Adaptive Wavelength Routing in All-Optical Networks

Ahmed Mokhtar, *Member, IEEE*, and Murat Azizoğlu, *Member, IEEE*

***Abstract*—In this paper we consider routing and wavelength assignment in wavelength-routed all-optical networks with circuit-switching. The conventional approaches to address this issue consider the two aspects of the problem disjointly by first finding a route from a predetermined set of candidate paths and then searching for an appropriate wavelength assignment. We adopt a more general approach in which we consider all paths between a source–destination (s–d) pair and incorporate network state information into the routing decision. This approach performs routing and wavelength assignment jointly and adaptively, and outperforms fixed routing techniques. We present adaptive routing and wavelength assignment algorithms and evaluate their blocking performance. We obtain an analytical technique to compute approximate blocking probabilities for networks employing fixed and alternate routing. The analysis can also accommodate networks with multiple fibers per link. The blocking performance of the proposed adaptive routing algorithms are compared along with their computational complexity.**

***Index Terms*—Adaptive routing, all-optical networks, blocking performance, wavelength assignment, wavelength routing.**

I. INTRODUCTION

IN AN ALL-OPTICAL network, signals remain in the optical domain from the source to the destination, thereby eliminating the well-known electrooptic bottleneck. While this approach allows information transfer rates to approach those allowed by optical devices, and significantly beyond the rates possible in an electronic network, it also introduces several challenges in the network design.

Two popular architectures have evolved as candidates for all-optical networks [1]. An attractive architecture for a local area network (LAN) with a small number of users is the *broadcast-and-select* network. Here, N nodes are connected through an $N \times N$ passive broadcast star; thus, the signal transmitted by any node is received by all nodes. Since all connections use a single optical hop, routing, management, and control of such connections admit relatively simple solutions.

The broadcast-and-select architecture is inadequate for a wide area network (WAN) due to power budget limitations and lack of wavelength reuse. Both of these result from the lack of switching and can be remedied by the introduction of wavelength routing. A wavelength router is an optical switch that is capable of routing a signal based on its input port and its wavelength. A wavelength router may have the additional capability of changing the wavelength of the signal it routes. A wavelength-routing node with nodal degree three and four wavelengths is shown in Fig. 1. Wavelength routing with or without wavelength conversion provides the network with the ability to localize the information flow, thereby allowing the same wavelength to be reused in spatially disjoint segments of the network. This capability is of fundamental importance in the design of wide-area all-optical networks [1]–[4].

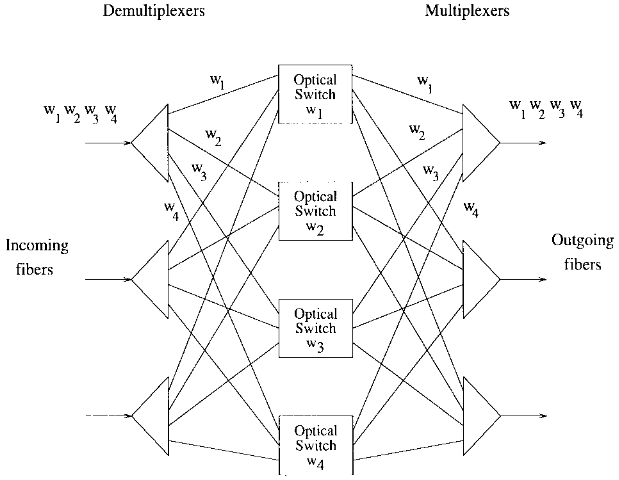

Fig. 1. A wavelength router.

In order to establish the terminology and the context in which the issue of wavelength routing will be addressed, we first review some basic aspects of routing in circuit-switched electronic networks. In these networks the routing of a call involves the selection of a path on which the call can be carried. In general, a routing algorithm can be classified as *static* or *adaptive*. A static routing algorithm is one in which the routing procedure does not vary with time. Adaptive routing algorithms use network state information at the time of connection establishment.

Fixed routing is a widely used static routing technique in which every source–destination (s–d) pair is assigned a single path [5]. A call is blocked if its associated path is not available. In *alternate routing* each s–d pair is assigned a set of paths. This set may be searched in a fixed or adaptive order to find an available path. Both fixed routing and alternate routing are “constrained” in the sense that a path is selected from a subset of all possible paths. An unconstrained routing scheme considers all paths between the source and the destination in the routing decision. This is accomplished by executing a dynamic shortest path algorithm with link costs obtained from network state information at the time of connection

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request. We call such a scheme *adaptive unconstrained routing* (AUR).

In wavelength-routed optical networks, the routing problem consists of two components. The first is to determine a path along which the connection can be established. The second component is to assign a wavelength to the selected path. In networks without wavelength converters a call must also use the same wavelength on all links along the selected path. The wavelength assignment must be such that no two calls sharing a link are assigned the same wavelength. To find a wavelength assignment, the set of wavelengths could be searched in a fixed order (fixed search wavelength assignment) or an adaptive order (adaptive wavelength assignment).

In this paper, we will consider both fixed and adaptive wavelength assignment in conjunction with unconstrained routing. We will use the convention "path selection technique/wavelength assignment technique" to classify a wavelength-routing algorithm. These two operations may be carried out sequentially in any order, jointly, or in an alternating fashion.

Most of the routing algorithms for wavelength-routed networks proposed in the literature use some of the techniques just described. In [6] a fixed routing algorithm with fixed-order wavelength search is proposed. Birman and Kershenbaum [7] propose algorithms that are based on fixed routing and alternate routing for path selection, and wavelength reservation schemes in conjunction with threshold protection. In [8] Birman calculates approximate blocking probabilities for fixed routing with random wavelength allocation. This technique has been recently extended to alternate routing with random wavelength allocation in [9]. In [10] the routing problem is considered in the context of linear lightwave networks (LLN's). Also proposed in [10] is the concept of adaptively ordering wavelengths according to their utilization, a technique which we shall utilize in this work. In [11] unconstrained routing is used in conjunction with an exhaustive search over the wavelength set in order to evaluate the effects of wavelength converters.

In [12] lower bounds on the blocking probabilities in networks with and without wavelength converters are obtained using an integer linear programming formulation, and in [13] an integer linear programming formulation of the same problem for multihop networks is presented. In [14], a traffic model for circuit-switched all-optical networks is proposed, which is then used to calculate the blocking probability along a path for networks with and without wavelength converters.

With the exception of [11], all of this work is based on constrained path selection (mostly fixed routing) in which a path is selected from a predetermined set of candidate paths. In this work, we employ adaptive techniques for path selection which consider all paths between an s–d pair. We show that these techniques outperform their constrained counterparts without a significant increase in the computational load. We will show in Section IV that fixed-order wavelength search outperforms random wavelength assignment and, accordingly, we present an analytical method to compute approximate blocking probabilities for fixed and alternate routing with fixed-order wavelength search.

The paper is organized as follows. We propose adaptive algorithms based on unconstrained routing for joint path selection and wavelength assignment in Section II. In Section III an analysis of the blocking performance of fixed routing and alternate routing algorithms with a fixed-order wavelength search is presented. Section III also includes an extension of the analysis to networks with multiple fibers per link. Numerical results on the blocking performance are presented in Section IV. A statistical model to quantify the average-case computational complexity of the proposed adaptive algorithms is introduced in Section V. Concluding remarks are presented in Section VI.

II. ROUTING AND WAVELENGTH ASSIGNMENT ALGORITHMS

In a network with K links and W wavelengths, the state of a link $i, 0 \leq i \leq K-1$ at time t can be specified by a column vector $\sigma_t^{(i)} = (\sigma_t^{(i)}(0), \sigma_t^{(i)}(1), \cdots, \sigma_t^{(i)}(W-1))^T$, where $\sigma_t^{(i)}(j) = 1$ if wavelength λ_j is utilized by some connection at time t and $\sigma_t^{(i)}(j) = 0$ otherwise. The state of the network at time t is then described by the matrix $\sigma_t = (\sigma_t^{(0)}, \cdots, \sigma_t^{(K-1)})$. Given a connection request that arrives at time t, the routing and wavelength assignment (RWA) algorithm searches for a path $P = (i_1, i_2, \cdots, i_l)$ from the source of the request to its destination such that $\sigma_t^{(i_k)}(j) = 0$ for *all* $k = 1, 2, \cdots, l$ and *some* j. The optimal RWA algorithm minimizes the call-blocking probability among all assignments.

It is easily shown that the optimal RWA problem is NP-complete by using the results of [6] on static lightpath establishment and by restricting the general problem to tree topologies. An integer programming formulation of the optimal RWA problem in presence of deterministic traffic[1] can be found in [15]. In [16] a similar formulation combined with randomized rounding has been presented. In this paper our interest is in real-time traffic where connection requests arrive randomly and established connections are terminated after a random connection time. Given the evidence of computational complexity, the RWA with dynamic traffic is best addressed through heuristic algorithms.

In fixed routing, a single path P_{sd} is assigned to each s–d pair (s, d); this corresponds to a fixed set of columns in the state matrix σ_t. The problem then reduces to finding a row j which has zero entries in each of these columns. The search over the wavelengths (rows) may be done in a fixed order, e.g., starting with λ_0 and proceeding until an available wavelength is found. The search order may be modified dynamically according to the network state σ_t [10]. Alternate routing is similar to fixed routing except that each (s, d) pair is allocated a fixed sequence of paths. Again, the wavelength search order may be fixed or adaptive, while the path search order is fixed *a priori*.

AUR utilizes RWA algorithms that are not limited to a set of predetermined paths or search sequences. These algorithms make use of the network state σ_t at the time of connection establishment to improve the blocking performance over

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[1] Deterministic traffic is one where all connection requests arrive simultaneously, and is an appropriate model for provisioned networks.

constrained techniques. Since the search for a route and a wavelength assignment may be viewed as a search over the rows and columns of the network state matrix, there are many ways in which an RWA algorithm may proceed. We adopt the following approach—for a connection request (s, d) that arrives at time t, the rows of σ_t are searched in an adaptively varying order. Each row i specifies the available topology at the corresponding wavelength; therefore, our approach is to search sequentially[2] over the wavelength set until an available path is found (a standard shortest path algorithm is used to find a path on the effective topology). If no path is found after exhausting the wavelength set, the connection request is blocked.

We investigate five adaptive RWA algorithms by considering different sorting mechanisms of the wavelength set. The first two algorithms below use a time-varying wavelength utilization vector $U_t = (u_t^{(0)}, u_t^{(1)}, \cdots, u_t^{(W-1)})$, where $u_t^{(j)} = \Sigma_i\, \sigma_t^{(i)}(j)$ is the number of links on which the wavelength λ_j is currently used. Note that the mapping from the state σ_t to U_t is suboptimal. We shall see in Section IV that the blocking performance depends only weakly on the adaptation mechanism of the wavelength search sequence, so our heuristic mapping will be satisfactory for practical purposes. The algorithms to be considered are as follows.

1) PACK: This algorithm attempts to route the session on the most utilized wavelength first, i.e., wavelengths are searched in descending order of utilization, in order to maximize the utilization of available wavelengths.
2) SPREAD: This algorithm attempts to route the session on the least utilized wavelength first, i.e., wavelengths are searched in ascending order of utilization, in order to achieve a near-uniform distribution of the load over the wavelength set.
3) RANDOM: This algorithm searches the wavelength set in a random order with a uniform distribution over the set of all permutations.
4) EXHAUSTIVE: All of the wavelengths are searched for the shortest available path and the shortest path among them is selected.
5) FIXED: The search order is fixed *a priori*, e.g., $\lambda_0, \lambda_1, \cdots, \lambda_{W-1}$.

The first two algorithms require information about global wavelength utilization, i.e., the vector U_t. This information could be obtained through periodic exchange of local wavelength utilization among the (neighboring) nodes. Our purpose in considering PACK and SPREAD is to determine whether this effort is necessary. A scheme similar to EXHAUSTIVE was used in [11] to evaluate the effects of wavelength converters on the network performance.

Before we discuss the performance of these algorithms, we present an analytical method to compute approximate blocking probabilities for networks using two popular constrained routing techniques.

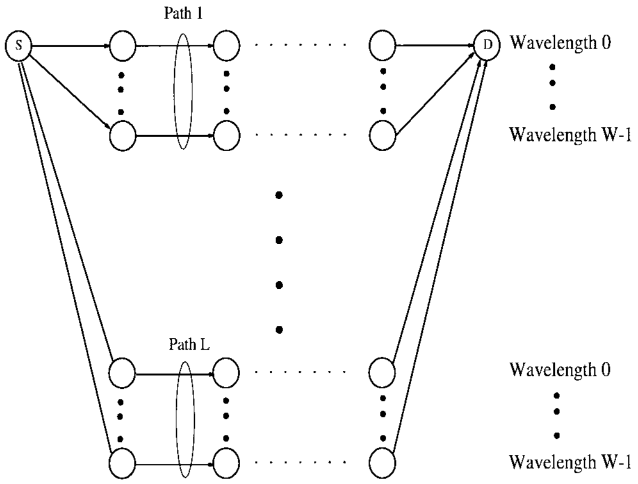

Fig. 2. A typical path tree.

III. ANALYSIS OF FIXED AND ALTERNATE ROUTING

In this section we present a method for obtaining approximate blocking probabilities for all-optical networks that use fixed and alternate routing in conjunction with a fixed-order search of the wavelength set. We first consider the case in which the nodes are interconnected by single-fiber links. We then generalize the analysis to the case where the nodes are interconnected by multiple fibers.

A. Single-Fiber Networks

In [8] an analytical approach for the computation of blocking probabilities with fixed routing was presented. The computation was based on the assumption of random wavelength allocation. In [9] this approach was extended to alternate routing with limited reservations; this work was also based on random wavelength allocation. We are interested in a fixed-order search of the wavelength set since it results in lower blocking probabilities than the random wavelength selection policy. The technique presented in [8] is not suitable to analyze the fixed-order search over the wavelength set, so we propose using another technique based on the Erlang fixed-point method for alternate routing [5].

In common implementations of alternate routing every s–d pair is assigned a set of L alternate paths (usually the shortest L paths in the physical topology) that is searched in a fixed order. We assume that these L paths are edge-disjoint, a feature that enhances fault tolerance of the routing algorithm against link failures. On each path, the wavelength set is searched in a fixed order to find a wavelength along which the call could be established. The search for a path and a wavelength may be viewed as a search over a sequence of LW logical paths, where a logical path is the combination of a physical path and a particular wavelength. If the logical path under consideration is available, then the connection is established. Otherwise, the connection request *overflows* to the next logical path. The connection is blocked if it overflows from the last logical path in the route tree. Fig. 2 shows a typical route tree for an s–d pair.

This structure is similar to that of alternate routing in circuit-switched networks. The method for computing approximate

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[2] It is conceptually simpler to view the search over the wavelength set as a sequential search. In implementation, the search can be done in parallel.

blocking probability that we present below is an adaptation of the corresponding techniques in [5] and [17].

The call arrival process is assumed to be a Poisson process with an average arrival rate of β_r for the rth s–d pair. The call holding times are exponentially distributed with mean $1/\mu_r$. Let $\alpha^r = \beta_r/\mu_r$.

Let K be the number of links in the network and let R be the number of s–d pairs in the network. Let S denote the $K \times RL$ link-path incidence matrix, defined as

$$S_{ij} = \begin{cases} 1, & \text{if link } i \text{ is utilized on the path } j \\ 0, & \text{otherwise} \end{cases}$$

where the first L columns correspond to the set of alternate paths for the first s–d pair, etc.

We will use r as the running index for s–d pairs, l as the running index for physical alternate paths, i as the running index for the logical paths (combination of physical paths and wavelengths), w as the running index for the wavelengths, and z as the running index for the links. Let A_i^r denote the offered traffic to the ith logical path for the rth s–d pair. Let a_{zw}^{rl} be the offered traffic to wavelength w on link z due to traffic from the rth stream on the lth alternate path, and let a_{zw} be the offered traffic to the wavelength w on link z due to all traffic streams, i.e.,

$$a_{zw} = \sum_{r=1}^{R}\sum_{l=1}^{L} a_{zw}^{rl}.$$

If x denotes an offered traffic quantity, we use $\overline{x}$ to denote the corresponding quantity for the carried traffic. We define P_i^r as the blocking probability on the ith logical path of traffic stream r, F_i^r as the probability that a call from the rth traffic stream overflows to the ith logical path, and B_{zw} as the probability of utilization of wavelength w on link z.

The state of each link z is represented by a W-component binary vector $\sigma^{(z)}$, where the ith entry $\sigma^{(z)}(i) = 0$ indicates that wavelength i on link z is idle and $\sigma^{(z)}(i) = 1$ indicates that it is busy. The probability of the event $\sigma^{(z)}(i) = 1$ is given by B_{zi}. The state vector entries of a link are assumed to be statistically independent, but not identically distributed due to the asymmetry induced by the fixed-order wavelength search. We assume that the link-blocking events are independent; however, link loads are not independent, i.e., we take into account the wavelength continuity constraint in obtaining the offered traffic for the links. These independence assumptions are standard in blocking analysis of circuit-switched networks [8], [9], [14].

To compute the blocking probabilities, we first set $A_0^r = \alpha^r$ and $F_0^r = 1$. Then, for all s–d pairs, we scan the route trees and for each logical path $(i = 0, 1, \cdots, LW - 1)$ execute the following procedure.

1) Approximate the carried load for the rth stream on the ith logical path by

$$\overline{A}_i^r = A_i^r(1 - P_i^r) = A_i^r \prod_{k=0}^{K-1} (1 - B_{k,i \bmod W})^{S_{k,(r-1)L+\lfloor i/W \rfloor}}$$

for all streams $r = 1, 2, \cdots, R$. This expression assumes that the link-blocking events are independent.

2) Use the fact that the traffic carried by a link on a logical path due to stream r is the same as the rth stream carried traffic on that logical path to obtain

$$a_{z,i \bmod W}^{rl} = \frac{\overline{a}_{z,i \bmod W}^{rl}}{(1 - B_{z,i;\bmod W})} = \frac{A_i^r \prod_{k=0}^{K-1} (1 - B_{k,i \bmod W})^{S_{k,(r-1)L+\lfloor i/W \rfloor}}}{(1 - B_{z,i \bmod W})} \tag{1}$$

for all links z on the lth alternate path of the traffic stream r.

3) Next, compute the probability of overflow and the offered traffic to the $(i+1)$th logical path for traffic stream r as

$$F_{i+1}^r = F_i^r \, P_i^r$$
$$A_{i+1}^r = A_i^r \, P_i^r.$$

This procedure is repeated until all logical paths of all s–d pairs have been processed. At the termination of this procedure, the total offered load a_{zw} for each z and w is given as a function of the link-blocking probabilities B_{zw}.

The link-blocking probability is then approximated[3] by the Erlang loss formula $E(A, N) = A^N/N!/\Sigma_{i=0}^N A^i/i!$ as

$$B_{z,w} = E(a_{zw}, 1) = \frac{\sum_{r=1}^{R}\sum_{l=1}^{L} a_{zw}^{rl}}{1 + \sum_{r=1}^{R}\sum_{l=1}^{L} a_{zw}^{rl}}. \tag{2}$$

Equations (1) and (2) define a set of nonlinear equations which must be solved to determine B_{zw} for all z and all w.

Once the B_{zw}'s are obtained, the call-blocking probability of the rth stream is found as $P_B^r = F_{LW}^r$ and the average call-blocking probability is given by

$$P_{av} = \frac{\sum_{r=1}^{R} P_B^r \alpha^r}{\sum_{r=1}^{R} \alpha^r}.$$

Note that the system of nonlinear equations is of the form $B_{zw} = a_{zw}(\boldsymbol{B})/1 + a_{zw}(\boldsymbol{B})$, where $\boldsymbol{B} = (B_{00}, \cdots B_{K-1,0}, \cdots, B_{0,W-1}, \cdots, B_{K-1,W-1})$. An iterative procedure described by

$$B_{zw}(n+1) = \frac{a_{zw}(\boldsymbol{B}(n))}{1 + a_{zw}(\boldsymbol{B}(n))}$$

is used in step 3 to solve this nonlinear system. The iterations are carried out until $\boldsymbol{B}(n+1)$ and $\boldsymbol{B}(n)$ are within a prescribed tolerance. The results of this numerical procedure will be described in the Section IV. While numerical results will be obtained for the case of uniform traffic, the method is equally applicable to nonuniform traffic. The procedure above includes fixed routing as a special case with $L = 1$.

[3] Overflow traffic is not Poisson.

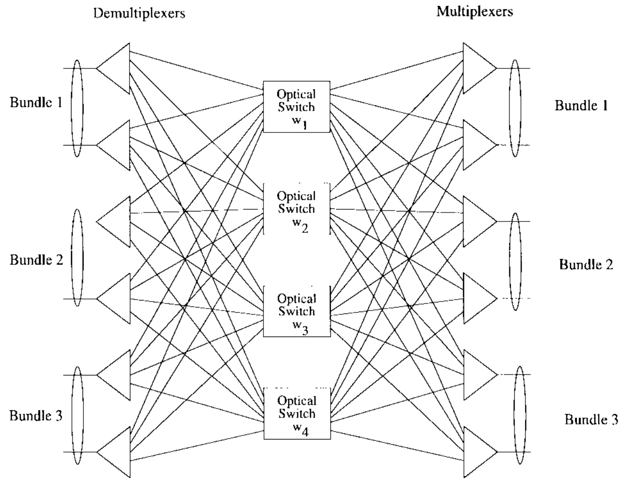


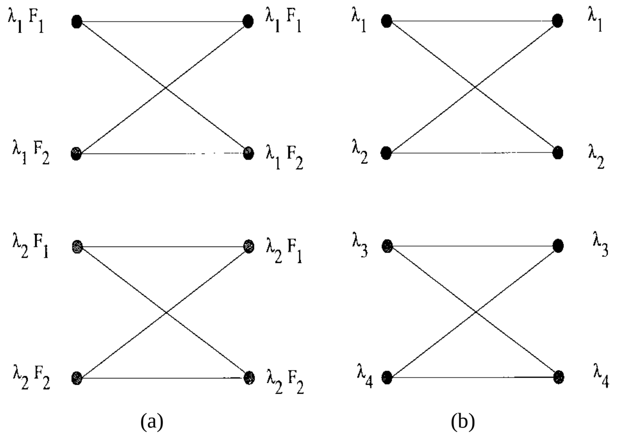
Fig. 3. Wavelength-routing node of degree three, $M = 2$ fibers, and four wavelengths.

B. Networks with Multiple-Fiber Links

Most of the previous work on routing and wavelength assignment focuses on single-fiber networks. There has been a recent interest in assessing the performance improvement due to the deployment of multiple fibers between node pairs [18]–[20]. This interest is motivated by the economic advantage of installing bundles of fibers for the purposes of fault tolerance and future network growth. We refer to a network that utilizes multiple fibers per link as a multifiber network. A wavelength-routing node of nodal degree three, and with two fibers and four wavelengths, is depicted in Fig. 3. In general, such a wavelength-routing node without wavelength conversion capability requires W optical switches of size $M\delta \times M\delta$, where M is the number of fibers used and δ is the nodal degree. An important design issue is to determine whether the increased cost of switching in multifiber networks trades off favorably with improved performance.

A multifiber network is an attractive alternative to a network with wavelength conversion capability. An M-fiber W-wavelength network is functionally equivalent to an MW-wavelength network with partial wavelength conversion of degree M. The latter network is one in which a signal on a wavelength can be converted to one of M wavelengths [18]. Both networks have the connectivity pattern shown in Fig. 4. The benefits of wavelength conversion at the wavelength-routing nodes have been considered by many authors [14], [21]–[25]. Multifiber networks may provide a viable and economical alternative to wavelength conversion.

The blocking analysis of a single-fiber network presented in Section III-A generalizes to a multifiber network with a slight modification. Here each logical link has a capacity of M; therefore, (2) is modified as $B_{zw} = E(a_{zw}, M)$ and the blocking probability is obtained using the same procedure outlined in Section III-A. The performance prediction of the analysis presented in this section will be compared with simulation results in Section IV and the benefits of multifiber networks with fixed and alternate routing will be assessed.



(a) (b)

Fig. 4. The connectivity pattern of a wavelength-routing network. (a) Multifiber network with $M = 2, W = 2$. (b) Partially wavelength-converting network with conversion degree two and $W = 4$.

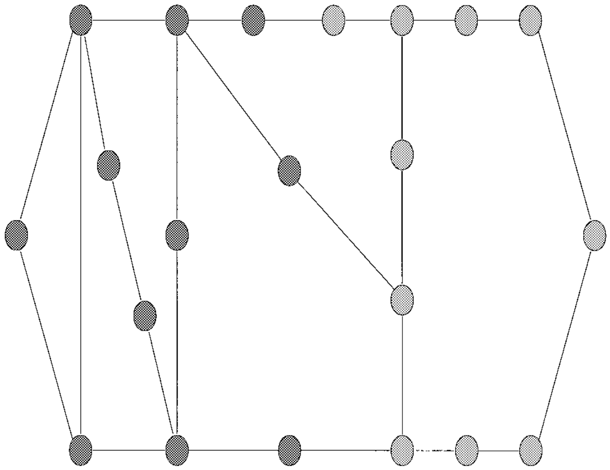


Fig. 5. The ARPA-2 network.

IV. Numerical Results

We evaluate the performance of the proposed adaptive RWA algorithms on two networks. The first network is the ARPA-2 network shown in Fig. 5, which has 21 nodes and 26 links. The second network has a randomly generated topology, shown in Fig. 6, with 15 nodes and 32 links.

We use a dynamic traffic model in which call requests arrive at each node according to a Poisson process with a network-wide arrival rate β. An arriving session is equally likely to be destined to any node in the network. The session holding time is exponentially distributed with mean $1/\mu$. Thus, the load per s–d node pair is $\rho = \beta/N(N-1)\mu$. Note that a node may engage in multiple sessions, and parallel sessions may be conducted between an s–d node. The results to be described below are obtained via extensive simulations unless otherwise noted.

First, we examine the performance of AUR in conjunction with the wavelength assignment schemes Pack, Random, and Spread. Figs. 7 and 8 show the call-blocking probability as a function of the load ρ (per s–d pair) for AUR/Pack, AUR/Random, and AUR/Spread for the ARPA-2 network with four and eight wavelengths, respectively. The Pack scheme has the best performance, followed by Random, and then by Spread. Similar behavior is observed in Figs. 9 and

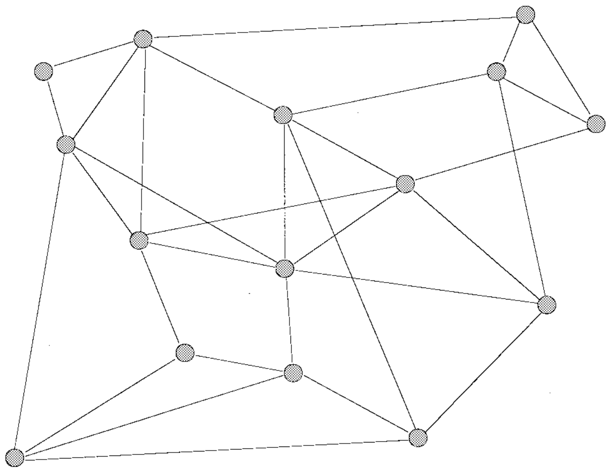


Fig. 6. A randomly generated topology.

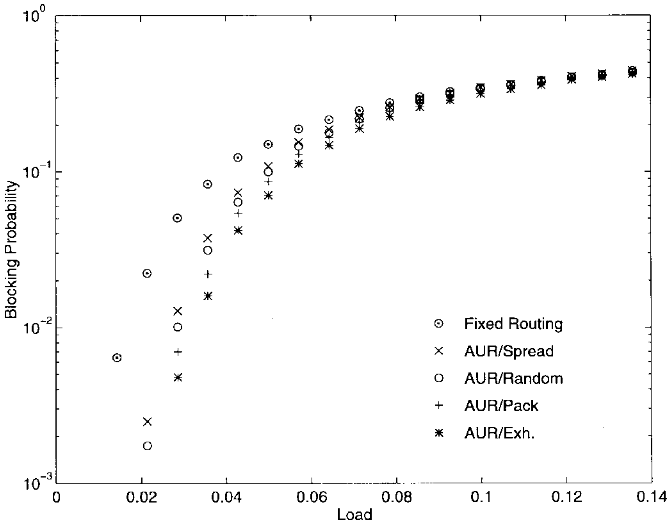


Fig. 7. Blocking probabilities for the ARPA-2 network with four wavelengths.

10 which depict the call-blocking probability for the random network with four and eight wavelengths, respectively. PACK maximizes the utilization of available wavelengths, while SPREAD reduces the probability of finding a route for a given session by evenly distributing the load over the wavelengths. RANDOM effectively equalizes the load on the wavelengths and therefore has a performance which is close to, but better than, SPREAD. When the number of wavelengths is small, the performance of the three wavelength assignment schemes are nearly identical, indicating that the blocking probability is determined primarily by resource limitations and not by the wavelength allocation scheme implemented. However, as the number of wavelengths increases, PACK outperforms the other schemes by a significant margin. For example, with ARPA-2, at a blocking probability of 10^{-2}, the network throughput can be increased by 15% over RANDOM when there are eight wavelengths. Figs. 7–10 also show the performance of AUR/EXHAUSTIVE scheme, which slightly outperforms PACK; however, the improvement is not significant in light of its higher computational complexity.

Figs. 11 and 12 compare the call-blocking probabilities for AUR/PACK and AUR/FIXED for the ARPA-2 network and the

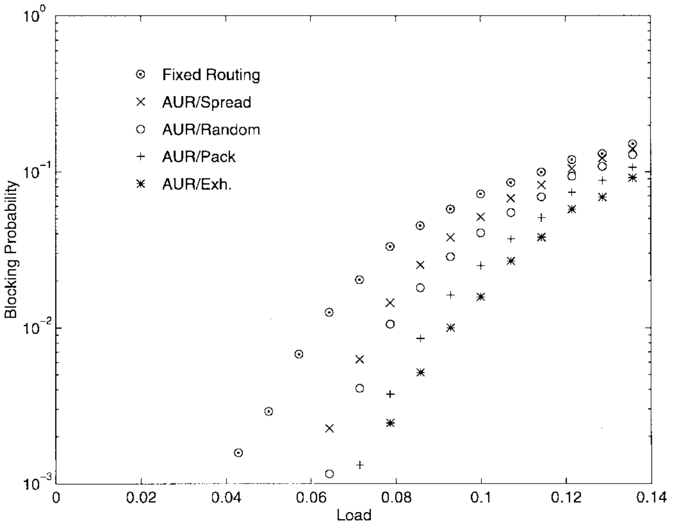


Fig. 8. Blocking probabilities for the ARPA-2 network with eight wavelengths.

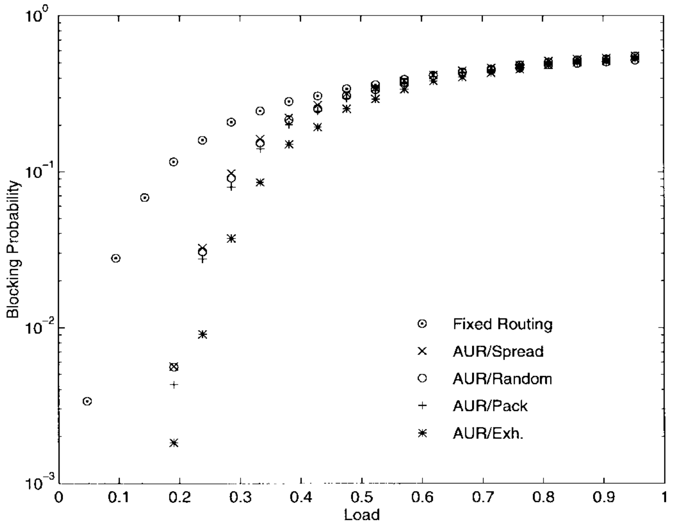


Fig. 9. Blocking probabilities for the RANDOM network with four wavelengths.

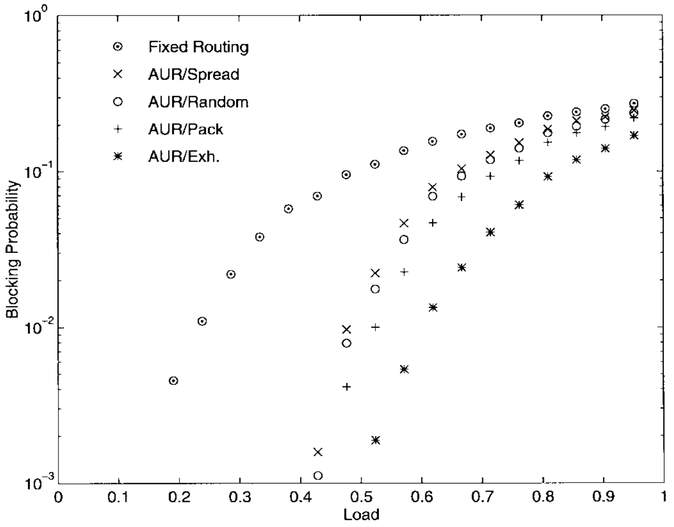


Fig. 10. Blocking probabilities for the RANDOM network with eight wavelengths.

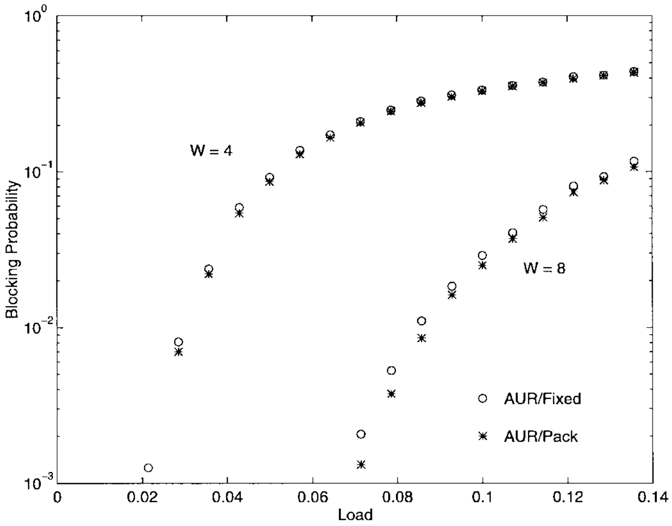


Fig. 11. Blocking probabilities with AUR/PACK and AUR/FIXED for the ARPA-2 network.

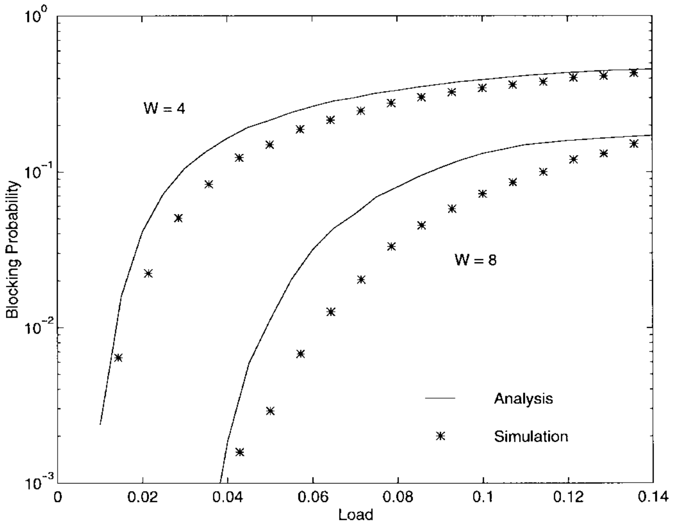


Fig. 13. Analysis and simulation of blocking probabilities for the ARPA-2 network.

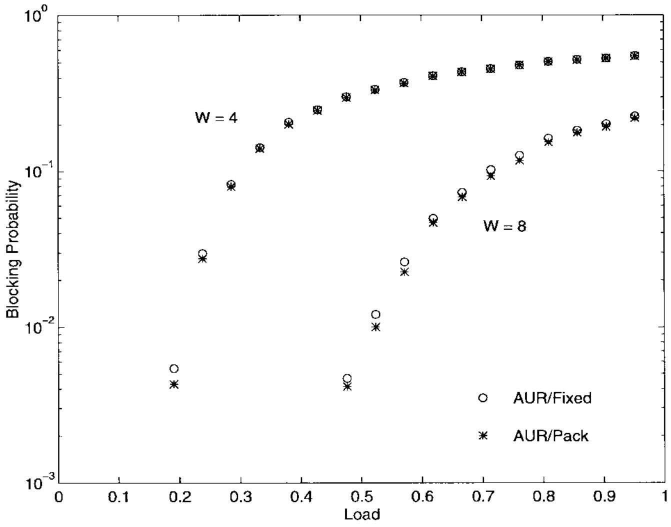


Fig. 12. Blocking probabilities with AUR/PACK and AUR/FIXED for the random network.

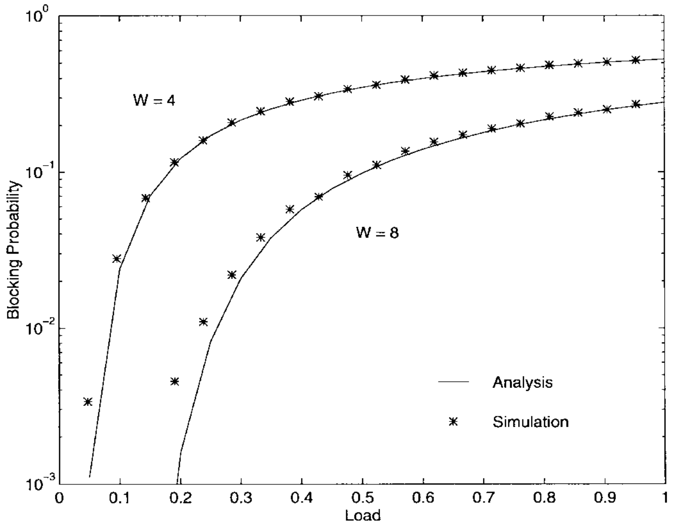


Fig. 14. Analysis and simulation of blocking probabilities for the random network.

random network, respectively. These results indicate that performance of FIXED is very close to that of PACK. This is because FIXED tends to assign most sessions to wavelengths that are searched first, thereby approximating PACK. Based on these results, AUR/PACK and its variant AUR/FIXED appear to achieve a good compromise between good blocking performance and, as will be seen in Section V, moderate complexity.

Next, we examine the relative performance of constrained versus unconstrained routing techniques. Figs. 7 and 8 depict the performance of fixed routing with fixed-order wavelength search along with unconstrained schemes for the ARPA-2 network. It is clear that unconstrained path selection is superior to its constrained counterpart in the load range of interest. This is because, at light loads, there is no need to restrict sessions to a predetermined set of shortest paths since the network resources are underutilized and using longer paths will not lead to congestion. Figs. 9 and 10, which show the same results for the random network, indicate that the performance gap is even larger in this case. This is due to the fact that the random network is denser than ARPA-2 and that unconstrained routing techniques benefit from the resulting multiplicity of paths.

In Figs. 13 and 14 we compare blocking performance of fixed routing with fixed-order wavelength search obtained using the analysis of Section III with simulation results. The figures indicate that the proposed method for performance evaluation is quite accurate for a small number of wavelengths. Recall that the model assumes Poisson arrivals at all logical links. This assumption fails to hold for logical alternate paths since they receive overflow traffic exclusively [5]. This effect is emphasized as the number of wavelengths increases, as successive overflows further deviate from Poisson statistics. It is also observed that the performance prediction is significantly more accurate for the random network. The ARPA-2 network has longer hop lengths than the random network, which might impair the quality of the link independence approximation.

Next, we investigate the performance of alternate routing with a fixed-order wavelength search. Figs. 15 and 16 compare

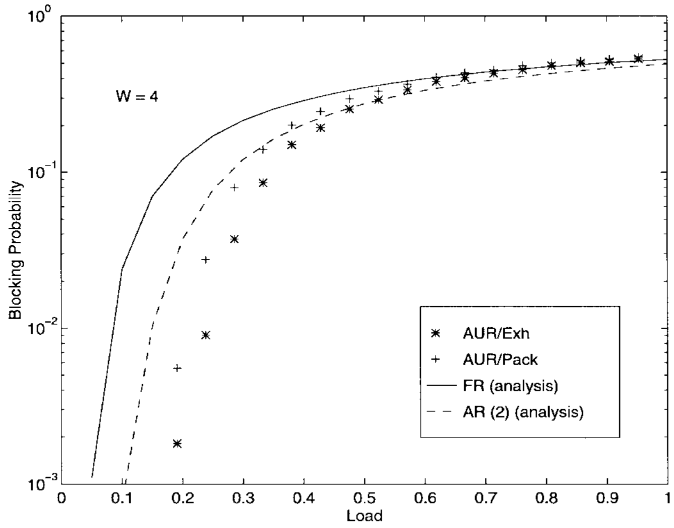


Fig. 15. Blocking probabilities for the random network with $W = 4$.

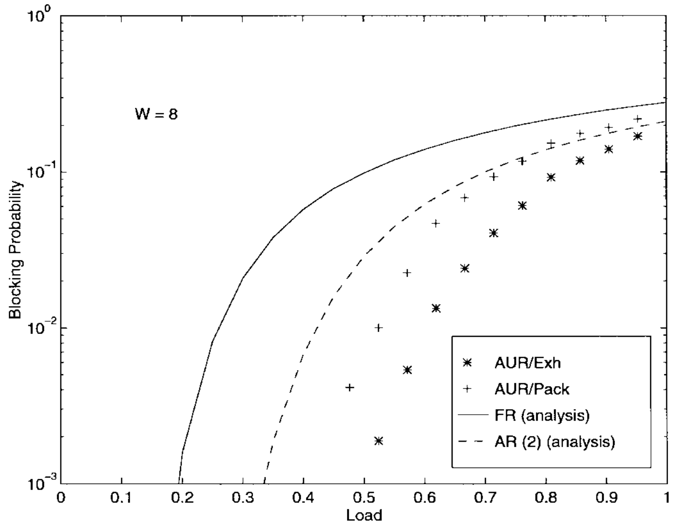


Fig. 16. Blocking probabilities for the random network with $W = 8$.

the performance of alternate routing with that of fixed routing and two unconstrained routing schemes. It is seen that alternate routing with two fixed candidate paths between each s–d pair results in a large reduction in the blocking probability. For example, with $W = 8$ and at a blocking probability of 10^{-3}, there is a 70% increase in the network throughput relative to fixed routing. While the throughput gap between alternate routing and unconstrained routing is significant, it is less than 50% of the gap with fixed routing. As expected, the performance improvement is more pronounced with a large number of wavelengths. These results indicate that alternate routing may be a practical tradeoff between fixed routing and AUR.

Finally, we consider the benefits of using multiple fibers in conjunction with fixed routing and alternate routing. Fig. 17 shows the blocking probability with one and two fibers per link for the random network. As expected, the blocking performance improves dramatically with the use of two fibers. The throughput increases by an approximate factor of four in both routing schemes. Furthermore, the throughput gain with alternate routing becomes more significant with two fibers.

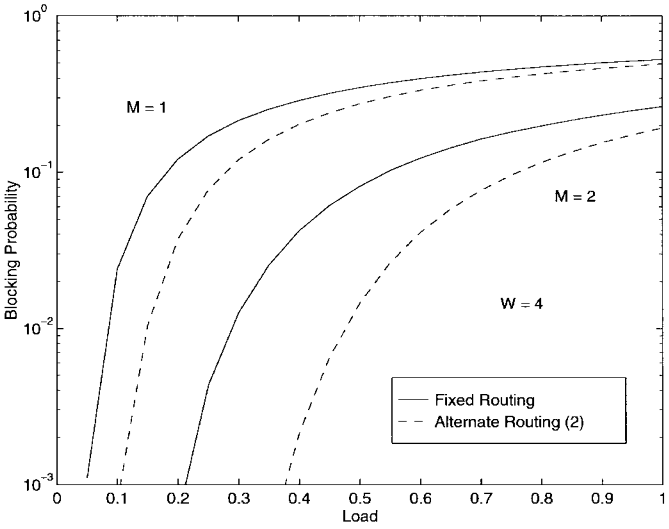


Fig. 17. Blocking probabilities for the random network with multiple fibers.

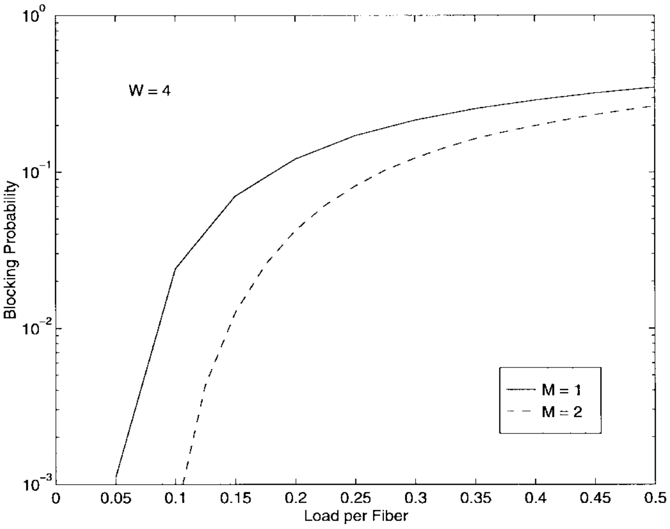


Fig. 18. Blocking probabilities with fixed routing as a function of the load per fiber for the random network.

Fig. 18 plots the blocking probability as a function of the load per fiber. It is observed that the two-fiber network can handle double the load of a single-fiber network (same load per fiber) at a much better blocking performance. This is the statistical multiplexing gain achieved by combining the network resources, in this case, fibers. Similar improvements are observed for alternate routing.

We have discussed earlier that doubling the number of fibers per link is akin to doubling the number of wavelengths per link, with the additional advantage of simulating a "partial wavelength conversion" capability. Consequently, a network with $W = 4$ and two fibers performs slightly better than one with $W = 8$ and a single fiber. This effect is shown in Fig. 19.

V. COMPLEXITY ANALYSIS

An important issue in choosing a routing and wavelength assignment scheme for implementation is the time complexity. All of the AUR schemes we have considered are based on sequential search of the wavelength set to find the shortest path in the dynamic topology. In the worst case, all algorithms

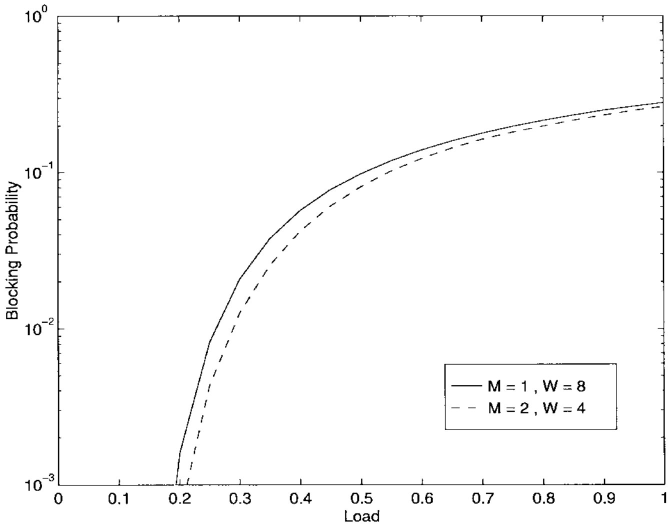


Fig. 19. Effect of simulated "partial wavelength capability" provided by multifiber networks on the blocking probability with fixed routing for the random network.

will search W wavelengths; therefore, they all have the same worst-case complexity. However, their average-case complexities will be different as PACK is more likely to fail to find a path in the first few wavelengths than RANDOM or SPREAD. Our goal in this section is to introduce an analytical model to quantify the average complexity of the RWA schemes. The model is based on order statistics and assumes a compound stochastic model for call blocking.

We measure the complexity of a wavelength assignment scheme by the average number of searches over the wavelength set to establish a typical connection. We assume that the blocking events at different wavelengths are statistically independent. Furthermore, the blocking probability Q_i at wavelength i will be modeled as a random variable with probability density function $p(\alpha)$ and probability distribution function $P(\alpha)$. Therefore, the blocking probability vector $\vec{Q} = (Q_1, Q_2, \cdots, Q_W)$ has the probability density function

$$p_{\vec{Q}}(\alpha_1, \cdots, \alpha_W) = \prod_{i=1}^{W} p(\alpha_i).$$

A given RWA searches the wavelength list $w = (1, 2, \cdots, W)$ in some adaptive permutation $\pi(w)$. Let B_i be the blocking probability of the ith wavelength in $\pi(w)$. Also, let K be the number of searches necessary to find an available wavelength. It can be shown that the average complexity is given by

$$E[K] = 1 + \sum_{n=1}^{W-1} E\left[\prod_{i=1}^{n} B_i\right]. \tag{3}$$

Given the distribution $P(\alpha)$ and the mapping between $\{Q_i\}$ and $\{B_i\}$, the average complexity can be determined from (3). The latter depends on the wavelength assignment scheme in use. For PACK, B_i is monotonically decreasing in i. Accordingly, we use $B_i = Q_{(W-i+1)}$, where $Q_{(i)}$ is the ith-order statistics of $\vec{Q}$, i.e., $Q_{(1)} \le Q_{(2)} \le \cdots \le Q_{(W)}$. Similarly, for SPREAD, we use $B_i = Q_{(i)}$. Finally, for RANDOM, $B_i = Q_i$.

TABLE I

Blocking Probability	Pack Sim.	Pack Model	Random Sim.	Random Model	Spread Sim.	Spread Model	Fixed Sim.
0.005	0.4896	0.4034	0.2959	0.3416	0.2778	0.2871	0.4702
0.010	0.5201	0.4442	0.3161	0.3638	0.2905	0.2969	0.4941
0.050	0.6088	0.5959	0.3975	0.4487	0.3500	0.3390	0.5875

TABLE II

Blocking Probability	Pack Sim.	Pack Model	Random Sim.	Random Model	Spread Sim.	Spread Model	Fixed Sim.
0.0002	0.3883	0.2795	0.1505	0.1865	0.1365	0.1369	0.3611
0.0006	0.4154	0.3245	0.1610	0.2015	0.1434	0.1401	0.3780
0.0020	0.4471	0.3930	0.1766	0.2310	0.1519	0.1447	0.4113

Let $a = \int_0^1 \alpha \, dP(\alpha)$ be the average blocking probability at a randomly selected wavelength. The overall blocking probability P_b is then given by $P_b = a^W$. Therefore, at a given traffic load, the mean of $P(\alpha)$ is fixed at $P_b^{1/W}$. The distribution $P(\alpha)$ may be empirically determined subject to this mean constraint. In obtaining our numerical results we use a uniform distribution on $(0, 2a)$. Then we obtain [26] for PACK

$$E[K] = 1 + \sum_{k=1}^{W-1} \frac{W!}{(W-k)!} \frac{(W+k-1)!!}{(W-k-1)!!} (2a)^k$$

and for SPREAD

$$E[K] = 1 + \sum_{k=1}^{W-1} \frac{W!}{(W-k)!} (2k-1)!!(2a)^k$$

where $(2j-1)!! = 1 \cdot 3 \cdots (2j-1)$ and $(2j)!! = 2 \cdot 4 \cdots (2j)$. The average complexity for RANDOM is given by

$$E[K] = \frac{1-a^W}{1-a}.$$

Tables I and II compare the analytical complexity model with simulations for four and eight wavelengths, respectively. The entries in the tables are the average number of wavelength searches normalized by the number of wavelengths. The model correctly predicts that SPREAD is the most efficient, closely followed by RANDOM, and then PACK. Simulations, however, indicate that the order statistics model is more suitable for SPREAD and RANDOM than it is for PACK. This is because these two schemes tend to distribute the load evenly over the wavelengths. This agrees with our assumption that the call-blocking probabilities at different wavelengths are identically distributed. Note that the normalized number of wavelength searches for EXHAUSTIVE is always one. As expected, FIXED has a computational complexity close to, but lower than, that of PACK.

VI. CONCLUSIONS

Through analytical modeling and extensive computer simulations, we have studied the effects of routing and wavelength assignment algorithms in circuit-switched all-optical WAN's. We have followed a routing approach in which we consider *all paths* connecting an s–d pair as candidate paths and incorporate network state information in the route selection process. The results indicate that the choice of routing and wavelength assignment algorithms affects the blocking performance considerably, especially with light load and relatively large number of wavelengths. The use of unconstrained routing yields significant improvements in the call-blocking performance over traditional constrained routing techniques. In particular, AUR outperforms fixed routing by a significant margin. AUR also performs better than alternate routing; however, as the number of alternate routes increases, the performance approaches that of AUR. The performance gains with adaptive routing are more pronounced in denser network topologies as AUR takes advantage of higher network connectivity. Incorporating network state information about wavelength utilization into the wavelength selection process is of secondary importance as it results in marginal improvements in the call-blocking probability. When the wavelength set is searched in a fixed order, the blocking performance is very close to schemes that search the wavelength set in an adaptive order. Complexity analysis of adaptive routing algorithms indicates that they achieve good results with a moderate increase in complexity. In light of the fact that optimal routing in wavelength-routed networks is computationally intractable, suboptimal adaptive routing techniques achieve the desired balance between performance and complexity.

We have also presented an analytical method for computing approximate blocking probabilities for networks using fixed routing and alternate routing with a fixed-order wavelength search. Alternate routing is found to be a good tradeoff between fixed routing and AUR. The analytical method is applicable to networks with multiple fibers per link. Multifiber networks are an attractive alternative for networks with wavelength conversion capability. The results indicate significant performance gains with two fibers per link over single-fiber links.

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