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Abstract

Sub-wavelength traffic grooming in optical networks has gained significant importance due to the prevailing fractional wavelength traffic requirement of end-users. Dynamic routing schemes improve the performance of WDM grooming networks compared to static routing as they can adapt to changes in the network state. In this paper, the significance of dynamic routing of fractional wavelength traffic based on request characteristics is illustrated. We propose a request-specific routing scheme, called available shortest path routing, and study its performance. The results are compared against other routing schemes that do not use request characteristics in selecting a path. It Is shown that request-specific routing can improve the network performance with respect to utilization and fairness metrics.

Keywords

wavelength division multiplexing, optical fibre networks, telecommunication network routing, telecommunication traffic

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Request-Specific Routing in WDM Grooming Networks

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***Abstract*—Sub-wavelength traffic grooming in optical networks has gained significant importance in recent years due to the prevailing fractional wavelength traffic requirement of end-users. Dynamic routing schemes improve the performance of WDM grooming networks compared to static routing as they can adapt to changes in the network state. In this paper, the significance of dynamic routing of fractional wavelength traffic based on request characteristics is illustrated. We propose a request-specific routing scheme, called Available Shortest Path Routing, and study its performance. The results are compared against other routing schemes that do not use request characteristics in selecting a path. It is shown that request-specific routing can improve network performance with respect to utilization and fairness metrics.**

***Index Terms*— Optical networks, Traffic grooming, Dynamic routing**

I. INTRODUCTION

Optical communication employing wavelength division multiplexing (WDM) has emerged as the most viable infrastructure for wide-area backbone networks. WDM divides the available fiber bandwidth into a set of wavelengths (WDM channels). The bandwidth on a wavelength is close to the peak electronic transmission speed. The transmission speed on a wavelength has been steadily increasing from 2.5 Gbps (OC-48) to 10 Gbps (OC-192) and is expected to increase up to 40 Gbps (OC-768) in the near future. The bandwidth on a wavelength is too large for certain traffic requirements. One approach to provisioning fractional wavelength capacity is to divide a wavelength into multiple time slots and multiplex traffic on the wavelength. The resulting multi-wavelength time-division multiplexed networks are referred to as *WDM-TDM networks* or *WDM grooming networks*. Nodes in such networks are capable of multiplexing/de-multiplexing lower rate traffic onto a wavelength and switching them from one *lightpath* to another, where a lightpath is defined as an all-optical full-wavelength connection between two nodes. Optical processing and storage technologies today are not mature enough to achieve run-time routing decisions at high-speeds. Therefore, WDM grooming networks are *circuit-switched* in nature.

WDM grooming networks can be classified into two categories [1]: dedicated-wavelength grooming (DWG) networks and shared-wavelength grooming (SWG) networks. In DWG networks, a lightpath between two nodes is shared only by the traffic between the nodes. In SWG networks, the lightpath can be shared by traffic from other nodes as well. The performance of SWG networks depends on efficient merging of fractional wavelength requirements into full or almost-full wavelength requirements. Such merging of smaller capacity requirements into higher capacity lightpaths is called *traffic grooming*.

Traffic grooming in SWG networks can be performed in a static or dynamic manner. In static grooming, the source-destination pairs whose traffic requirements will be combined are pre-determined. In dynamic grooming, connections of different source-destination pairs are combined based on the existing lightpaths at the time of a request arrival.

Nodes in a WDM grooming network can be classified into various categories depending on the level of grooming capability available. If a node can multiplex and de-multiplex low-rate traffic only on *dropped* wavelengths at an add-drop multiplexer (ADM), it is referred to as an *ADM-constrained grooming* (ADM-CG) node. ADM-CG nodes have fewer number of ADMs as compared to the total number of wavelengths in the links connected to the node. If a node can switch connections across different lightpaths but cannot convert them from one wavelength to another, it is termed as a *wavelength continuity constrained grooming* (WC-CG) node. WC-CG nodes have dedicated ADMs for every wavelength on every link. Connections are dropped at these nodes even if they are not destined for them. If a node can switch connections in any permutation from one wavelength to another, then it is termed as a *full grooming* (FG) node.

Dynamic routing in WDM grooming networks has received very little attention thus far in the literature [2]. It has been extensively studied in the context of Quality-of-Service (QoS) routing for single-channel networks [3]. A single-channel network is equivalent of an optical network with one wavelength. In our preliminary work [2], a methodology for dynamic routing of fractional wavelength traffic in WDM grooming networks is developed. The performance of three destination-specific routing algorithms, namely shortest-widest path, widest-shortest path, and fixed alternate path routing, are studied.

In this paper, we propose and study a request-specific routing algorithm called *available shortest path routing*. The paper is organized as follows: Section II describes the steps involved in dynamic routing and different routing paradigms. Section III describes the network model and dynamic routing schemes that are considered for performance evaluation. The experimental setup, performance metrics, and results are discussed in Section IV. Conclusions are presented in Section V.

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II. DYNAMIC ROUTING

Dynamic routing consists of two basic steps: (a) collection of network state information and (b) selection of a path using the gathered information.

The state of the network is defined by a set of link and node parameters. The bandwidth available on a wavelength, delay, etc. are examples of link parameters. The grooming capability available at a node is an example of a node parameter. The network state information is collected at a node using either link state or distance-vector protocols [4]. In link state protocols, every node transmits its node-specific and link-specific information to every other node in the network. Hence every node in the network is aware of the entire network topology. In a distance-vector protocols, the network state is gradually updated at every node by exchanging the distance information with its neighbors. In this approach, the nodes in the network are not aware of the network topology. Every node maintains a routing table that indicates the preferred neighbor to reach any other node.

The second step in dynamic routing is to identify a path from a source to destination using the collected network state information. The path selection strategies can be divided into two categories: source routing and distributed routing.

In *source routing*, each node maintains the global network state. Upon a request arrival at a node, a path to the destination is selected from a set of *feasible paths* and a control message is sent along the path. If resources are available in all the links of the path, the connection is established and the link state information is updated accordingly. Otherwise, the connection is rejected. In *distributed routing*, as the name suggests, the routing decisions are made in a distributed manner. When a connection request arrives at a node, the preferred neighbor to reach the destination is identified and the request is forwarded. This approach relies only on the neighborhood information. The intermediate nodes have the flexibility of re-routing a request depending on the network dynamics.

Dynamic routing schemes can be classified into two categories based on the information used for selecting a path [5]: *destination-specific* and *request-specific*. In the destination-specific approaches, the path selection algorithms select the *best* possible route to reach a destination without the knowledge of the request. This technique is well-suited for networks where all the requests are of same nature. The traditional shortest-path routing based on hop-length is an example of destination-specific routing. In the request-specific approach, a path is selected based on the characteristics of a request. The choice of the preferred neighbor for different requests to the same destination could be different. This approach is well-suited for networks in which the characteristics of the requests vary significantly.

III. NETWORK MODEL

A WDM grooming network consists of switching nodes interconnected by one or more optical fibers. Each fiber carries a certain number of wavelengths. Each wavelength is divided into frames which are further sub-divided into time slots. Let L denote the number of links at a node, F denote the number of fibers per link, W denote the number of wavelengths per fiber, and T denote the number of time slots per frame on a wavelength. A timeslot on successive frames is referred to as a *channel*.

In this paper, a WDM grooming network with WC-CG nodes are considered. The choice of studying this node type is due to the increasing interest in developing all-optical solutions for traffic grooming. It is well understood that all-optical wavelength conversion is an expensive proposition, hence is not likely to be employed in the networks in the near future. Hence, the first generation technology in all-optical grooming is expected to obey wavelength continuity constraint.

Every node in the network is assumed to maintain the global state information through a link state protocol. Every link in the network is denoted by a *link state vector*. The vector consists of a set of properties associated with a link, eg. available bandwidth on individual wavelengths, hop-length, fiber length etc. Each entity in the vector is referred to as a *metric*. Every path from a source to destination has a *path-vector* that is obtained by combining the link state vectors of the links in the path. Note that a link vector is a special case of a path vector when the path has only one link.

The information collection and path selection schemes considered in this paper are based on two metrics: available wavelength capacity and hop length. A path with W wavelengths with C channels per wavelength is denoted by a vector $\{(A_1, A_2, ..., A_W); H\}$, where each A_w ($0 \leq A_w \leq C$) denotes the number of available channels on a wavelength and H denotes the hop-count. For a link vector, the value of H is 1. The available capacity on a wavelength w and hop length of a path p is denoted by A_p^w and H_p, respectively.

A. Extended Dijkstra's shortest path algorithm

Traditional Dijkstra's shortest path algorithm [4] employs one metric referred to as *cost*. The cost of a path is computed as the sum of the cost of individual links. A path with minimum cost is chosen to establish a connection between a given source and destination.

In this paper, we extend the Dijkstra's shortest path algorithm to the above link state vector, referred to as *extended Dijkstra's shortest path (EDSP) algorithm*, and is employed at every node in the network. The EDSP algorithm uses the link state vector as defined above instead of a single metric that is traditionally used. The EDSP algorithm has two important operations: (1) combining two path vectors and (2) selecting the best path vector. Let ψ_{ik} and ψ_{kj} denote the path vectors from node i to k and from node k to j, respectively. The path vector from node i to j through k is obtained by combining the path vectors ψ_{ik} and ψ_{kj}, denoted by $\psi_{ij} = \psi_{ik} + \psi_{kj}$. The vectors are combined in different ways depending on the grooming capability of the node k.

In wavelength-level grooming networks, connections cannot be switched from one wavelength to another. Hence, wavelength continuity constraint is obeyed. Two paths vectors ψ_{ik} and ψ_{kj} are combined at a WG node to obtain ψ_{ij} where $A_{ij}^w = min(A_{ik}^w, A_{kj}^w)$ and $H_{ij} = H_{ik} + H_{kj}$.

The second operation of selecting the best path vector from a given set of path vectors is defined by a specific path selection policy.

B. Path selection algorithms

Path selection algorithms specify the rule for selecting the best path vector in the EDSP algorithm. For example, the traditional shortest path algorithm selects a path with minimum hop length. The three path selection schemes that are considered in this paper are:

Widest-Shortest Path Routing (WSPR): In this approach, the available wavelength capacity vector on a path is ordered in descending values of the individual wavelength capacities. Thus an available wavelength capacity vector $A'_p = (A'_1, A'_2, ..., A'_W)$ is said to be ordered descending if $A'_i \geq A'_j$ for $i < j$ and $1 \leq i, j \leq W$.

An ordered vector $A' = (A'_1, A'_2, ..., A'_W)$ is said to be lesser than another ordered vector $B' = (B'_1, B'_2, ..., B'_W)$ if for some i ($1 \leq i \leq W$), $A'_i < B'_i$ and for all $j < i$ $A'_j = B'_j$. The vectors are said to be equal if $A'_i = B'_i$, for all i, where $1 \leq i \leq W$. Otherwise, A is said to be larger than B. A path with the largest path-vector is said to be the *widest* path and is chosen for establishing a connection. If two paths are same with respect to this metric, then the path with the minimum hop length is chosen. In case of tie on both metrics, one of the paths is chosen at random.

Shortest-Widest Path Routing (SWPR): This approach is the conventional shortest-path routing based on hop length. If the hop length of two paths are same, then the widest among them is chosen. In case of a tie on both metrics, one of the paths is chosen at random.

Available Shortest Path Routing (ASPR): In this approach, the shortest path among those that can accommodate the request is chosen. The paths that can accommodate the request are those that have at least one wavelength that can accommodate the request. If two paths that can accommodate the request have same hop length, then one of them is chosen at random.

WSPR and SWPR are examples of destination-specific routing schemes while ASPR is an example of request-specific routing. In ASPR, the set of feasible paths is chosen based on the capacity requirement of the request.

C. An example

Consider the example network shown in Fig. 1. Assume that every link carries two wavelengths and each wavelength is divided into 4 time slots. The tuples shown in the figure correspond to the available wavelength capacity on each wavelength.

Consider a request that originates from Node 2 destined to Node 6. The SWPR algorithm selects the path $2 \rightarrow 5 \rightarrow 6$ with path vector {(0,0);2}. However, the request cannot be accommodated due to lack of capacity on link $5 \rightarrow 6$. The WSPR algorithm selects the path $2 \rightarrow 1 \rightarrow 3 \rightarrow 4 \rightarrow 6$ with path vector {(0,4);4}. These paths are chosen irrespective of the request requirements.

The ASPR algorithm selects the path based on the request. If the request is for one time slot, then the path $2 \rightarrow 1 \rightarrow 4 \rightarrow 6$ with a path vector {(0,1);3} or $2 \rightarrow 3 \rightarrow 4 \rightarrow 6$ with path vector {(2,2);3} is chosen. If the request is for 2 time slots, the path $2 \rightarrow 3 \rightarrow 4 \rightarrow 6$ with path vector {(2,2);3} is chosen. If the request is for 3 or 4 time slots, then the path $2 \rightarrow 1 \rightarrow 3 \rightarrow 4 \rightarrow 6$ with path vector {(0,4);4} is chosen.

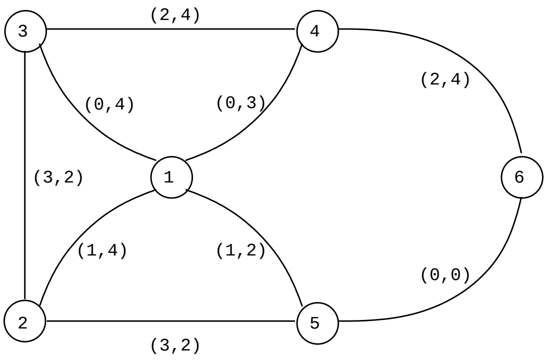

Fig. 1. An example network.

IV. PERFORMANCE EVALUATION

The performance of various path selection algorithms described in the previous section are evaluated on the NSFnet and ARPA-2 networks. Similar performance trends were observed for these networks. Due to space constraints the results of the NSFnet network alone are discussed in this paper. The 14-node 22-link NSFnet network is shown in Fig. 2.

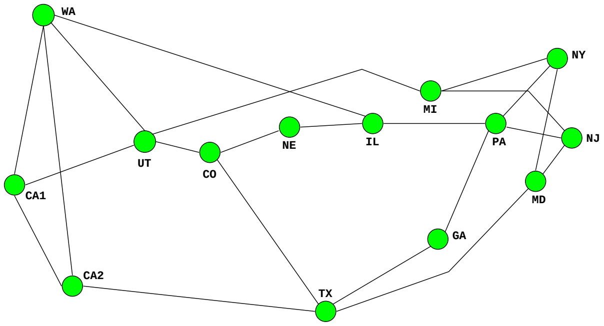

Fig. 2. The NSFnet network.

A. Experimental setup

The experimental setup for the simulation is based on the following assumptions: (1) The arrival of requests at a node follow a Poisson process with rate λ and are equally likely to be destined to any other node; (2) The holding time of the requests follow an exponential distribution with unit mean; (3) The capacity requirement of a request (in time slots) is equally likely to take integer values from 1 to 8; (4) Every link has 128 channel capacity divided over W wavelengths; and (5) Connections are setup based on the best-fit wavelength assignment on a chosen path.

A network with links having W wavelengths and T channels per wavelength are referred to as $W \times T$ network. Two different wavelength-channel combinations are considered: (1) 16×8 and (2) 1×128. Note that as the number of wavelength decreases, the grooming capability increases. A total of 6×10^5 requests were generated with performance metrics being measured in batches of 10^5 requests. The average of the performance metrics observed over six set of experiment runs are reported in the results. The confidence interval for the reported results were found to be 95% around 5% of the average, except for values of blocking probability below 10^{-4}.

B. Performance metrics

The performance metrics that are measured are: (1) request blocking probability; (2) network utilization; (3) average path length of an established connection; (4) average shortest-path length of an accepted request; and (5) average capacity of an accepted request.

While the computation of most of the above metrics are intuitive, the network utilization is computed as below: Consider a request for capacity b from source s to destination d. If the shortest path length from the source to destination is h_s, then the effective capacity requirement of the request is defined as $b \times h_s$. This is the minimum capacity that is required in the network to accommodate the request, irrespective of the routing scheme employed. The path length of the connection that is established for an accepted request may be greater than the shortest path length between the source and destination.

The effective network capacity utilized at an instant of time, denoted by U, is defined as the sum of the effective network capacity requirement of all the connections that are active at that instant. The value of U at any instant of time is bounded by $L \times C$, where L is the total number of links in the network and C is the capacity on each link. The network utilization is then computed as the ratio of the effective used capacity to the maximum capacity of the network as $\frac{U}{L \times C}$. The offered network load is computed as the effective network utilization of all the requests generated in the network.

C. Performance results

Fig. 3 shows the blocking performance of different routing algorithms on 16×8 and 1×128 NSFnet networks. It is observed that ASPR performs better than SWPR and WSPR. It is also observed that as the network load is increased, the blocking performance of WSPR worsens as it routes connection over wider but longer paths resulting in wastage of bandwidth.

Fig. 4 shows the network utilization under different routing algorithms on 16×8 and 1×128 NSFnet networks. It is observed that ASPR achieves the the maximum utilization compared to WSPR and SWPR.

More insights into the working of the algorithms are obtained by observing the average path length of the connections established. Fig. 5 shows the average path length of connections established in the networks by different routing algorithms. It is observed that WSPR selects longer paths for establishing connections as compared to ASPR and SWPR. This difference is significant when the grooming capability in the network is increased. This indicates that increasing the grooming capability helps dynamic routing algorithms in finding more paths but at the expense of longer path lengths. SWPR has the least value for this metric as it selects only shortest paths. The average path length of SWPR for 1×128 network is higher than that of 16×8 network because more connections are accepted in the former network.

Fig. 6 shows the average shortest path length of accepted requests for different routing schemes. At low loads, very few requests are rejected. Hence, the average shortest path length of accepted requests is the same for different routing schemes. When the offered load to the network is increased, requests with longer shortest path length experience more blocking resulting in a bias in favor of requests with smaller shortest path length. The lower the value of this metric for a routing algorithm, the stronger is the bias in favor requests with smaller path length. ASPR performs the best with respect to this fairness metric. It is observed that increasing the grooming capability enhances the performance of the routing schemes with respect to this metric.

The routing schemes also exhibit a bias in favor of smaller capacity connections when the offered load to the network is increased. Requests for larger capacity experience more blocking than the ones for smaller capacity. Such a behavior is pro-

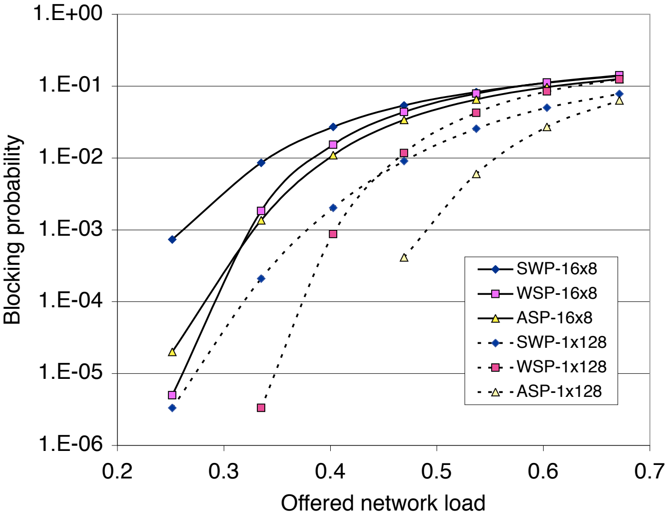

Fig. 3. Blocking performance of different routing algorithms on 16×8 and 1×128 NSFnet networks.

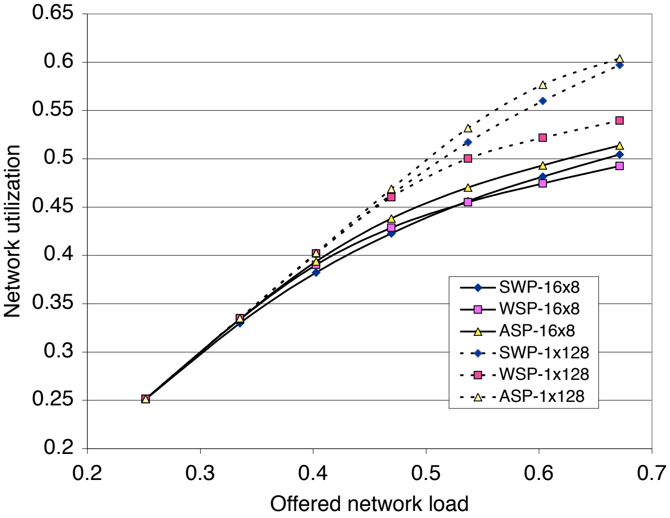

Fig. 4. Network utilization by different routing algorithms on 16×8 and 1×128 NSFnet networks.

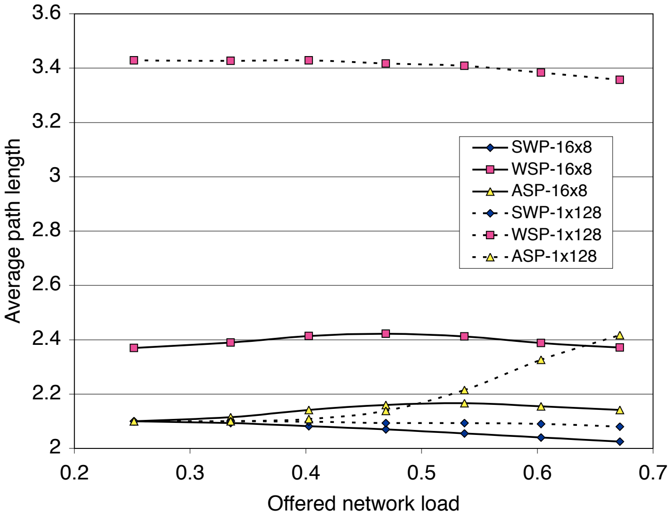

Fig. 5. Average path length of connections established by different routing algorithms on 16×8 and 1×128 NSFnet networks.

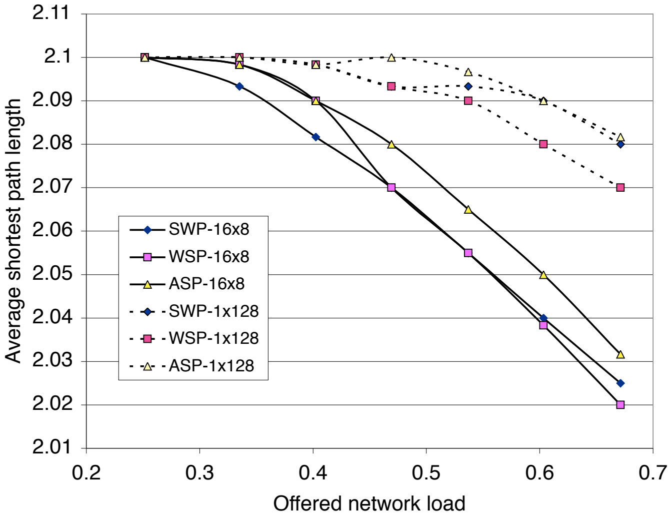

Fig. 6. Average shortest path length of accepted requests by different routing algorithms on 16×8 and 1×128 NSFnet networks.

nounced in networks that have lesser grooming capability. Fig. 7 shows the average capacity of accepted requests for different routing schemes. It is observed that increasing the grooming capability enhances the fairness of the routing algorithms with respect to requests of different capacity requirement.

The average shortest path length and average capacity of accepted requests quantify the fairness property of the routing algorithms. An ideal routing algorithm would have a constant value for these metrics at all network loads.

SWPR aims at efficient utilization of the available resources by routing requests along the shortest path only. WSPR attempts to find paths dynamically however emphasizes on distributing the load in the network. ASPR attempts to mimic SWPR among those paths that can accommodate a request.

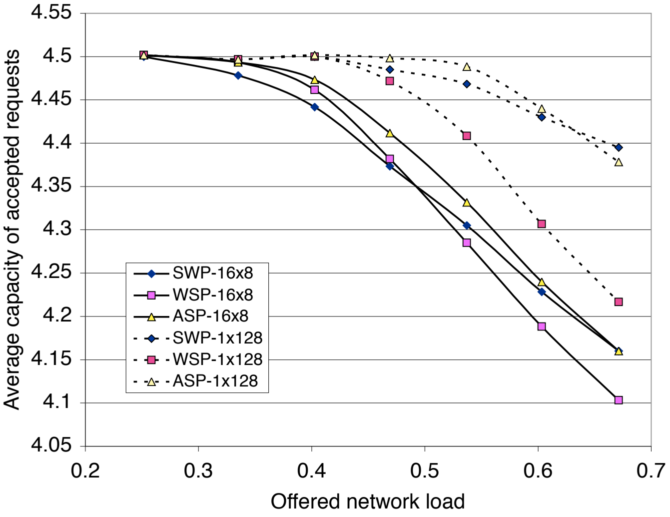

Fig. 7. Average capacity of accepted requests by different routing algorithms on 16×8 and 1×128 NSFnet networks.

It is observed from the performance results that request-specific routing schemes can improve network performance with respect to utilization and fairness schemes as compared to destination-specific routing schemes.

Similar performance trends were observed in 8×16 and 4×32 NSFnet networks as well. The performance of these networks are not reported in this paper due to space limitations, however can be interpolated from the results presented in this paper for the NSFnet network with extreme cases of grooming capability.

V. CONCLUSION

This paper illustrates the significance of employing request-specific routing in WDM grooming networks. We propose and study a request-specific routing scheme called Available Shortest Path Routing (ASPR). ASPR considers the capacity requirement of a request and selects the shortest path among those that can accommodate the request. It is shown through simulations that ASPR enhances the performance of the network with respect to utilization and fairness metrics as compared to destination-specific routing schemes.

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