Adaptive Weight Functions for Wavelength-Continuous WDM Multi-fiber Networks

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Abstract- **In this paper we address the problem of efficient Routing and Wavelength Assignment (RWA) in multi-fiber 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 even and uneven WDM multi-fiber networks in terms of blocking probability and overall link utilization.**

Index Terms—**Dynamic traffic, Multi-fiber WDM networks, Weighted graph, RWA algorithm, Wavelength continuity.**

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 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 employed for 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 (color) 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. 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.

Further more the RWA problem must cope with 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 is typically trying 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. 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 the other hand, adaptive algorithms use network state

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information at the time of request arrival to find a route and a wavelength for a lightpath request. 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 links 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 sd-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 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 [9] 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, least utilized wavelength is assigned to the lightpath. Therefore, the load is uniformly distributed over the wavelength set. In [9], 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 sd-pair are searched in the routing. The simulations show that, pack scheme has the best performance followed by random and spread schemes. An extension of the above scheme for multifiber networks was made in [10].

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 sd-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

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

where π denote 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} denote 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 [11] for dynamic RWA. In MCR, the lightpaths are routed on the least congested path and first-fit wavelength assignment is done.

In [12], [13], and [14], graph based methods for finding optimal routes and wavelengths for lightpaths using shortest path routing are proposed. In [12], 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 [13], a similar approach is used to construct a graph that facilitates the routing and wavelength assignment by virtually separating the wavelengths into different paths. The approach is called *layered graph approach*. In this model, limited-range wavelength conversion is considered. In [14], 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 [15]. 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 [16].

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 WRN specific information to the links of a multifiber-WRN, 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. Also the network considered here has no node wavelength conversion capability, but employs the benefits of spatial reuse of wavelengths provided by the multi-fiber property of a link.

Some of the notations used:

Λ^{A}_{ijk}: available wavelengths in fiber k of link i-j

Λ^{T}_{ijk}: 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 scheme takes in account only the hop count for establishing a lightpath between a source – destination node pair. Hence,

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

When selecting a route based only on the number of nodes traversed, it is expected to chose those routes which contain as many multifiber 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.

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

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:

$$\Lambda^{T}_{ij} = \sum_{k=1}^{F_{ij}} \Lambda^{T}_{ijk} \tag{4}$$

Similarly the number of available wavelengths will be:

$$\Lambda^{A}_{ij} = \sum_{k=1}^{F_{ij}} \Lambda^{A}_{ijk} \tag{5}$$

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

$$p_a = \frac{\Lambda^{A}_{ij}}{\Lambda^{T}_{ij}} \quad ,\forall(\mathrm{i,j}) \in \mathrm{E} \tag{6}$$

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

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

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:

$$p_{u\_all} = p_u^{\Lambda^{A}_{ij}} \tag{8}$$

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.

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

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.

$$w-selection = \sum W_{ij} \quad ,\forall \mathrm{i,j} \in \mathrm{r} \tag{11}$$

When coupling together the above weight schemes 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).

$$W_{ij} = -\log\left(\left(1-\left(1-\left(\frac{\Lambda^{A}_{ij}}{\Lambda^{T}_{ij}}\right)^{F_{ij}}\right)^{\Lambda^{A}_{ij}}\right)\right) * \frac{1}{F_{ij}} \tag{12}$$

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 depended upon the weight scheme used. It is important to note that for our proposed scheme at every call request between an s-d 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.

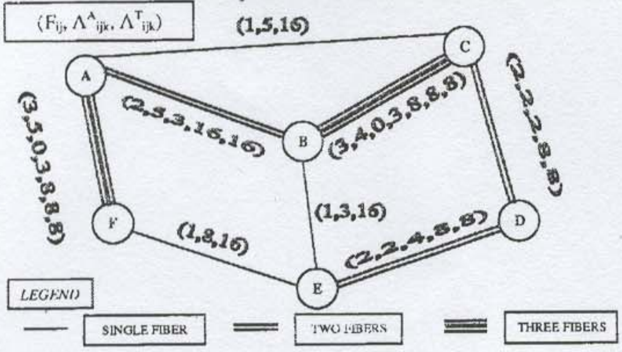

Fig. 1. A sample network demonstrating the path selection depending on the proposed weights

TABLE I
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

IV. PERFORMANCE ANALYSIS

We use discrete event simulation to test the behavior of the network for the different weight schemes and algorithms. The network is randomly generated and consists of 26 nodes, Fig. 2. It has an average node degree δ of 2.96 which is defined as,

$$\delta = \frac{\sum_{i=1}^{N} i_d}{N} \tag{13}$$

where i_d is the number of links terminating/emanating from a given node and N the number of nodes.

We examine the network with two versions. In the first it is assumed to consist of even links, meaning that the number of fiber per link remains constant throughout the network. In the second version each link has a fiber bundle which can vary from having 2,4 or 8 fibers. Call -lightpath requests- are assumed to arrive at the network according to an independent Poisson process with arrival rate λ. The source-destination node pairs are randomly chosen according to an uniform distribution. Each call has a duration or call holding time which is exponentially distributed. A sufficient number of calls were generated in order to ensure reliable results. Each data point was obtained using 10^5 call requests. The parameters varied are the arrival rate λ and the number of wavelengths -nominal capacity- on each fiber. We assume that every fiber can accommodate the same number of wavelengths.

As performance metrics we use blocking probability and link utilization. The blocking probability is expressed as the fraction of the 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, and LLR. We vary the admissible path list from having 1 or 4 paths and the search parameter for extra hops from having 0 or 2.

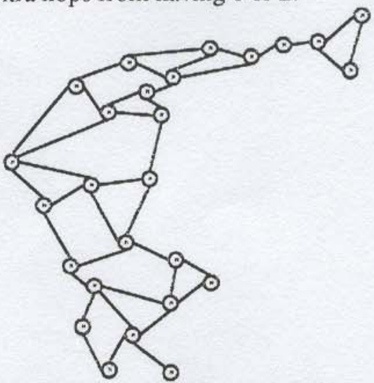

Fig. 2. The hypothetical WDM network used in our study.

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. We see that there is a reduction of almost 200% in blocking probability when comparing the two extreme cases, for the same arrival rate.

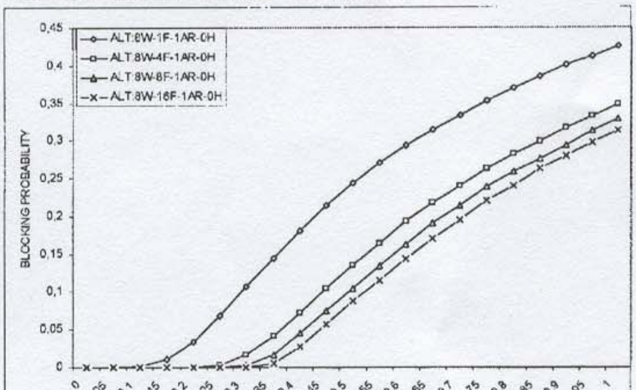

Fig. 3. The benefits of using multiple fibers in terms of blocking probability in an even network with shortest path routing.

In Fig. 4 we show that when having links with the same nominal capacity it is better to have multiple fibers in a link. Having 8W and 4F is superior to having 32W 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.

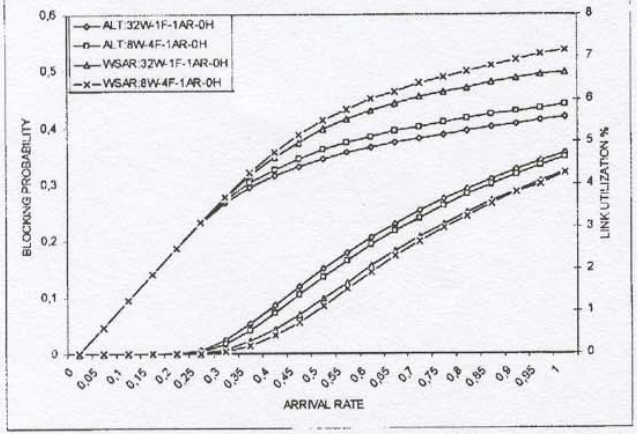

Fig. 4. Increased throughput –lower set of curves- and increased utilization -upper set of curves- as the result of using multiple fibers in links with the same nominal capacity in an even network, with SPR and WSAR.

In the case of the even network every link in the network has the same number of fibers, 8 per link. We first set the number of total wavelengths per fiber to 8. When setting the parameter of alternate paths to 1 (shortest path routing) we observe that the blocking probability is very identical for the two examined algorithms and notably better with our proposed approach, Fig 5. The same goes for the utilization as well. When we increase the number of alternate paths to 4, Fig. 6, then we notice that all blocking probabilities are very close. Utilization however shows that our algorithm performs better since it spreads traffic more through the network with LLR following close by. When the search parameter is increased to 2 then the utilization for the network is further increased since longer paths are searched and selected.

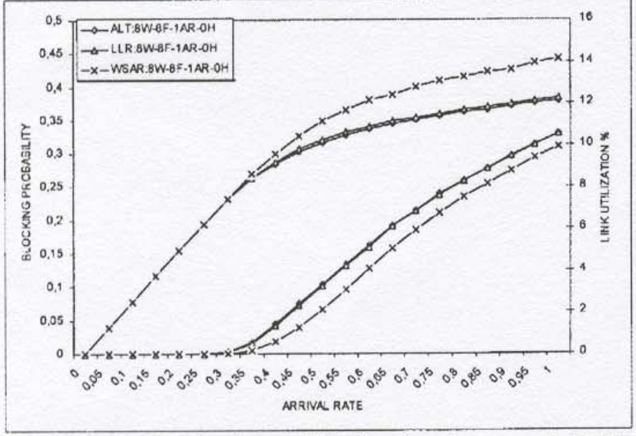

Fig. 5. Comparing the three RWA algorithms in terms of blocking probability –lower set of curves- and link utilization -upper set of curves- in an even network with a single alternate path.

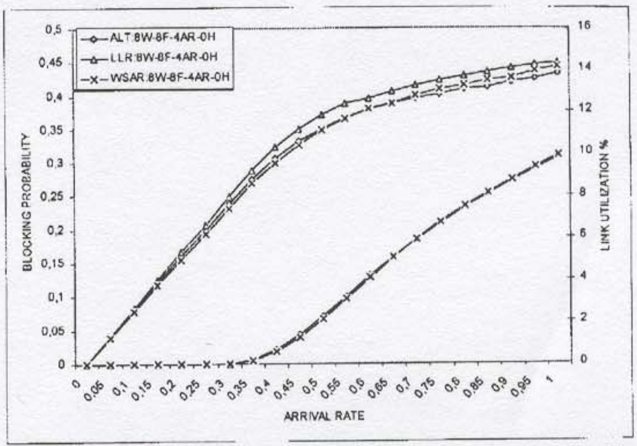

Fig. 6. Comparing the three RWA algorithms in terms of blocking probability –lower set of curves- and link utilization -upper set of curves- in an even network with four alternate paths.

In the case of the uneven network the number of fibers varies throughout the network with distinct values 8, 4 and 2 fibers per optical link. The total number of wavelengths is again set at 8. When having only one alternate route, our algorithm outperforms the other two approaches which result in roughly the same performance Fig. 7. The same goes for the utilization of the network. If we increase the number of alternate routes to 4 with a search parameter of 2 extra hops, Fig. 8, we notice an increase in performance for LLR . In an uneven network the availability of wavelengths is not constant so WSAR which takes in consideration the multi-fiber segments as well shows better results from LLR which only considers least loaded links only.

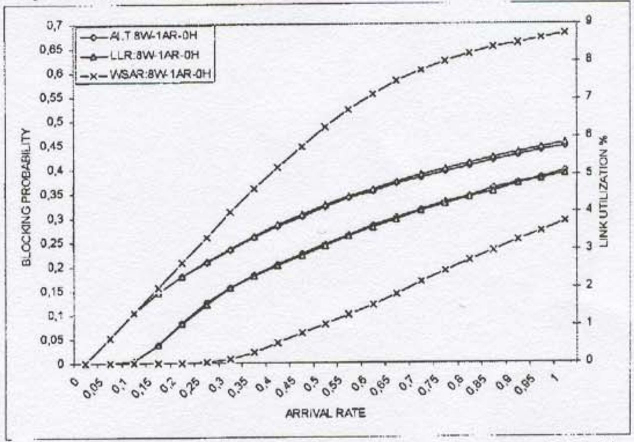

Fig. 7. Comparing the three RWA algorithms in terms of blocking probability –lower set of curves- and link utilization -upper set of curves- in an uneven network with a single alternate path, the shortest one.

When we increase the wavelength pool from 8 to 16 wavelengths 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 uneven network case Fig. 9. In the even network blocking probabilities follow roughly the same reduction curve Fig. 10. As far as link utilization is concerned in both network cases we observe an increase in the range of 48~52% with the uneven case approaching the upper-portion of the afore mentioned interval.

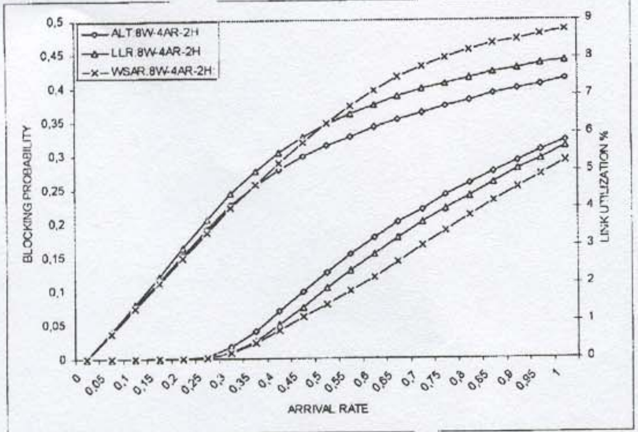

Fig. 8. Comparing the three RWA algorithms in terms of blocking probability –lower set of curves- and link utilization -upper set of curves- in an uneven network with 4 alternate paths and 2 hops as a search parameter.

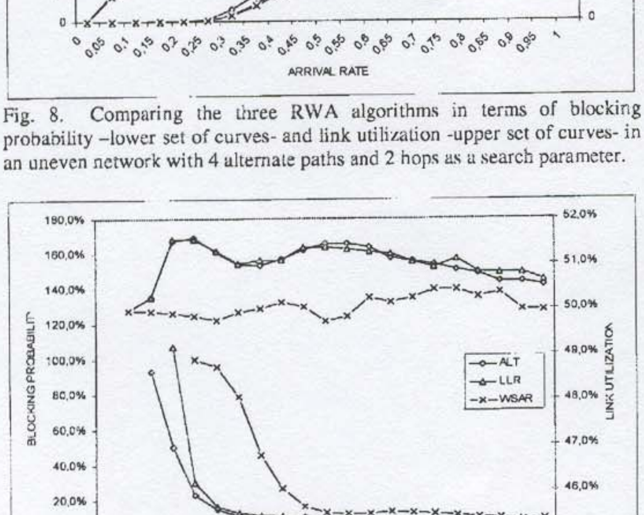

Fig. 9. Reduction of the blocking probability -lower set of curves- and increase of the link utilization in an uneven network with 1 alternate path when the wavelength table is increased from 8 to 16 wavelengths per fiber.

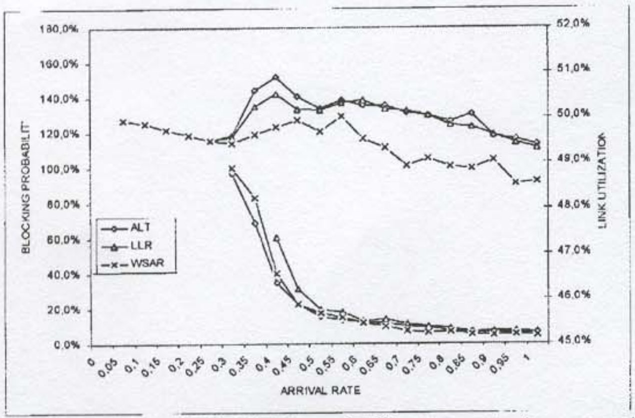

Fig. 10. Reduction of the blocking probability -lower set of curves- and increase of the link utilization in an even network with 1 alternate path when the wavelength table is increased from 8 to 16 wavelengths per fiber.

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.

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