A Heuristic Wavelength Assignment Algorithm for Multihop WDM Networks with Wavelength Routing and Wavelength Re-Use

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Abstract—In this paper, we present a heuristic algorithm for effectively assigning a limited number of wavelengths among the access stations of a multihop network wherein the physical medium consists of optical fiber segments which interconnect wavelength-selective optical switches. Such a physical medium permits the limited number of wavelengths to be re-used among the various fiber links, thereby offering very high aggregate capacity. Although the optical connectivity among the access stations can be altered by changing the states of the various optical switches, the resulting optical connectivity pattern is constrained by the limitation imposed at the physical level. We also study two routing schemes, used to route requests for virtual connections.

The heuristic is tested on a realistic traffic model, and the call blocking performance of new requests for virtual connections is studied through extensive simulations and compared against the blocking performance of an ideal infinite capacity centralized switch (lowest possible call blocking caused exclusively by congestion on the finite capacity user input/output links, never by the switch fabric itself). Surprisingly, we find that, for a wide range of parameters, the blocking performance of the lightwave network is almost the same as that of the ideal centralized switch. From these results, we conclude that the heuristic algorithm is effective and the routing scheme is efficient.

I. INTRODUCTION

MULTIHOP LIGHTWAVE networks based on wavelength division multiplexing have emerged as promising candidates for next-generation networks capable of offering high-speed packet-based transport to a large population of users [1]-[4]. With this approach, each user connects to the network through its respective access station, and pairs of access stations are interconnected by point-to-point optical channels which are wavelength-multiplexed on the optical medium. The resulting connection graph allows packets injected by any originating station to be routed to any destination station, possibly through several optical channels. By changing the wavelength assignment, the resulting connection graph can be adapted to changing traffic patterns, station failure, and station additions [5].

In this paper, we consider a multihop lightwave network in which the physical medium consists of segments of optical fiber, each of which interconnects two wavelength-selective optical switches. Here, a limited set of available wavelengths can be re-used among the various fiber links, thereby permitting the creation of scalable large connection graphs without requiring a commensurately large number of wavelengths. Each link of the connection graphs, referred to as a lightpath in [6]-[8], consists of a single wavelength which has been routed through the optical switches to its intended receiver. There is no wavelength conversion within a lightpath. Since the number of wavelengths and the number of transceivers are limited, the connection graph whose links are lightpaths are not fully connected. Therefore, multihopping between lightpaths may be necessary. Information forwarding from lightpath to lightpath is performed in the electronic domain. The connection graphs can be altered by appropriately changing the states of the various switches. However, with this approach, freedom to choose the connection graph is limited by constraints imposed by the physical medium.

Design of the optical network involves the construction of a realizable optical connection graph which reflects the physical wavelength assignment constraints and the development of efficient routing schemes on the optical virtual connection graph. The problem of designing "optimal" virtual topologies without taking the physical wavelength assignment constraints into consideration has been addressed and has been conjectured to be NP-hard in [5]. The optimality criteria used in [5] seeks to minimize the maximum flow in the network. The problem of establishing lightpaths for a given static or dynamic set of circuit demands is considered in [6]. For a given fixed number of wavelengths, the performance measure used in [6] is the lightpath blocking probability. In [7] and [8], the problem of embedding the regular optical/virtual networks into the original fiber topology is studied. In [7], bounds on the number of wavelengths required to realize a regular topology are presented. Algorithms for embedding alternative regular topologies are described and their performances evaluated. In [8], the formulation of the optimization problem is presented. Here, the optimality criteria seeks to minimize the average propagation delay encountered by all packets and two heuristic algorithms (the greedy approach and simulated annealing) for embedding the hypercube into a physical fiber topology are studied. While regular virtual topologies have the advantages of simplified routing and easy implementation, they do not perform well under nonuniform traffic.
In this paper, we present a heuristic algorithm, which is driven by the user-to-user traffic intensity matrix, to produce a realizable connection graph (i.e., one which reflects the wavelength assignment constraints presented by the physical medium). Once the optical connection graph is obtained, we have a network that is analogous to a circuit-switched telephone network or loss network as studied in [9]-[11]. Two routing schemes (used to route requests for virtual connections) are studied. The heuristic is tested by simulating the call blocking performance of new requests for virtual connections for each of the two routing schemes, and compare these against the blocking performance of an ideal infinite capacity centralized switch (lowest possible call blocking caused exclusively by congestion on the finite capacity user input/output links, never by the switch fabric itself). Surprisingly, we find that, for a wide range of parameters, the blocking performance of the logical connection graph (which remains static but “matched” to the average traffic pattern) is virtually indistinguishable from that of the ideal centralized switch. This is indeed an encouraging finding, for it indicates that under these conditions, the optical network presents no impedance whatsoever to the flow of user-to-user traffic.

The paper is organized as follows. In Section II we present a brief description of the network architecture. The mathematical formulation and a heuristic algorithm for wavelength assignment are presented in Section III. In Section IV, two routing schemes are described. Simulation results are reported in Section V and conclusions are given in Section VI.

II. NETWORK ARCHITECTURE

The network architecture we are considering is based on (1) the use of high-density wavelength division multiplexing (WDM), (2) the use of wavelength to route each signal to its intended destination in the network (wavelength routing), and (3) the use of multihop switching and multiplexing/demultiplexing. These three principles permit networks to be built, in which the number of nodes is essentially unlimited and is independent of the number of wavelengths available. The network consists of an all-optical inner portion which contains the wavelength routing cross-connection or switching elements, each capable of independently routing each of the incident wavelengths, and an outer portion which contains user access stations which attach to the optical medium and permit a limited number of wavelengths available to each to enable full virtual circuit connectivity, if desired, among all the users. By utilizing the properties of the wavelength across-connects, the optical connectivity among access stations can be dynamically rearranged. This rearrangeability will allow the dynamic allocation of wavelength and capacity throughout the network to meet changing traffic, service, and performance requirements and to provide a robust, fault-tolerant network. The electronically controlled wavelength translation function consists of receiving a signal at one wavelength and retransmitting it at another, and is necessary to the attainment of full connectivity at the virtual circuit.

These functions are illustrated in Fig. 1. The WDM cross-connects (which may be based on acousto-optic technology [12]) are shown in circles within the all-optical portion, and the squares are the network access stations. Wavelength λ₃ carries a one-optical-hop signal (no intermediate detection or wavelength translation) from node A to node E, while a signal from node A to node C is carried in two optical-hops: A to B on λ₁ and B to C on λ₂. Wavelength λ₁ is reused to carry a signal from C to D.

The fiber topology of such a network, determined by the fiber connections between the optical switches, is fixed. The optical topology or connection graph, representing the optical channels which exist among the user access stations (e.g., an optical channel using wavelength λ₁, originating at station i, and routed through a series of switches to terminate at station j which corresponds to a directed link from i to j, which is referred to as an optical-hop or lightpath), is rearrangeable by altering the states of the switches.

Since the number of transmitters and receivers per access station is limited, the optical connectivity among the stations is not full. Thus, most of the end-to-end connections will require multiple hops, through a sequence of optical channels or lightpaths. These connections are referred to as virtual connections in Asynchronous Transfer Mode (ATM) networks. The virtual connectivity (which can be full) is provided by using intermediate stations as cooperating relay nodes. When a new virtual connection request is generated, the job of the admission controller is to decide whether to admit or block the request by finding a path capable of handling the virtual connection. A virtual connection request is blocked if the controller is unable to find or create a path, without...
unacceptably degrading the quality of service enjoyed by other virtual connections.

For a given physical topology (fiber interconnection pattern) which consists of $N$ nodes, long term average traffic demand matrix $(t_{ij})$, and number of wavelengths available, $P$, a possible objective is to find a wavelength assignment algorithm and a routing scheme such that the call blocking probability is minimized, subject to the following physical constraint: on each fiber link, no two virtual connections use a common wavelength. This problem is however conjectured to be NP-hard [8], [13]. To proceed, we decompose this problem into two separate problems, and provide a heuristic approach to solve each:

**Problem I:** Find a wavelength assignment algorithm which tends to favor the one-optical-hop traffic (i.e., pairs of stations exhibiting large traffic flow receive optical links from the resulting optical connection graph; heavy traffic flow is thereby handled in one hop, reducing the burden on the other optical links).

**Problem II:** For the resulting optical connection graph, develop routing schemes which produce low call blocking probability.

In the next section, we will present the mathematical formulation and heuristic for wavelength assignment.

### III. THE WAVELENGTH ASSIGNMENT PROBLEM

In this section, we first formulate the wavelength assignment problem such that the one-optical-hop traffic is maximized, subject to the following physical layer constraint: on each optical link, no two connections use a common wavelength. Because of the constraint, the mathematical formulation of the problem is difficult, and a mixed linear integer problem results. In order to obtain an exact solution, one must solve the linear integer problem, which could be a very difficult task for large values of $N$ and $P$. Instead, we will seek a heuristic algorithm to solve the integer part of the problem.

#### A. Mathematical Formulation

Define a connection-link indication matrix

$$ m = (m_{ij}, (l,m)), $$

where

$$ m_{ij}, (l,m) = \begin{cases} 
1 & \text{if connection } (i,j) \text{ and connection } (l,m) \text{ use a common link} \\
0 & \text{otherwise} 
\end{cases} \quad (1) $$

We assume here that each connection is set up along a fixed path with the minimum number of fiber hops (if there are more than one paths with the same minimum hops, one path is chosen randomly). From (1), it is easy to see that the matrix is symmetric. Different path set-up strategies for the connections will result in different connection-link indication matrices.

The maximum one-optical-hop traffic carried on the optical channel between $i$ and $j$ is

$$ \sum_{k=1}^{P} z_{ij}(k)C, $$

where $z_{ij}(k)$ indicates that if connections $(i,j)$ and $(l,m)$ use a common link, $z_{ij}(k)$ and $z_{lm}(k)$ cannot be equal to 1 at the same time, i.e., connections $(i,j)$ and $(l,m)$ cannot use wavelength $k$ at the same time.

The problem CP is a nonlinear integer programming problem, which can be formulated as follows.

$$ CP: \max \sum_{ij} \min(t_{ij}, \sum_{k=1}^{P} z_{ij}(k)C), $$

subject to the constraints

$$ \sum_{m=1}^{N} z_{im}(k) \leq 1, \quad \text{and} \quad \sum_{m=1}^{N} z_{mj}(k) \leq 1, \quad k = 1, 2, \ldots, P, \ i, j = 1, 2, \ldots, N \quad (2) $$

$$ m_{ij}, (l,m)(z_{ij}(k) + z_{lm}(k)) \leq 1, \quad k = 1, 2, \ldots, P, \ \text{for all distinct pairs } \ i, j \text{ and } l, m \quad (3) $$

and

$$ z_{ij}(k) = 0, 1, \quad k = 1, 2, \ldots, P, \ \ i, j = 1, 2, \ldots, N. $$

For each wavelength, constraint (2) states that there should be at most one connection starting from node $i$ and at most one connection terminating at node $j$, respectively. Constraint (3) indicates that if connections $(i,j)$ and $(l,m)$ use a common link, $z_{ij}(k)$ and $z_{lm}(k)$ cannot be equal to 1 at the same time.

The problem CP is a nonlinear integer programming problem, which can be difficult to solve when $N$ and $P$ are large. By introducing additional continuous variables, we can convert this nonlinear problem into a mixed linear integer programming problem as follows. We note that if $C \geq t_{ij}$, then

$$ \min(t_{ij}, \sum_{k=1}^{P} z_{ij}(k)C) = t_{ij} \sum_{k=1}^{P} z_{ij}(k), $$

subject to the constraint

$$ \sum_{k=1}^{P} z_{ij}(k) \leq 1. \ \text{Let } LT = \{ij|t_{ij} \leq C\}. $$

For each element $ij \notin LT$, let $x_{ij} = \min(t_{ij}, \sum_{k=1}^{P} z_{ij}(k)C)$ then

$$ x_{ij} \leq t_{ij} \quad \text{and} \quad x_{ij} \leq \sum_{k=1}^{P} z_{ij}(k)C. $$
The problem CP can then be converted into the following mixed integer linear programming problem
\[
\text{CP}_{\text{mix}}: \max \left( \sum_{ij \in LT} t_{ij} \sum_{k=1}^{P} z_{ij}(k) + \sum_{ij \notin LT} x_{ij} \right)
\]
such that
\[
\sum_{k=1}^{P} z_{ij}(k) \leq 1, \quad \text{if } ij \in LT,
\]
\[
x_{ij} \leq \sum_{k=1}^{P} z_{ij}(k), \quad x_{ij} \leq t_{ij}, \quad \text{if } ij \notin LT,
\]
\[
\sum_{m=1}^{N} z_{im}(k) \leq 1, \quad \text{and} \quad \sum_{m=1}^{N} z_{mj}(k) \leq 1,
\]
\[
k = 1, 2, \ldots, P; i, j = 1, 2, \ldots, N \\
\m_{i,j}(l,m)(z_{ij}(k) + z_{lm}(k)) \leq 1, \quad k = 1, 2, \ldots, P
\]
for all distinct pairs \(i, j\) and \(l, m\)

\[\text{(5)}\]

and
\[
z_{ij}(k) = 0, 1, \quad k = 1, 2, \ldots, P; \quad i, j = 1, 2, \ldots, N
\]

Note: if \(t_{ij} \leq C\) for all the \(ij\)'s, (constraint (5) does not exist), then the problem is a binary linear programming problem.

The problem CP or \(\text{CP}_{\text{mix}}\) can be approximately decomposed into the following \(P\) iterative subproblems. Each subproblem is a binary linear integer programming problem and is the same as the problem CP with \(P = 1\), i.e., the problem of finding the assignment for one wavelength.

Let \(z_{ij} = \begin{cases} 1 & \text{if the wavelength is assigned to node pair } i \text{ and } j \\ 0 & \text{otherwise} \end{cases}\)

\[\text{CP1: } \max \sum_{ij} \min(t_{ij}, C)z_{ij}
\]
such that
\[
\sum_{k=1}^{N} z_{ik} \leq 1 \quad \text{and} \quad \sum_{k=1}^{N} z_{kj} \leq 1, \quad i, j = 1, 2, \ldots, N
\]
\[
m_{i,j}(l,m)(z_{ij} + z_{lm}) \leq 1, \quad \text{for all distinct pairs } i, j \text{ and } l, m
\]
\[\text{(8)}\]

and
\[
z_{ij} = 0, 1, \quad i, j = 1, 2, \ldots, N
\]

Let \(z_{ij}^{*}\) be the optimal solution of CP1. Modify the traffic matrix \(T\) as follows
\[
\bar{t}_{ij} = \max(t_{ij} - Cz_{ij}^{*}, 0)
\]

Solve problem CP1 with \(t_{ij}\) replaced by \(\bar{t}_{ij}\). The problem CP can be solved approximately by repeating the above procedure \(P\) times.

Even though problem CP1 is relatively easier to solve than problem CP or \(\text{CP}_{\text{mix}}\), it is still difficult when \(N\) is large.

B. Heuristic Algorithm for CP1

In this section, we present a heuristic (in polynomial time) solution for an approximate solution to CP1. The heuristic is a greedy allocation algorithm which iteratively attempts to assign each wavelength to as many connections as possible without violating the physical constraints. Since our objective is to maximize the sum of one-optical-hop traffic, it is desirable that wavelengths should be assigned to optical connections between access station pairs with the largest traffic demands. Therefore, we first number all the connections (corresponding to nonzero entries in the demand matrix) in descending order. The algorithm first assigns a wavelength to the optical connection with the largest pairwise traffic demand, then to the connection with the next largest pairwise traffic demand among the connections which do not use the links used by the first connection. The algorithm repeats until no more connections can be assigned.

The connection-link indication matrix \(m\), defined in (1), is generated according to the order of traffic demand. In the matrix \(m\), each connection corresponds to one column (or row). In the following algorithm, we use "connection" and "column" interchangeably. Once the matrix \(m\) is obtained, the algorithm can be implemented as follows: Assign the wavelength to the first row (or column). All the columns with zero elements in the first row are candidates for the next wavelength assignment and the first such column, say column \(i\), \(i > 1\), is chosen. Next, the wavelength is assigned to the first column with zero elements in both row \(i\) and row \(i\). The procedure is repeated until no such column can be found.

Algorithm:
1) Generate the matrix \(m\) as described above.
2) Assign the wavelength to connection 1, and set \(k = 1\).
3) Remove column \(j\) with \(m_{k,j} = 1\), for \(j = k + 1, \ldots, N\).
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4) Assign the wavelength to the first column (connection) not removed from the matrix in the \( k \)-th row, say connection \( l, l > k \). If no such \( l \) exists, STOP.

5) Set \( k = l \), goto step 3.

There are \( N(N - 1) \) possible connections. In the worst case, one has to check all the \( O(N^4) \) elements, so the complexity of the algorithm for CP1 is \( O(N^4) \).

Note: The optical connection graph created by using the heuristic algorithm is not guaranteed to be connected. If the optical connection graph created is not connected, we can reserve one wavelength connecting all the nodes in a circle and the remaining \( P - 1 \) wavelengths are then assigned using the heuristic algorithm. A more efficient approach is as follows. After assigning the first \( P - 1 \) wavelengths using the heuristic algorithm, identify the subnets which are not connected and connect all the subnets in a circle (choosing one node per subnet) using the \( P \)-th wavelength. Using the \( P \)-th wavelength, assign as many lightpaths as possible starting with node pairs with maximum traffic between them (except those connections already assigned; the traffic between those subnets could be included when computing the maximum traffic pairs, treating each subnet as one node).

IV. ROUTING

Recall that, once the optical connection graph is set up, each user/node can have a virtual connection to any other user/node in the network. Each virtual path travels along a sequence of optical channels. Intermediate access stations may serve as relay stations for the virtual connections. Virtual paths are created and torn down by the network in response to instantaneous user-to-user calling patterns.

In the established optical connection graph, for each pair of nodes, we first find up to \( K \) sets of paths; paths in the same set have equal length (in optical-hops), using the algorithm in [14]. The \( K \) sets are numbered according to their path lengths in ascending order of traffic demand. \( (K = 1) \) set: minimum distance paths; \( K = 2 \) set: all paths of a length which is greater than minimum distance but which, except the minimum distance paths, are of shortest length; etc.) When a new call request is generated, the controller decides whether or not to admit this call by seeking to find one path capable of handling the call from the \( K \) sets according to one of the two schemes.

Scheme 1: The controller finds the shortest path from among the \( K \) sets that can accommodate the call. If there is one or more path (with equal length) which can accommodate the call, among those paths with equal length, a path which has minimum load is chosen. The load on each optical link is defined as the bandwidth allocated to existing connections passing through the optical link; the load on a path is defined as the maximum link-load among all the links on the path). If none of the paths in the \( K \) sets is available, the call is blocked.

Scheme 2: The controller finds one path, from the \( K \) sets, which can accommodate the call and has the minimum load. If none of the paths in the \( K \) sets is available, the call is blocked.

When \( K = 1 \) (minimum distance paths only), the two schemes are the same.

V. SIMULATION RESULTS

In evaluating call blocking, we assume that the fiber layout of the network is fixed, and, for illustration purposes, is shown in Fig. 2. The long term average traffic demand matrix \( T = (t_{ij}) \) predicted for year 1995 and year 2003, assumed for this 24 node network, is given in Tables I and II, respectively, where \( t_{ij} \) is the relative traffic demand between nodes \( i \) and \( j \).

Fig. 2, Tables I and II correspond to a realistic but unidentified regional service network. The call blocking probability is obtained through extensive simulation by generating calls randomly. We assume that all optical channels run at some common data rate \( C \), and that the capacity of each access node is an integer multiple of \( C \) (that is, the access node's capacity is some integral multiple of the basic optical channel rate; if the optical channel rate is 2.4 Gb/s, then the node access rate may be 2.4 Gb/s, 4.8 Gb/s, 7.2 Gb/s, etc.). The node capacity (normalized by the optical channel's capacity) should be less than or equal to the number of wavelengths available. We impose an access node capacity to determine if the blocking occurs at the access node or inside the network.

A. Traffic Model

Calls at node \( i \) are generated independently of calls originating at other nodes according to a Poisson process with rate \( \lambda \sum_{j=1}^{N} t_{ij} \). With probability \( \bar{h}_{ij} = \sum_{j=1}^{N} t_{ij} \), the call is destined

\[ \bar{h}_{ij} \]

1

1 It is predicted that, after the initial deployment of high speed networks, new demands will emerge and therefore the demand in year 2003 will be different from that in year 1995.

TABLE I

<table>
<thead>
<tr>
<th>TRAFFIC DEMAND MATRIX PREDICTED FOR YEAR 1995</th>
</tr>
</thead>
</table>
| \( \begin{array}{cccccccccc}
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| \end{array} \) |

TABLE II

<table>
<thead>
<tr>
<th>TRAFFIC DEMAND MATRIX PREDICTED FOR YEAR 2003</th>
</tr>
</thead>
</table>
| \( \begin{array}{cccccccccc}
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
| \end{array} \) |

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to node \( j \). We assume that call durations are independent and identically governed by an exponential distribution with mean \( 1/\mu \). All the calls are assumed to have the same bandwidth, \( b \), measured in the same units as the optical channel capacity.

Define the call granularity

\[
g = \frac{\text{capacity per wavelength}}{\text{bandwidth required per call}} = \frac{C}{b} \tag{11}\]

which is the number of calls supported on one wavelength (optical channel). Let \( n_{ij} \) denote the number of ongoing calls between nodes \( i \) and \( j \) at the moment when a new call arrives. Let \( n_c \) denote the access node capacity in units of \( C \), where \( 1 \leq n_c \leq P \). A call is admitted if

\[
1 + \sum_{j=1}^{N} n_{ij} \leq n_c g, \quad 1 + \sum_{i=1}^{N} n_{ij} \leq n_c g \tag{12}\]

and a path with sufficient bandwidth (found through either scheme 1 or scheme 2) exists.

We define the offered load to be: \( \rho = \frac{\lambda}{\text{max}(\sum_{i=1}^{N} t_i)} \). The average call blocking probability is defined by

\[
P_{B_{av}} = \frac{\text{total number of calls blocked}}{\text{total number of calls generated}}. \tag{13}\]

B. Centralized Switch

For comparison, we consider the following ideal centralized switch. There are \( N \) input ports and \( N \) output ports in the switch. The capacity of each input/output port is \( n_cC \). A new call arriving on input link \( i \) and destined to output link \( j \) is admitted only if (12) is satisfied. The centralized switch gives the lowest possible call blocking, caused exclusively by congestion on the user/node input/output links, never by the switch fabric itself. The call blocking probability of the centralized switch for the same traffic model is obtained through simulation.

C. Results

In the simulation, we first create, for a four-wavelength network, the optical connection graph using the heuristic algorithm. Then, we generate a total of \( 10^8 \) calls to ensure that steady state has been reached (within 95% confidence interval). Statistics are collected after 1000 additional calls have been generated. (i.e., the first 1000 calls are discarded). In Figs. 3-6, both logical topology and blocking probability are obtained using the traffic demand predicted in year 1995.

In Fig. 3, the blocking probability is plotted versus the offered load for schemes 1 and 2, with \( K = 1, 2, 3 \), respectively. The number of wavelengths is equal to 4 and the node capacity is also equal to 4. The blocking probability for \( K = 2 \) is significantly lower than that for \( K = 1 \), while the improvement of the blocking probability from \( K = 2 \) to \( K = 3 \) is very small. The blocking probability under scheme 2 is lower than that under scheme 1. (Similar results have also been obtained for \( g = 5, 50 \), not shown here). Therefore, we conclude that scheme 2 is better than scheme 1. However, it should be noted that scheme 1 is easier to implement because it does not require to check the loads on all the paths. In the following, we only present the results for scheme 2.

In Fig. 4, the blocking probability of the four-wavelength network for scheme 2, with node capacity equal to 3, is compared with that of a centralized switch with node capacity equal to 3. When \( K = 2 \) or 3, the blocking probability is surprisingly indistinguishable from that of the centralized switch, that is, the network is nearly nonblocking. This also indicates that the heuristic algorithm is effective and the routing scheme is efficient. One reason for such a good performance is that the optical connection is obtained according to the nonuniform traffic demand. In other words, the heuristic algorithm captures the nonuniformities of the traffic demand and produces a good optical connection graph (i.e., the heaviest traffic flows are handled by one-hop paths). As traffic pattern changes, the network can be reconfigured so that the blocking probability or load supported by the network (for a given blocking probability) can improve. (Fig. 7 provides additional support.)

In Figs. 5 and 6, the blocking probability for scheme 2, \( K = 3 \) and node capacity = 4 is compared with that of a centralized switch. The number of calls one wavelength
Fig. 5. Blocking probability versus offered load.

Fig. 7. Blocking probability versus offered load.

Fig. 6. Blocking probability versus offered load.

Fig. 8. Blocking probability versus offered load.

can support is assumed to be 10 and 50, respectively. The blocking probability in both cases is higher than that of the centralized switch. We see that when the node capacity is equal to the number of wavelengths, blocking occurs due to network congestion.

In Fig. 7, we plot the blocking probability for the traffic demand predicted for year 2003. The solid curve is the blocking probability under the logical topology obtained using the traffic demand predicted for year 1995. Since the traffic in year 2003 is quite different from that in year 1995, it is desirable to reconfigure the logical topology according to the traffic demand in year 2003. The dashed curve represents the blocking probability after the logical topology has been reconfigured according to the traffic in year 2003. We notice from the figure that, for a blocking probability of $10^{-3}$ after the reconfiguration, the offered load can be increased by 20%. The advantage of reconfiguration becomes clear.

As mentioned before, a regular virtual topology is used in [6]-[8]. In the following, we compare the performance of the proposed heuristic algorithm with that of a fixed regular ShuffleNet virtual connection [1]. To realize a 24 node ShuffleNet with fan-out equal to 2, based on the heuristic algorithm (with little modification), a total of 9 wavelengths is required. Since the fan-out of this ShuffleNet is 2, the node capacity should be at most 2 (even though 9 wavelengths are required in the network). In Fig. 8, the blocking probability for scheme 2, $K = 3$, is compared with that of ShuffleNet connection. The blocking probability for node capacity of 4 is significantly lower than that of the ShuffleNet. Recall that a total of 9 wavelengths are required to realize the ShuffleNet pattern. The advantages of the heuristic algorithm becomes apparent.

VI. CONCLUSION

From the results of this study, two conclusions can tentatively be drawn. First, as long as the capacity of access node (normalized by the optical channel capacity, $C$) is less than the number of wavelengths (transmitters or receivers) per access station, then, the traffic-handling capacity of the multihop lightwave network is virtually indistinguishable from that of an ideal centralized switch. Second, the heuristic algorithm
which we have proposed to create the optical connection graph, and, the routing scheme which we have studied, are both quite effective in utilizing the resources of the network. Both conclusions are, of course, strictly predicated upon lightweight network service provisioning over a region bearing traffic pattern and fiber plant similar to those of the model which we have studied, and robustness of the approaches suggested in this paper must be tested against other wider-area models. However, our results are indeed encouraging since they suggest that known traffic pattern nonuniformities can effectively be exploited, and, further, that excellent results can be obtained from static connection graphs which do not need to be reconfigured to accommodate each new request for a virtual connection. Thus, a polynomial time connection graph algorithm, such as the one which we have proposed, needs to be executed only infrequently, i.e., when the long-term average traffic pattern have changed, and the basic optical network architecture can therefore be scaled to very large configurations.

For traffic patterns that change with time of day or day of week, one first needs to compute the gain in terms of the network capacity for a given blocking probability requirement if the network is reconfigured using the proposed algorithm. Then the performance gain obtained must be justified for the complexity involved in performing the reconfiguration every several hours. In other words, for multi-hour traffic, the trade-off between complexity and efficiency must be studied. It should be pointed out that 1) the proposed algorithm is a centralized one; for large networks, a scalable distributed algorithm should be investigated. 2) Other distribution for call durations as well as call arrival processes, like the ones presented in [15], should be considered in the future.

ACKNOWLEDGMENT
The authors would like to thank G. Brown, S. Jaganath, and Y. Hou for many useful discussions during the course of this work, and the anonymous reviewers for their valuable comments.

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