Dynamic Wavelength Routing Using Congestion and Neighborhood Information

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Abstract— **In this paper, we present two dynamic routing algorithms based on path and neighborhood link congestion in all-optical networks. In such networks, a connection request encounters higher blocking probability than in circuit-switched networks because of the wavelength-continuity constraint. Much research has focused on the shortest-path routing and alternate shortest-path routing. We consider fixed-paths least-congestion (FPLC) routing in which the shortest path may not be preferred to use. We then extend the algorithm to develop a new routing method: dynamic routing using neighborhood information. It is shown by using both analysis and simulation methods that FPLC routing with the first-fit wavelength-assignment method performs much better than the alternate routing method in mesh-torus networks (regular topology) and in the NSFnet T1 backbone network (irregular topology). Routing using neighborhood information also achieves good performance when compared to alternate shortest-path routing.**

Index Terms— **Alternate shortest-path routing, circuit switching, neighborhood-information-based routing, wavelength routing.**

I. INTRODUCTION

WE STUDY routing algorithms in all-optical networks using wavelength division multiplexing (WDM) and wavelength routing in WAN's. One of the main requirements in such networks is that the same wavelength must be assigned to a connection on every link on a path if wavelength converters are not available at the switching nodes. A connection request encounters higher blocking probability than it does in circuit-switched networks because of the wavelength-continuity constraint. Routing and wavelength assignment algorithms play a key role in improving the performance of WDM networks [1], [2]. Many researchers have proposed the use of the shortest-path (SP) routing and alternate shortest-path (ASP) routing. In [3]–[5], [17] the performance of the SP and ASP routing methods are investigated through approximate analysis and simulation. Since the shortest paths are statically computed and an attempt is made to set up a connection request on fixed paths without acquiring the information of current network status, it is not possible to further improve the network performance in terms of blocking probability by using these routing approaches.

Dynamic routing approaches are more efficient than static routing methods. In [5], [6], [16], [17], simulation results show that the dynamic routing method can significantly improve the network performance compared to the SP and the ASP. Routing and wavelength assignments are considered jointly and adaptively in [7], [16]. All feasible paths between a source–destination pair are computed, and one of them is selected according to a specific criterion to set up a request. Least-loaded routing (LLR) algorithms are introduced as dynamic routing methods in [3], [8]. However, only fully connected networks are investigated and no performance comparison is provided between LLR and static routing algorithms in these papers. Dynamic routing methods are also discussed in [9]. The main problems with these dynamic-routing methods are longer setup delays and higher control overheads, including the introduction of a central control node that keeps track of the network's global state.

In this paper, we consider alternate dynamic routing algorithms in all-optical networks. We first introduce a dynamic routing algorithm, called fixed-paths least-congestion (FPLC) routing, and compare its performance to that of the SP and the ASP. This algorithm routes a connection request on the least-congested path out of a set of predetermined paths. A set of routes[1] connecting the source–destination pair are searched in parallel, and the route with the maximum number of idle wavelengths is selected to set up the connection. If a request cannot be accommodated by any of the routes, it is blocked.

The FPLC still has higher setup delay and higher control overhead. To overcome these shortcomings, a new routing method using neighborhood information is also proposed and investigated in this paper. In this method, for each source–destination pair, a set of preferred paths are precomputed and stored at the source. Moreover, instead of searching all the links on the preferred routes for availability of free wavelengths, only the first k links on each path are searched. A route is selected based on the availability of free wavelengths on the first k links on the preferred paths. If several free wavelengths are available on the selected route, a wavelength is selected according to a pre-specified wavelength assignment algorithm. If no free wavelengths are available on the first k links of all the preferred routes, the request is blocked. An essential observation here is that the parameter k depends on the diameter and topology of the network and the network performance requirement. It is shown that a value of $k = 2$ is generally enough to ensure good network performance in

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[1] The words "path" and "route" are used interchangeably throughout this paper.

a 4 × 4 mesh-torus network and in the NSFnet T1 backbone network.

Several approximate analytical methods on the blocking probabilities of networks are proposed in the literature. In [4], [11], two models to compute the approximate blocking probability are presented. However, these models are inappropriate for networks with sparse topologies because they do not consider the correlation among the use of wavelengths between successive links of a path. An improved model with the consideration of this dependence is proposed in [12]. A Markov-chain-based reduced-load model with a state-dependent arrival rate is presented in [3]. A more accurate model with modest complexity in [15] accounts for link-load correlation. We use and extend the link-load correlation model to analyze the approximate performances of our algorithms.

This paper is organized as follows. In Section II, we introduce a new analytical model to compute the blocking performance of the FPLC. To our knowledge, this is the first analytical model that can be used not only in regular networks, but irregular networks with FPLC routing. Routing using neighborhood information is introduced and analyzed in Section III. Section IV presents numerical results of the routing algorithms. The routing algorithms are compared to the SP and ASP with different wavelength assignment methods in both mesh-torus networks and the NSFnet T1 backbone network. Our conclusions are presented in Section V.

II. FIXED-PATHS LEAST-CONGESTION ROUTING

In FPLC routing, we first statically compute a set of routes to be used for each source–destination pair in a network and store the routes information at each source node. Upon arrival of a connection setup request, the source node searches the available number of wavelengths on the routes in parallel by sending *needle packets*[2] requesting a path setup toward the destination node. At the destination node, a route with the maximum number of idle wavelengths is selected to set up the connection. If no wavelength is available on any of the routes, the request is blocked. In this paper, we only use two edge-disjoint shortest paths for the analysis and simulation. We refer to these routes as the first and second route. The length of the first route is less than or equal to that of the second route. If two routes have the same number of idle wavelengths, the first route is selected to set up the request. We restrict the number of preferred routes to two because network resources cannot be used efficiently if many longer routes are allowed in the network. One reason that the two routes are required to be edge-disjoint is that we try to search two paths in parallel. Another consideration is fault tolerance. If one path fails, the connection can be rerouted to another path [18], [19]. We also noticed that using more than two paths do not significantly improve performance [6], [17]. The detailed rules of the routing algorithm are presented in [20]. In this section, we analyze the FPLC routing algorithm, using and extending the link load correlation model presented in [15]. The numerical results and performance comparisons are presented in Section IV.

A. Analysis of the FPLC Routing

We assume that call requests arrive at each node according to a Poisson process with rate λ. The destination of a call is uniformly distributed to other nodes. Call holding time is exponentially distributed with mean $(1/\mu)$. The number of wavelengths F is same on all links. Wavelengths are randomly assigned to a session from the set of free wavelengths on the associated path.

The basic idea of the link-load correlation model is that the blocking probability on a two-hop path can be computed with the consideration of link-load correlation. Then the blocking probability on a l-hop path can be computed recursively by viewing the first $l-1$ hops as the first hop and the lth hop as the second hop of a two-hop path. For lack of space, we omit the details of the correlation model and refer the reader to [15]. The following steady-state probabilities are defined to obtain the blocking probabilities in the correlation model.

- $S(y_f|x_{pf}) = \Pr\ \{y_f$ wavelengths are free on a link of a path $|x_{pf}$ wavelengths are free on the previous link of a path$\}$.
- $U(z_c|y_f, x_{pf}) = \Pr\ \{z_c$ calls (wavelengths) continue to the current link from the previous link $|y_f$ wavelengths are free on the current link, and x_{pf} wavelengths are free on the previous link$\}$.
- $R(n_f|x_{ff}, y_f, z_c) = \Pr\ \{n_f$ wavelengths are free on a two-hop path $|x_{ff}$ wavelengths are free on the first hop, y_f wavelengths are free on the second hop, and z_c calls use both hops$\}$.
- $T_P^{(l)}(n_f, y_f) = \Pr\ \{n_f$ wavelengths are free on an l-hop path P and y_f wavelengths are free on hop $l\}$.

We know from [15] that we get (1), found at the bottom of the page. Let $Q_P(w_f)$ be the probability that w_f wavelengths are free on a path P with length $l(P)$. $Q_P(w_f)$ becomes

$$Q_P(w_f) = \sum_{y_f=0}^{F} T_P^{(l(P))}(w_f, y_f). \tag{2}$$

A fundamental assumption made in the correlation model is that the path used by a call does not depend on the state of the links on the path. For a fixed shortest-path routing on regular networks, it is possible to assume that the effect of blocking probability on the carried load can be neglected, and the arrival rate on each link is the same for keeping the analysis simple.

$$T^{(l)}(n_f, y_f) = \sum_{x_{pf}=0}^{F} \sum_{x_{ff}=0}^{F} \sum_{z_c=0}^{\min(F-x_{pf}, F-y_f)} R(n_f|x_{ff}, z_c, y_f)U(z_c|y_f, x_{pf})S(y_f|x_{pf})T^{(l-1)}(x_{ff}, x_{pf}). \tag{1}$$

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[2] The *needle packets* can be sent out through a control network, either out-of-band or inband, as proposed in [13].

However, these assumptions become invalid when the FPLC is used. In this case, a path for a request is selected using the current network status. Thus, the arrival rate on each link is continuously changing. No steady state is reached in the strict sense when the FPLC is used. We propose to use a technique based on the Erlang fixed-point method for alternate routing [10] to solve this problem. We need the following further notations.

- Let $R_j^{(1)}$ be the set of first-shortest routes that employ link j, and $R_j^{(2)}$ be the set of second-shortest routes that employ link j.
- Let $R_{i,j}^{(1)}$ be the set of first-shortest routes that have a subset of route from link i to j. Let $R_{i,j}^{(2)}$ be the set of second-shortest routes that have a subset of route from link i to j.
- Let $\Pr(P_\alpha^1)$ and $\Pr(P_\alpha^2)$ be the probabilities that a call for a source–destination pair α is set up on the first and second path, P_α^1 and P_α^2, respectively.

In the FPLC, a call request is set up on the first-shortest path if the number of free wavelengths on the second-shortest path is less than the number of free wavelengths on the first-shortest path. Otherwise, it is set up on the second-shortest path assuming that the path has at least one free wavelength. Therefore

$$\Pr\,(P_\alpha^1) = \sum_{i=1}^{F} Q_{P_\alpha^1}(i)\left(\sum_{n=0}^{i} Q_{P_\alpha^1}(n)\right) \tag{3}$$

$$\Pr(P_\alpha^2) = \sum_{i=1}^{F} Q_{P_\alpha^2}(i)\left(\sum_{n=0}^{i-1} Q_{P_\alpha^2}(n)\right). \tag{4}$$

Recall that λ is the call arrival rate at each node. The arrival rate of calls that enter at link i and continue to link $j, \rho_c(i,j)$ becomes

$$\rho_c(i,j) = \sum_{P_j \in R_{i,j}^1} \lambda \Pr\,(P_j) + \sum_{P_j \in R_{i,j}^2} \lambda \Pr\,(P_j). \tag{5}$$

The arrival rate of calls that leave from link i, $\rho_l(i)$ includes calls that use link i as the first or second route, but do not continue to link j

$$\rho_l(i) = \sum_{P_i \in R_i^1} \lambda \Pr\,(P_i) + \sum_{P_i \in R_i^2} \lambda \Pr\,(P_i) - \rho_c(i,j). \tag{6}$$

The arrival rate of calls that enter at link j, $\rho_e(j)$ includes calls that use link j as the first or second route, but do not include calls that continue from link i to link j

$$\rho_e(j) = \sum_{P_j \in R_j^1} \lambda \Pr\,(P_j) + \sum_{P_j \in R_j^2} \lambda \Pr\,(P_j) - \rho_c(i,j). \tag{7}$$

Given the arrival rates to each link, the conditional probabilities $S(y_f|x_{pf})$, $U(z_c|y_f, x_{pf})$, and $R(n_f|x_{ff}, y_f, z_c)$ can be derived (see [20] for details). Let L_α be the blocking probability for source-destination pair α. L_α can be derived from (1) and (2) as

$$L_\alpha = Q_{P_\alpha^1}(0) \times Q_{P_\alpha^2}(0). \tag{8}$$

Let J be the number of links in a network. The algorithm given below iteratively computes the approximate blocking probabilities for the traffic on all the routes. Let ϵ be a small positive number that is used as convergence criterion.

1) Initialization. For each source–destination pair α let $\overline{L}_\alpha = 0$. Choose $\rho_e(i), \rho_c(i,j)$, and $\rho_l(i), i,j = 1, \cdots, J$ arbitrarily for all links.
2) Calculate $Q_P(w_f)$ for every path of each source-destination pair using (1) and (2).
3) Calculate the blocking probability L_α for every source-destination pair α using (8). If $\max_\alpha |L_\alpha - \overline{L}_\alpha| < \epsilon$ then terminate. Otherwise let $\overline{L}_\alpha = L_\alpha$, go to next step.
4) Calculate ρ_e, ρ_l, and ρ_c for each link using (5)–(7), then go back to step 2.

Since the arrival rate for each link can be computed individually, this method is suitable for analysis of irregular networks. The method is also applicable to alternate routing approaches with small modifications of (3) and (4).

B. Time Complexity of the Analytical Model

The computational time complexity of the analytical model can be analyzed as follows. Given call arrival rates $\rho_l(i), \rho_c(i,j)$, and $\rho_e(j)$, the conditional probability matrices R, U, and S in (1) can be computed in $O(F^3)$ time units [20]. Let H be the maximal number of links along a path over all possible paths, i.e., H is the diameter of the network. We know from (1) and (2) that the time needed to compute $Q_P(w_f)$ is $O(HF^4)$. Let N be the number of node in a network. The total source-destination pairs in such a network is $N*(N-1)$. Hence, step 2 in the algorithm can be finished in $O(N^2HF^5)$ time units. Given every element of Q obtained in step 2, the arrival rates of each link can be computed in $O(F^3)$ units. Therefore, the time complexity of the algorithm is dominated by the computation of the free wavelength distribution matrix, Q, which takes $O(N^2HF^5)$ time units in the worst case. In the implementation, multiple iterations are required to solve the Erlang fixed-point equation. We observed that most of the results shown in the next section are obtained in less than ten iterations.

Note that the computational complexity mainly results from the link-load correlation model, which is the best model available so far in the literature in terms of accuracy, while maintaining reasonable complexity. The reduced-load model in [3] has also been extended to analyze the performance of the FPLC in [20]. The results show that the reduced-load model is more complex and less accurate than the correlation model. We should also point out that the complexity of the analytical model does not affect the efficiency of the routing algorithms.

III. ROUTING USING NEIGHBORHOOD INFORMATION

We will see in the next section that the FPLC routing method improves network performance compared to static routing approaches. However, problems still exist when using this dynamic routing method in a large network. The main difficulties remaining are the control overhead, setup delay, and possible conflicts in wavelength usage when multiple paths are being set up simultaneously on one link. In this section, we propose a new routing algorithm using neighborhood information that tries to achieve the setup efficiency and lower control overhead of static routing with low blocking probability. Using analytical and simulation methods, we show that routing using neighborhood information can achieve high network performance, compared to static routing approaches. This approach also reduces the possible conflicts in wavelength usage.

In the neighborhood-information-based routing, a set of edge-disjoint shortest paths is statically computed and stored at each node. Upon the arrival of a connection request, the source node uses the route-selection process that is similar to the FPLC. However, instead of searching all the links on the preferred paths, only the neighborhood including the links up to distance k are searched and the results are compared to decide which route to select. There are two possibilities for collecting the neighborhood information: it can be either collected when needed or exchanged periodically. If no wavelength is available on the selected route, the connection request is blocked. This routing algorithm is called FPLC-N(k).

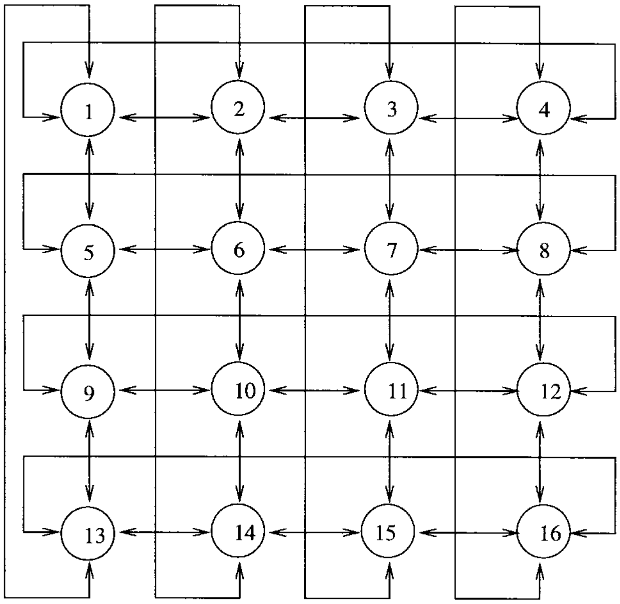


Fig. 1. A 4 × 4 mesh-torus network.

A. Analysis of the FPLC-N(k)

We extend the approximate analytical models discussed in the previous section to the FPLC-N(k). We use the same terminology as before.

Let $\hat{Q}^k_{P_j}(w)$ present the probability that there are w free wavelengths available on route P_j up to neighborhood distance k. $\hat{Q}^k_{P_j}(w)$ is given by

$$\hat{Q}^k_{P_j}(w) = \sum_{y_f=0}^{F} T^{(k)}_{P_j}(w, y_f).$$

Let $V^l_P(n_f, x_{pf})$ be the probability that n_f wavelengths are free on an l-hop path P, and x_{pf} wavelengths are free on the first link. Then we have (9), shown at the bottom of the page. Considering the first k hops as the first hop as we do in the previous section, $V^{(l-k)}(0, x_{pf})$ is the probability that x_{pf} wavelengths are available on the first k hops of an l-hop path, but none of the x_{pf} wavelengths is available on the following $l-k$ hops.

Let $\hat{\Pr}(P^1_\alpha)$ be the probability that a call for a source–destination pair α is set up on the first-shortest path P^1_α, and $\hat{\Pr}(P^2_\alpha)$ be the probability that a request is set up on the second-shortest path P^2_α using neighborhood information. In the FPLC-N(k), a call request is attempted to be set up on the path that has more free wavelengths on the first k links. The request is successfully set up if at least one wavelength is free on the first k links, and at least one of the free wavelengths can continue on the following links of the path. Therefore

$$\hat{\Pr}(P^1_\alpha) = \sum_{i=1}^{F} \hat{Q}^k_{P^1_\alpha}(i) \left(\sum_{n=0}^{i} \hat{Q}^k_{P^2_\alpha}(n) \right) \left(1 - V^{(l-k)}_{P^1_\alpha}(0, i)\right) \tag{10}$$

$$\hat{\Pr}(P^2_\alpha) = \sum_{i=1}^{F} \hat{Q}^k_{P^2_\alpha}(i) \left(\sum_{n=0}^{i-1} \hat{Q}^k_{P^1_\alpha}(n) \right) \left(1 - V^{(l-k)}_{P^2_\alpha}(0, i)\right). \tag{11}$$

The arrival rate of calls that enter at link i and continue to link j becomes

$$\rho_c(i,j) = \sum_{P_j \in R^1_{i,j}} \lambda \hat{\Pr}\,(P_j) + \sum_{P_j \in R^2_{i,j}} \lambda \hat{\Pr}\,(P_j). \tag{12}$$

The arrival rate of calls that leave from link i becomes

$$\rho_l(i) = \sum_{P_i \in R^1_i} \lambda \hat{\Pr}\,(P_i) + \sum_{P_i \in R^2_i} \lambda \hat{\Pr}\,(P_i) - \rho_c(i,j). \tag{13}$$

The arrival rate of calls that enter at link j becomes

$$\rho_e(j) = \sum_{P_j \in R^1_j} \lambda \hat{\Pr}\,(P_j) + \sum_{P_j \in R^2_j} \lambda \hat{\Pr}\,(P_j) - \rho_c(i,j). \tag{14}$$

Blocking probability L_α for the FPLC-N(k) consists of three terms: 1) the probability that the first route is selected using neighborhood information (there are i free wavelengths on the first route up to neighborhood distance k and the corresponding alternate route has less than or equal to i idle wavelengths up

$$V^l_P(n_f, x_{pf}) = \sum_{y_f=0}^{F} \sum_{z_c=0}^{\min(F-x_{pf}, F-y_f)} \sum_{x_{ff}=0}^{y_f} R(n_f | x_{pf}, z_c, x_{ff}) U(z_c | y_f, x_{pf}) S(y_f | x_{pf}) V^{(l-1)}_P(x_{ff}, y_f). \tag{9}$$

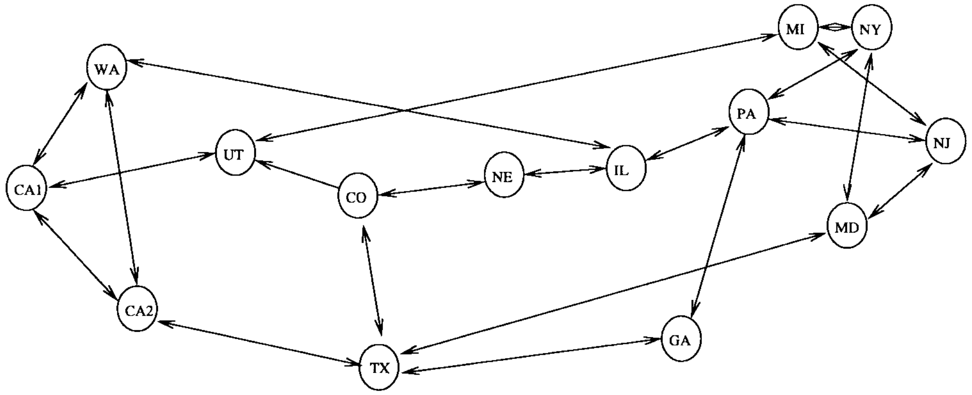


Fig. 2. The NSFnet T1 backbone network.

to neighborhood distance k), but blocked at other links on the first route after distance k; 2) the probability that the second route is selected using neighborhood information (there are i free wavelengths on the second route up to neighborhood distance k and the corresponding alternate route has less than i idle wavelengths up to neighborhood distance k), but blocked at other links on the second route after distance k; and 3) the probability that no wavelength is available on any of the two routes up to distance k. Thus

$$L_\alpha = \sum_{i=1}^{F} \hat{Q}^k_{P^1_\alpha}(i) \left(\sum_{n=0}^{i} \hat{Q}^k_{P^2_\alpha}(n) \right) V^{(l-k)}_{P^1_\alpha}(0, i + \sum_{i=1}^{F} \hat{Q}^k_{P^2_\alpha}(i)) \cdot \left(\sum_{n=0}^{i-1} \hat{Q}^k_{P^1_\alpha}(n) \right) V^{(l-k)}_{P^2_\alpha}(0, i) + \hat{Q}^k_{P^1_\alpha}(0)\hat{Q}^k_{P^2_\alpha}(0) \qquad (15)$$

Using the same algorithm given in Section II-A, we can compute the blocking probabilities for the traffic on all the routes.

IV. NUMERICAL RESULTS AND ANALYSIS

In this section, we assess the accuracy of the analytical model by comparing it with the simulation results. The analytical model is applied to two network topologies, a regular 4 × 4 mesh-torus network depicted in Fig. 1, in which all adjacent nodes are connected by bi-directional links, and an irregular NSFnet T1 backbone network shown in Fig. 2, with 14 nodes and 21 bi-directional links. We also compare the performance of the FPLC to the ASP and SP. We show using analytical and simulation results that one neighborhood information is sufficient to guarantee high performance in the FPLC-N(k) compared to that in the ASP.

A. Performance Analysis of the Mesh-Torus Networks

Fig. 3 shows the network blocking probability versus the traffic load per source-destination pair for eight wavelengths per link. In the approximate analysis, multiple iterations are required and the convergence criteria is set to be 10^{-6} for the blocking probabilities. Each data point in the simulations was obtained using 10^7 call arrivals. The same criteria were set for all the analysis and simulation results in this paper. From the figure, we observed that the analytical results follow the trend of the simulation results. The analytical results are in good agreement with simulation results for heavy to moderate traffic (traffic load >0.30). However, the analytical results are not very accurate when traffic load is light (traffic load ≤ 0.30).

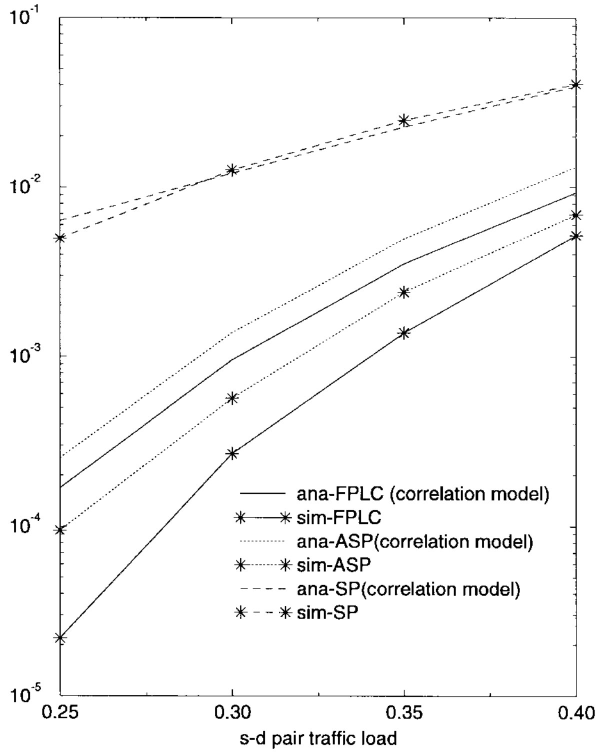


Fig. 3. Blocking probability versus source–destination pair traffic load. Performance comparison of different routing algorithms with random wavelength assignment.

We also observed that the FPLC improves the blocking probability when the traffic load is low. As the traffic load increases, the performance of the FPLC gets closer to the ASP. One of the reasons that the FPLC performs better than the ASP and SP is that the FPLC distributes the traffic evenly in the network. Smooth traffic is carried on each link [20]. We also noticed that in the FPLC, the network performance can be significantly improved by using the first-fit wavelength assignment compared to the random wavelength assignment. Fig. 4 shows the performance of the ASP and the FPLC using different wavelength assignment methods through simulation. As reported in [5], the first-fit wavelength assignment strategy

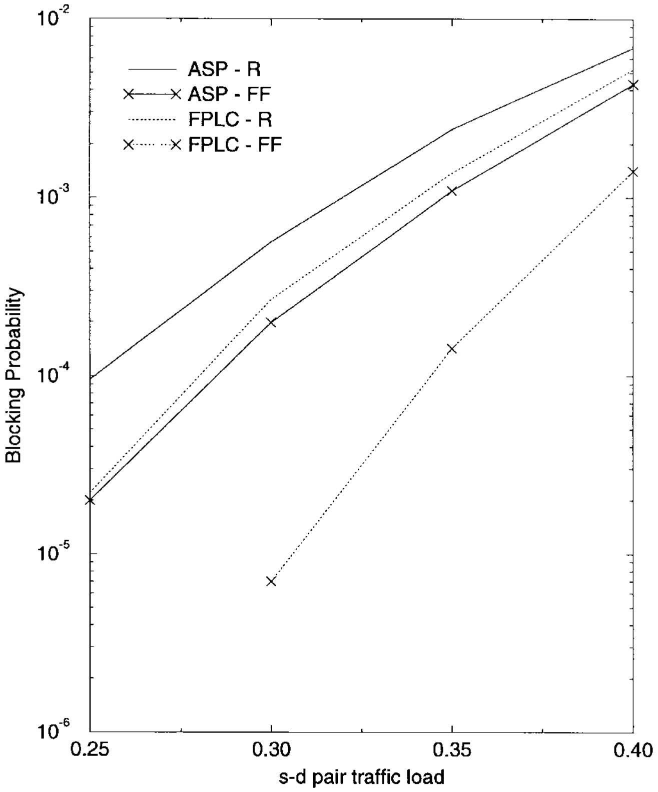


Fig. 4. Blocking probability versus source–destination pair traffic load. Performance comparison of different routing algorithms with first-fit wavelength assignment.

can slightly improve the blocking probability in the ASP. While using the FPLC, the first-fit wavelength assignment performs much better than the random strategy under light load condition. The reason can be explained intuitively as follows.

Compact wavelength assignment methods (i.e., most-used) perform better than spread wavelength assignments (i.e., least-used) as suggested in [6], [14]. In the FPLC, a request is set up on the least-congested route. The wavelengths with lower index have more chances to be employed when compared to the ASP. Using the first-fit wavelength assignment, this compact wavelength assignment effect is enhanced.

Our simulation results also show that more sophisticated wavelength assignment algorithms, such as using the most-used wavelength assignment, do not significantly improve the network performance in FPLC. Since accurate global state of a large network is hard to obtain, we observed that the first-fit wavelength assignment is a good candidate to assign wavelengths in a distributed routing network.

Fig. 5 shows the blocking probability versus the traffic load for $F = 8$ using the FPLC-N(1). The route to set up a connection request is determined by 1-neighborhood information. Similar to the original observation for the FPLC, we again noticed that the analytical and the simulation results match when the traffic load is heavy to moderate, but analytical results are less accurate for light traffic.

The performance of the FPLC-N(k) with different values of k is compared using analytical results shown in Fig. 6 $(F = 8)$. The diameter of our network topology is 4, so the FPLC-N(3) is the same routing method as the FPLC. Thus, the FPLC is the lower bound on the FPLC-N(k). It is observed from the figure that the blocking probability is not linearly decreasing with the increase of neighborhood distance. The difference of the blocking probabilities between $k = 0$ and $k = 1$ is much higher than the difference between $k = 1$ and

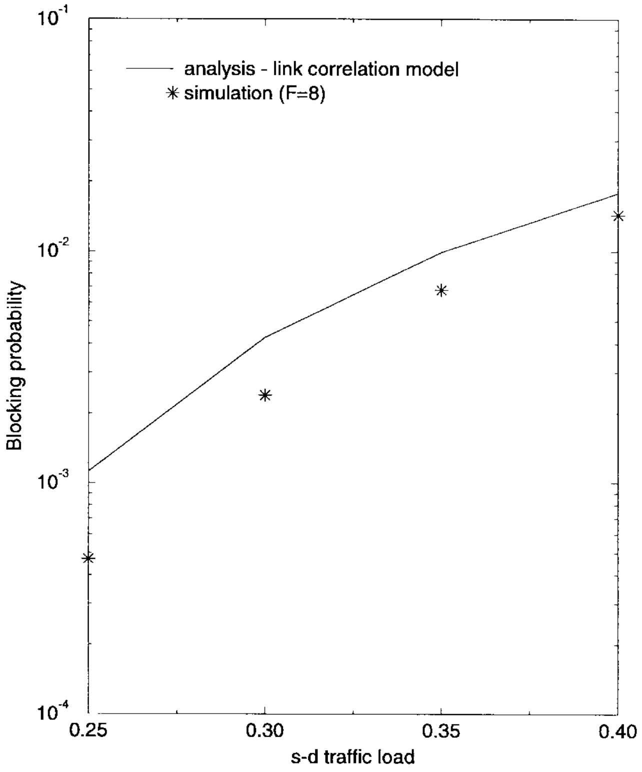


Fig. 5. Blocking probability versus traffic load using the FPLC-N(1).

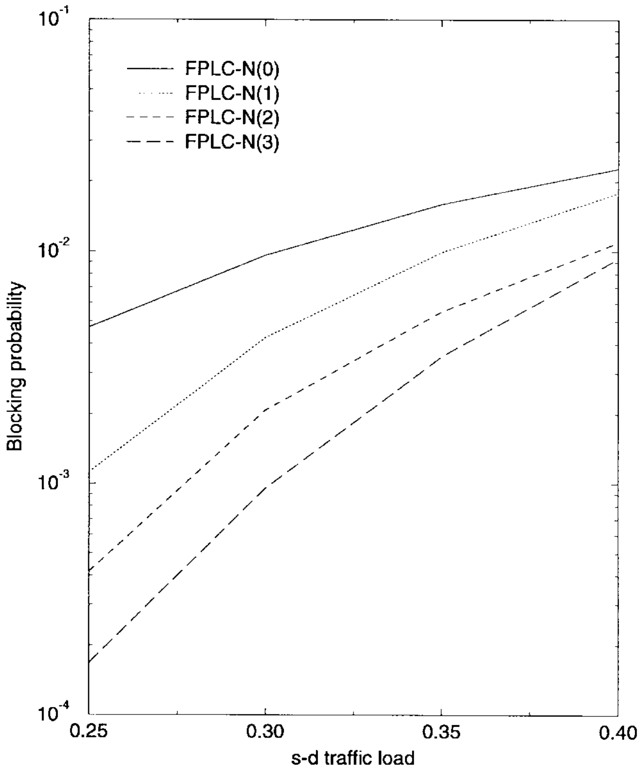


Fig. 6. Performance comparison using different neighborhood information.

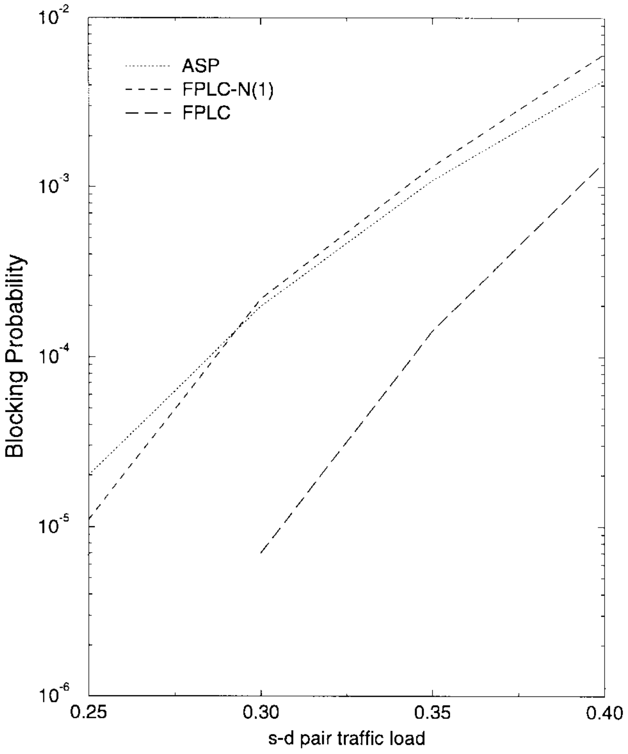


Fig. 7. Performance comparison of using the ASP, the FPLC-N(1) and the FPLC.

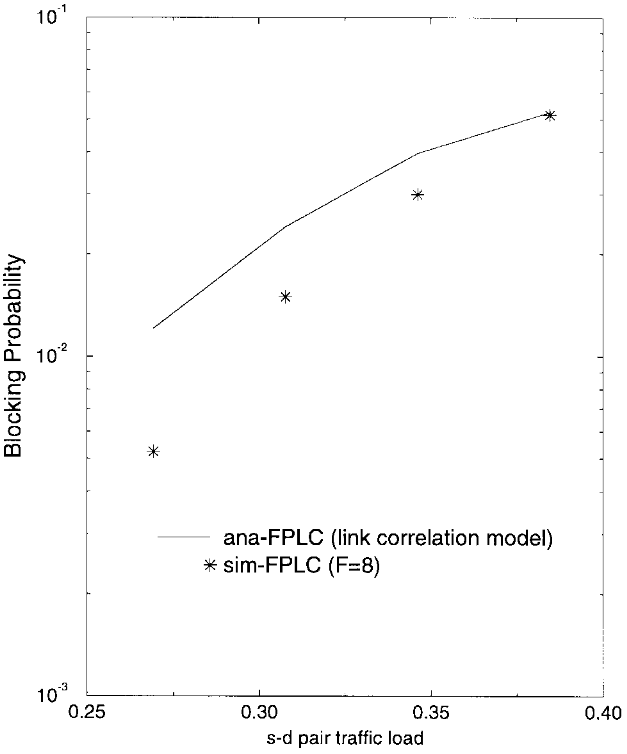
$k = 2$ and the difference between $k = 2$ and $k = 3$ under light traffic conditions.

From Fig. 4 we know that for the FPLC, the first-fit wavelength assignment method performs much better than random strategy under light traffic. The same is true for the FPLC-N(k) as shown by our simulation results depicted in Fig. 7 $(F = 8)$. In comparison to the results of Fig. 5, we noted that the blocking probability is significantly improved when the first-fit wavelength assignment is used. The FPLC-N(1) can achieve the performance similar to the ASP. Thus, we conclude that 1-neighborhood information is sufficient to ensure good network performance in terms of blocking probability in a 4 × 4 mesh-torus network.

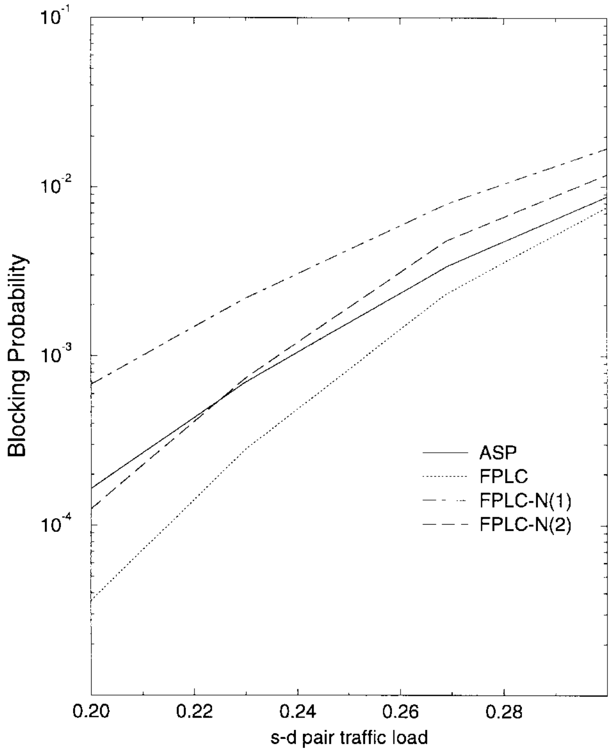
B. Performance Analysis of the NSFnet

Since we analyze the blocking performance individually for each s-d pair, our analytical model is also applicable for irregular networks. The analytical results using the link correlation model compared to simulation results in NSFnet are shown in Fig. 8(a). We observed from the figure that the link correlation model performs well on the NSFnet. The analytical results are accurate under heavy and moderate traffic load. It is not very accurate under light traffic.

Simulation results for the ASP, the FPLC, the FPLC-N(1) and the FPLC-N(2) is shown in Fig. 8(b). The performance of the FPLC is better than the ASP in the NSFnet when the traffic load is light and it gets closer to the ASP as the traffic load increases. Routing using neighborhood information does not perform as well in the NSFnet as it does in mesh-torus network. However, the performance of the FPLC-N(1), which employs 1-neighborhood information, is close to the ASP. By using 2-neighborhood information, the FPLC-N(2) can achieve similar performance to the ASP. Thus one can use the FPLC-N(1) or the FPLC-N(2) to achieve the similar performance as the ASP and keep the setup time and control overhead low.



(a)



(b)

Fig. 8. (a) Blocking probability versus traffic load in the NSFnet. (b) Simulation results of the average blocking probability in the NSFnet.

The network performance could be further improved by using wavelength reservation, protection threshold, or limited trunk reservation methods proposed in [3], [5], but this is out of the scope of this paper.

V. CONCLUSION

In this paper, we proposed two new dynamic routing methods in all-optical wavelength-routed networks. An approximate analytical approach is developed for the FPLC routing and the routing using neighborhood information algorithms. Numerical results show that the FPLC routing with the first-fit wavelength assignment method significantly improves network performance compared to the alternate paths routing algorithms. The reason is that more wavelengths are left free on a network when the FPLC with the first-fit wavelength assignment method is used.

The routing using neighborhood information algorithm is employed as a trade-off between network performance in terms of blocking probability versus setup delay and control overhead when using dynamic routing algorithms. It is shown that the routing using neighborhood information method achieves good performance when compared to static routing approaches. 1-neighborhood information is sufficient to ensure network performance in a 4 × 4 mesh-torus network and in the NSFnet T1 backbone network.

Since we take the link-load correlation into account in our analytical model, the time complexity of the analytical model is $O(N^2HF^5)$. A concern remains on the scalability of the analytical model in large networks with large number of wavelengths. Simple models, e.g., the independence model in [4], may be used to reduce the time complexity at the cost of accuracy in some specific topologies. However, development of accurate models with less complexity remains to be investigated in the future.

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