

[25] J. Spath, "Dynamic routing and resource allocation in WDM transport networks," *Computer Networks*, pp. 519–538, 2000.

[26] S. Xu, L. Li, and S. Wang, "Dynamic routing and assignment of wavelength algorithms in multi-fiber wavelength division multiplexing networks," *IEEE J. Select. Areas Commun.*, vol. 18, no. 10, pp. 2130–2137, Oct. 2000.



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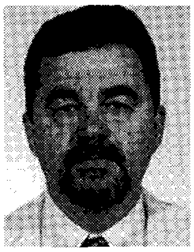

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