Photon Netw Commun (2006) 11:287–299
DOI 10.1007/s11107-005-7356-2

ORIGINAL ARTICLE

On-line routing in WDM–TDM switched optical mesh networks

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Received: 14 June 2005 / Revised: 22 December 2005 / Accepted: 22 December 2005

Abstract This paper considers the on-line traffic grooming problem in WDM–TDM switched optical mesh networks without wavelength conversion capability. In such a network, provisioning of connection requests with fractional wavelength capacity requirements is achieved by dividing a wavelength into multiple time slots and multiplexing traffic on the wavelength. In this paper, we present an on-line traffic grooming algorithm for the concerned problem. The objective is to efficiently route connection requests with fractional wavelength capacity requirements onto high-capacity wavelengths and balance the load on the links in the network at the same time. To do so, we propose a cost function, which not only encourages grooming new connection requests onto the wavelengths that are being used by existing traffic, but also performs load balancing by intelligently increasing the cost of using wavelengths on links. The performance results obtained by experiments on a representative sized mesh network show that the proposed algorithm outperforms the other existing algorithms.

Keywords On-line routing · Optical WDM–TDM switched networks · Optical time slot interchanger (OTSI) · Traffic grooming · Load balancing

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Introduction

Wavelength Division Multiplexing (WDM) optical networks provide enormous bandwidth, and are promising candidates for information transmission in high-speed networks [1]. In WDM networks, the fiber bandwidth is partitioned into multiple data channels in which different data can be transmitted simultaneously on different wavelengths. The bandwidth available on each wavelength in commercial WDM systems is in the order of OC-48/OC-192/OC-768 (2.48 Gbps/10 Gbps/40 Gbps). However, as most applications require only sub-wavelength capacities, the available bandwidth on a single wavelength far exceeds the capacity requirement of a typical connection request. For example, HDTV works well with just *20 Mbps*.

As wavelengths are critical resources in WDM optical networks, the available bandwidth on wavelengths needs to be utilized efficiently. To overcome the disparity between the bandwidth required by connection requests and the available bandwidth on wavelengths, a technique called *traffic grooming* has been proposed [2]. One approach to provisioning sub-wavelength capacity requests (traffic grooming) is to divide a wavelength into multiple time slots and multiplex different requests onto different time slots [3, 4]. Thus, upto p connection requests can share the same wavelength, assuming each request occupies one time slot and each wavelength is divided into p time slots. The resulting multiwavelength optical time division multiplexed network is referred to as a *WDM–TDM network* or a *WDM grooming network*. WDM–TDM networks can be classified into two types—(i) dedicated-wavelength TDM networks and (ii) shared-wavelength TDM networks [5]. In the former, entire wavelengths are dedicated to connection requests between specific source-destination pairs. Connection requests between other source-destination pairs cannot use these dedicated resources and switching is

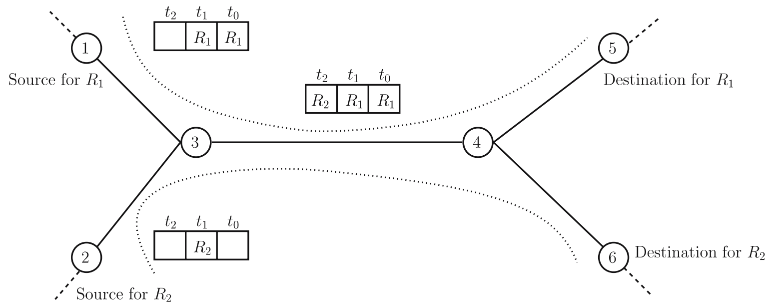


Fig. 1 A WDM–TDM switched network

not performed in the time domain at the intermediate nodes along the routing path. In the latter, time slots within a wavelength, rather than the entire wavelength, are dedicated to specific source-destination pairs. Various other connection requests can share the same wavelength on a link by using different time slots for information transmission. The bandwidth available in such networks is used more efficiently than in networks which dedicate entire wavelengths between specific source-destination pairs.

The nodes in a WDM–TDM network have the functionality of multiplexing (demultiplexing) low rate traffic onto (from) a wavelength, and switching them from one lightpath to another, where a *lightpath* is an all-optical, full-wavelength-capacity transmission medium that uses the same wavelength along the links in the routing path. A WDM–TDM switched network can be viewed as a special case of the shared-wavelength TDM network [6], where all the nodes in the network are capable of grooming traffic and lightpaths to neighboring nodes are established permanently. A connection between a source node and a destination node is setup by assigning time slots on every link in the routing path. Intermediate nodes along the path then switch time slots from one link to the next. Development in optical switching technology has paved the way for fast all-optical switches [7–9]. All-optical switching seeks to eliminate electronic switching components and avoids O/E/O conversion. It has other potential benefits such as protocol transparency and bit rate independence, thus overcoming the drawbacks of traditional wavelength routed networks. Use of such all-optical switches in conjunction with fiber delay lines as time slot interchangers have helped realize WDM–TDM switched networks [10, 11].

A *wavelength converter* is a device that converts a signal on one wavelength on to another wavelength. In optical networks without wavelength converters, a signal can only be switched from a certain wavelength at an input port to the same wavelength on an output port. This is the well known *wavelength continuity constraint*. Although wavelength converters improve the network blocking performance, it is well known that all-optical wavelength converters are prohibitively expensive. Due to the increasing interest in developing all-optical solutions for traffic grooming, the first generation optical switching technology is expected to obey the wavelength continuity constraint [3, 4], i.e., a connection between two endpoints can be setup on one wavelength only, and wavelength conversion is not allowed at the intermediate nodes along the routing path. Therefore, a node in such a WDM–TDM network can switch time-slots from an incoming wavelength signal at an input port to different time-slots on the outgoing wavelength signal at any output port. The switching, however, is subject to the wavelength continuity constraint.

To illustrate the concept of a WDM–TDM switched network, we use an example (see Fig. 1), in which each link is assumed to carry two wavelengths and each wavelength is further divided into three time slots. Request R_1 originating from node 1 and requiring two time slots of bandwidth occupies time slots t_0 and t_1 on link 1–3. Request R_2 originating from node 2 and requiring one time slot of bandwidth occupies time slot t_1 on link 2–3. In traditional wavelength routed networks, two wavelengths would be required to route these requests on link 3–4 since no two requests can use the same wavelength on the same link. As these requests need only fractional wavelength capacities, allocating full wavelength capacity leads to poor utilization of wavelength resources. However, in WDM–TDM switched networks, only one wavelength would be required, as shown in the figure. Time slots from requests R_1 and R_2 can be aligned at node 3 before the signal is switched on to link 3–4. An OTSI at node 3 delays R_2 by one time slot duration so that it can be mapped on to time slot t_2 on the resulting outgoing wavelength. It is evident that WDM-TDM switched networks with OTSIs use network resources more efficiently and provides an effective all-optical approach to traffic grooming.

Related work

Previous research on traffic grooming mainly focused on WDM/SONET rings, with the objective to minimize the total network cost in terms of the number of SONET add-drop multiplexers [12–14]. In [15], the authors consider the problem of designing a virtual topology that minimizes electronic routing in an optical ring network. Ref. [16] provides network designs for OADM rings that minimize the overall network cost rather than just the number of wavelengths. The authors include the cost of transceivers required at the nodes and the number of wavelengths as metrics for the total network cost.

As WDM networks evolve from rings to arbitrary mesh topologies, addressing the traffic grooming problem in the context of mesh networks is extremely pragmatic. A detailed survey of traffic grooming can be found in [17]. In [18], the authors provide an overview of the architectures for traffic grooming. Static traffic grooming has been widely investigated in the literature [19–24]. An Integer Linear Program (ILP) formulation can be developed to optimize a certain objective, e.g., network throughput [19], number of transceivers [20], or wavelength usage [21]. Ref. [22] presents a Lagrangian-based heuristic for the problem, while [23] investigates the problem using a novel graph model in which different edges can be used to represent various network constraints and different grooming policies can be realized by appropriately manipulating the weights on the edges. In [24], the authors propose a novel all-optical transport network architecture based on time sliced wavelength channels (WDM–TDM networks) and study static traffic grooming with time slot continuity constraint.

On-line traffic grooming in traditional WDM networks is investigated in [25–30]. In [25], on-line traffic grooming algorithms are proposed to route connection requests on single/multiple lightpaths, whereas in [26], an agent based mechanism is proposed to achieve higher throughput when grooming traffic at the nodes. In [27], the authors propose a dynamically changing light-tree model using a layered graph to address the problem. In [28], the authors consider the sparse placement of grooming nodes in WDM mesh networks. The connection requests are not uniformly distributed between all node pairs. By appropriately selecting only a subset of grooming nodes, they show that the resulting performance is similar to networks where all the nodes are capable of grooming traffic. In [29,30], the authors extend their previous work [23] by applying the graph model to solve the on-line traffic grooming problem. Four different grooming policies are presented— (i) Minimize the Number of Traffic Hops on the Virtual Topology (MinTHV), (ii) Minimize the Number of Traffic Hops on the Physical Topology (MinTHP), (iii) Minimize the Number of Lightpaths (MinLP), and (iv) Minimize the Number of Wavelength-Links (MinWL). The experimental results indicate that MinTHV and MinTHP always outperform MinLP and MinWL.

On-line traffic grooming in WDM–TDM switched networks was first investigated in [5]. The work examines the effect of wavelength conversion and time slot interchange on the performance of WDM–TDM networks. Their study concludes that, in networks with small number of wavelengths and large number of time slots per wavelength, significant performance gains can be achieved without the use of wavelength conversion but with the use of time slot interchange alone. In [31], the authors study the effects of wavelength conversion, time slot interchangers and switch reconfigurability on the blocking performance of routing sub-wavelength demands in WDM–TDM networks. In [32], the authors investigate a call admission control mechanism to provide fairness control in WDM grooming networks. A Markov Decision Process approach is used to derive an optimal connection admission control policy. In [33], the authors consider online traffic grooming in time division multiplexed WDM networks under the assumption that the nodes in the network do not have time slot interchangers. As a result, a connection request between a source node and a destination node must occupy the same time slot(s) along the links in the path. This can lead to a high blocking probability when compared to networks that incorporate time slot interchange functionality. The problem is solved by first partitioning it into three sub-problems: routing, wavelength assignment and time slot allocation. For every new incoming connection request, each of these sub-problems is then solved separately to determine the route, wavelength and time slot on which to route the request. In [3, 4], the authors consider the general problem of on-line routing in WDM–TDM switched networks with OTSIs, while in [6], they propose a generalized network model called the Trunk Switched Network (TSN) to facilitate modeling and analysis of WDM–TDM switched networks. An analytical model is developed to evaluate the blocking performance of TSNs.

It must be mentioned that in [34], the authors use an exponential cost function and present an on-line routing algorithm for permanent virtual circuits that minimizes the required bandwidth. They show that the algorithm achieves an $O(\log n)$ competitive ratio with respect to maximum congestion, where n is the number of nodes in the network. The simulation study in [35] concludes that in traditional electronic networks, routing permanent virtual circuits using an exponential cost function leads to improved network performance. The ideas presented in this paper have also been extended to solve the *on-line multicast routing problem* in WDM grooming networks [36].

Our contributions

In this paper, we introduce a novel exponential cost function and propose an on-line routing algorithm for traffic grooming in WDM–TDM switched mesh networks. The algorithm integrates traffic grooming and load balancing with the aim of maximizing the network throughput. It combines path selection and wavelength assignment rather than performing routing and wavelength assignment separately. We show through experimental results that the proposed heuristic algorithm outperforms other well-known algorithms discussed and analyzed in [3, 4] for traffic grooming in WDM–TDM switched networks.

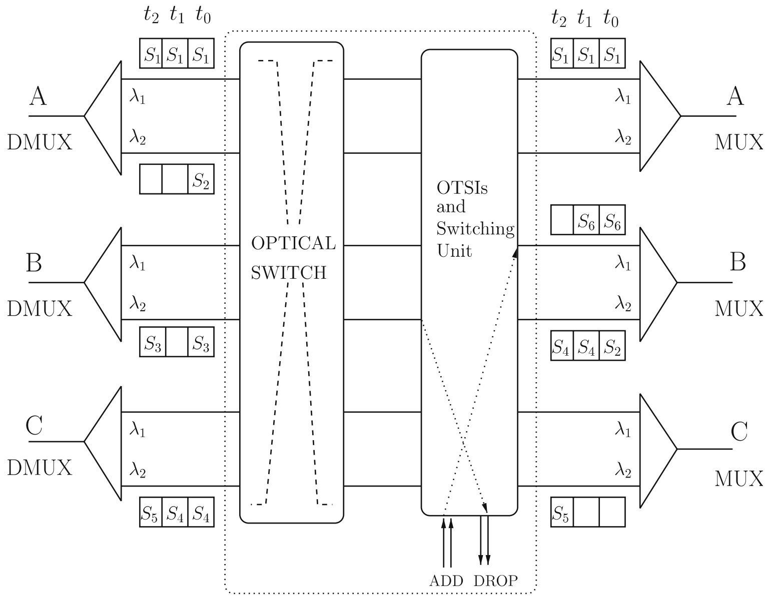


Fig. 2 Node architecture for sub-wavelength demand traffic grooming with all-optical switches and OTSIs

The rest of the paper is organized as follows. The node architecture and the problem definition are introduced in Section 2. The proposed heuristic algorithm is presented in Section 3 and the simulation results are discussed and analyzed in Section 4. We conclude the paper in Section 5.

Preliminaries

In this section, we first introduce the node architecture used in our study and then formally define the on-line traffic grooming problem. We then provide a brief overview of the existing algorithms for the concerned problem.

Node architecture

A WDM–TDM switched mesh network consists of switching nodes with communication fiber links interconnecting the nodes. Each fiber link carries a certain number of wavelengths and each wavelength is further divided into a number of time slots. The node architecture for sub-wavelength demand traffic grooming in such a WDM–TDM switched mesh network is shown in Fig. 2.

The figure represents a node supporting three links (A, B, C), two wavelengths per link (λ_1, λ_2) and three time slots per wavelength (t_0, t_1, t_2). S_1, S_2, S_3, S_4, S_5, and S_6 are sessions utilizing 3, 1, 2, 2, 1, and 2 time slots of bandwidth respectively. Session S_1 occupying the full bandwidth on λ_1 is switched from input link A to the same output link. S_2 occupying time slot t_0 is switched to the same time slot from input link A to output link B on λ_2. Session S_3 arriving on λ_2 from input fiber link B is dropped locally at the node while session S_6 is added at the node and switched to output link B on λ_1. As there are three time slots per wavelength, the optical switch can be set in only three possible settings at any given time. When the switch is set to time slots t_0 and t_1, the signal S_4 occupying these time slots on λ_2 is switched from input link C to output link B. Signals can be delayed using Optical Time Slot Interchangers (OTSIs), therefore, time slots on an incoming signal can be mapped on to different time slots on the outgoing signal. Thus, before signal S_4 is sent on output link B, it undergoes a delay of one time slot duration so that time slots t_0 and t_1 on the incoming signal are mapped on to time slots t_1 and t_2 on the outgoing signal respectively. When the switch is set to time slot t_2, S_5 is switched on λ_2 to the same time slot on the output link C. As wavelength conversion is not incorporated in this architecture, the wavelength of an outgoing signal is the same as its incoming wavelength.

Problem definition

The physical topology of a WDM-TDM switched mesh network is represented by an undirected graph $G = (V, E)$, consisting of $|V| = n$ nodes and $|E| = m$ links interconnecting the nodes. Each link in the physical topology is bidirectional and is modeled as a pair of unidirectional links. $W = \{\lambda_1, \lambda_2, \ldots\ldots, \lambda_w\}$ is the set of available wavelengths in the network. A connection request i is represented by a quadruple $(s_i, d_i, \beta_i, \Delta_i)$, where $s_i \in V$ is the source, $d_i \in V$ is the destination, β_i is the required bandwidth and Δ_i is the duration of the request.

Given the current network state (routes and wavelengths being used by existing traffic), the *on-line traffic grooming problem* is to construct a minimum cost bandwidth guaranteed path P_i^λ on wavelength $\lambda \in W$ that connects the source node s_i to the destination node d_i. The aim is to maximize the network throughput. We assume that the established requests cannot be interrupted. The connection requests arrive one after the other and the arrival sequence is not known in advance.

Routing algorithms

Traffic grooming in WDM–TDM switched networks can be classified into two types—static and dynamic. In static traffic grooming, all source-destination pairs and their associated bandwidth requirements are known in advance. On the other hand, in dynamic traffic grooming, also known as on-line traffic grooming, connection requests with varying bandwidth requirements arrive one at a time. Efficient on-line routing algorithms will be needed to determine the routing path on which to establish these requests. Based on the information used for establishing a path between the source node and the destination node [37], on-line routing algorithms can be classified into two types, (i) destination-specific routing algorithms and (ii) request-specific routing algorithms. Destination-specific routing algorithms try to establish the best possible routing path between the source node and the destination node *without* the knowledge of the incoming connection request. In other words, they establish routing paths without taking into account the bandwidth requirement of connection requests. An example is the shortest path routing based on just minimizing the hop count between the source node and the destination node. These routing algorithms are suited for networks where all the connection requests have similar characteristics. On the other hand, request-specific routing algorithms aim to establish the best possible routing path between the two endpoints taking into account the bandwidth requirement of the incoming connection request. This technique is well suited for networks where the request characteristics vary significantly.

In [3, 4], the authors propose and study a new request-specific routing algorithm called *Available Shortest Path* (ASP) and compare its performance with two other destination-specific routing algorithms—*Widest Shortest Path* (WSP) and *Shortest Widest Path* (SWP). Their results indicate the importance of using request-specific routing algorithms for improving the performance of WDM–TDM switched networks. ASP outperforms the two destination-specific routing algorithms not just in terms of blocking probability but also with respect to other metrics such as fairness and utilization. For completeness, we briefly outline these algorithms below. It is to be noted that, since wavelength conversion is not allowed, the routing algorithms are iteratively executed for each $\lambda \in W$ to determine the best possible path and wavelength on which to route the request.

(i) Widest shortest path (WSP). Dijkstra's algorithm is used to find the widest path between the source node and the destination node. If two or more paths are the same with respect to this metric, the path with the minimum hop count is selected. If two paths have the same hop count, then the tie is broken by choosing the path corresponding to the first-fit wavelength assignment policy.

(ii) Shortest widest path (SWP). This is similar to the conventional shortest path routing based on the hop count. If the hop count of two or more paths are the same, then the widest one among them is chosen. In case of a tie, the path corresponding to the first-fit wavelength assignment policy is selected.

(iii) Available shortest path (ASP). In this approach, *only* links with sufficient bandwidth capacity to accommodate the request are considered for route computation. Dijkstra's algorithm is then used to determine the shortest path between the source node and the destination node. If two or more paths can accommodate the request, then the path with the minimum hop count is chosen. If there is a tie, then the tie is broken by using the first-fit wavelength assignment policy.

To illustrate how heuristic ASP works, we consider the example shown in Fig. 3, that represents a five node subnet — 0, 1, 2, 3, 4, of a large mesh network.

Assume that the current network configuration of this subnet is as follows. One wavelength λ_0 is available on links 0–1 and 1–2, and two wavelengths λ_0, λ_1 are available on links 0–4, 4–3 and 3–2 respectively. We further assume that the total capacity available on a wavelength is 1, with sessions requiring fractional wavelength capacities. The order of sessions arriving are: S_1: $0 \to 2$, S_2: $0 \to 2$ and $S_3 : 1 \to 2$. Each session requests bandwidth equivalent to half of the wavelength capacity. The value within the parenthesis along the links in the figure indicates the amount of free bandwidth available on λ_0 and λ_1 respectively.

S_1 is routed as shown in Fig. 3(d) on λ_0. To facilitate full-duplex communication, the bandwidth requested by sessions is reserved along the links in either direction. Thus, following the establishment of S_1, S_2 is routed as shown in Fig. 3(e), also on λ_0. As a result, node 1 is *logically disconnected* from the network along with the links 0–1 and 1–2, since no further wavelengths are available on these links while S_1 and S_2 continue to remain active. By logical disconnection we mean, the links incident to a node *cannot* be used by future connection requests as they do not have any more wavelengths available. In provisioning high speed connections, traffic requests are expected to have long holding times [16]. Thus, logical disconnection of nodes result in fewer routing paths for each subsequent connection request, increasing the number of blocked requests, and in turn leading to significant loss of revenue. Consequently, the new session S_3 is blocked due to the lack of available wavelengths to route it.

On-line traffic grooming algorithm (OTGA)

In this section, we first give an overview of the proposed algorithm. We then introduce the cost function and describe how

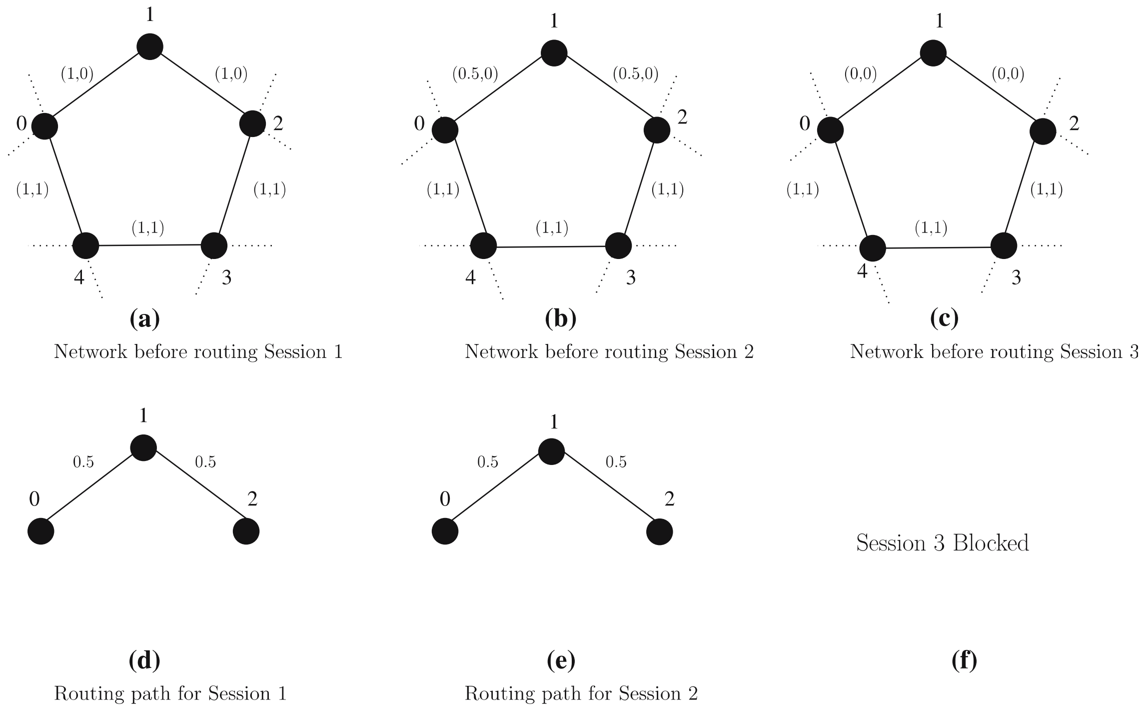


Fig. 3 Example illustrating the Available Shortest Path (ASP) routing scheme

it realizes traffic grooming and load balancing. We finally detail the proposed algorithm.

Overview of the proposed algorithm

We propose a routing scheme, OTGA, which (i) encourages grooming new sub-wavelength connection requests onto the wavelengths that are being used by existing traffic, and (ii) incorporates load balancing functionality simultaneously. To do so, we introduce a cost function that takes into consideration the *total load on a link* and the *residual available bandwidth on each wavelength*. For every new incoming connection request, Dijkstra's shortest path algorithm is used to establish the routing path between the source node and the destination node. As each connection request can only be routed on a single wavelength, at most w shortest paths can be generated, where w is the total number of wavelengths available in the network. Out of all the resulting wavelengths that can be used to establish the request, the wavelength corresponding to the least cost routing path is selected. Here, the cost of establishing the request is the sum of the cost of all the wavelength-links in the routing path. If two paths have the same cost, then the first-fit wavelength assignment policy is employed to break the tie. The bandwidth required by the connection request is then reserved along the links in the path. In the following, we use an example (see Fig. 4) to explain the idea behind the proposed algorithm.

As in the ASP scheme, S_1 is routed as shown in Fig. 4(d) on λ_0. This increases the load on the links 0–1 and 1–2. Since links 0–4, 4–3, and 3–2 have more wavelengths, it is desirable to use these links to route future connection requests and prevent the depletion of wavelengths on links 0–1 and 1–2. Therefore, higher costs are assigned to λ_0 on links 0–1 and 1–2 for subsequent connection requests. As a result, S_2 is routed on λ_0 along the shortest path as shown in Fig. 4(e). Now S_3 can be successfully established on λ_0 as shown in Fig. 4(f). Therefore, unlike in the Available Shortest Path routing strategy, S_3 is not blocked in the proposed routing scheme. Note that if links 0–1 and 1–2 had two wavelengths instead of one, then it might be desirable to groom connection S_2 along with the already established connection S_1.

We define *distance* as the minimum number of hops needed by *any* routing algorithm to route a connection request between the source node and the destination node. In other words, distance is the number of hops in the *shortest path* between the two endpoints in $G = (V, E)$ *without* considering the availability of wavelengths on links. The shortest path between nodes 0 and 2 in the mesh network (Fig. 3) consists of only two hops. Therefore, the distance between nodes 0 and 2 is 2. The number of hops used by OTGA to establish connection request S_2 between nodes 0 and 2 is 3 (see Fig. 4(e)). From these two hop counts we note that, in some cases, the number of hops needed by OTGA, and hence the amount of wavelength resources used by it is greater than the corresponding resources needed by the ASP routing scheme.

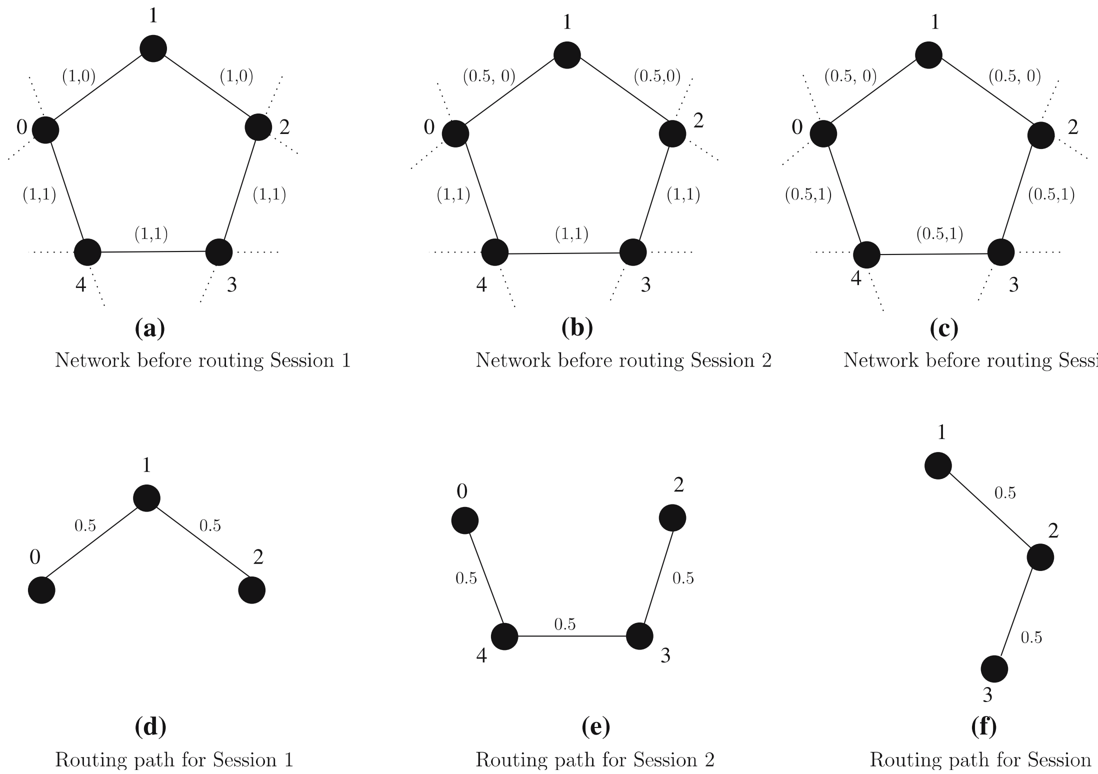


Fig. 4 Traffic grooming using the proposed OTGA routing scheme

To minimize the utilization of additional wavelength resources, we introduce the following connection admission policy. Let D_i be the distance (computed a priori) between the nodes s_i and d_i, and ε be the *additional* number of hops OTGA can take to establish the connection request between the nodes s_i and d_i. This implies that, even if sufficient bandwidth is available on wavelength $\lambda \in W$ to route request i, the request is *blocked* if the total number of hops in the resulting routing path is greater than $(D_i + \varepsilon)$. Note that ε is independent of the two endpoints of the connection request and the associated bandwidth requirement. Instead, it is an experimental parameter that is tuned depending on the physical topology of the network.

Cost function

The cost function used in the algorithm is described below.

We denote Ω as the total available bandwidth per wavelength. Let $\mu_{u,v}$ represent the total available bandwidth on a link between nodes u and v. Therefore, we have

$$\forall (u, v) \in E: \qquad \mu_{u,v} = w \times \Omega. \tag{1}$$

For convenience, we normalize the requested bandwidth to the total available bandwidth on a link. Therefore,

$$\hat{\beta}_i(u, v) = \frac{\beta_i}{\mu_{u,v}}. \tag{2}$$

Let $\mathcal{P} = \{P_1, P_2, P_3, \ldots\ldots\ldots, P_k\}$ be the set of routing paths assigned to connection requests 1 through k. If a request j is rejected, or terminates before the arrival of a new request, then $P_j = \emptyset$, where P_j is the routing path for request $j (1 \le j \le k)$. Therefore, the load on link $(u, v) \in E$ after considering request k is defined as

$$l^k_{u,v} = \sum_{\substack{j=1 \\ (u,v) \in P_j}}^{k} \hat{\beta}_j(u, v). \tag{3}$$

In WDM–TDM switched networks, bandwidth requirements of connection requests are expressed in terms of the number of time slots. In this work, we assume that each wavelength is sub-divided into 16 time slots and the capacity of each time slot is equivalent to 1 OC-3 channel. Therefore, the total capacity of each wavelength is equivalent to 1 OC-48 channel, and we have $\Omega = 16$ OC-3s.

Let $\tau_{j,\lambda'(u,v)}$ be the number of OC-3 channels being used on link (u, v) by request j on wavelength $\lambda' \in W$. Then, after considering request k, the total number of λ' OC-3 channels being used on link (u, v) is

$$U^{k,\lambda'}_{u,v} = \sum_{\substack{j=1 \\ (u,v) \in P_j}}^{k} \tau_{j,\lambda'(u,v)}. \tag{4}$$

When a new connection request i arrives, we assign costs to each wavelength $\lambda' \in W$ on the links in E as follows.

(i) If the capacity of λ' available on link (u, v) is equal to Ω, i.e. λ' is not being used by any existing connection request, then the cost of using λ' on it is

$$\Psi_{u,v}^{\lambda'} = a^{l_{u,v}^{k}} \left(a^{\hat{\beta}_i(u,v)} - 1 \right). \tag{5}$$

(ii) Otherwise, λ' is currently being used by existing traffic, and two cases arise.

Case 1. If the residual capacity of λ' on link (u, v) is less than Ω, but is no less than the requested bandwidth β_i, then the cost of using λ' on it is

$$\Psi_{u,v}^{\lambda'} = \frac{a^{l_{u,v}^{k}} \left(a^{\hat{\beta}_i(u,v)} - 1 \right)}{b^{R_{\lambda'}(u,v)}}, \tag{6}$$

where a and b are appropriately chosen constants. Here, $R_{\lambda'}(u, v)$ is the residual capacity of λ' on link (u, v) after considering the first k requests, and is given by

$$R_{\lambda'}(u, v) = 1 - \frac{U_{u,v}^{k,\lambda'}}{\Omega}. \tag{7}$$

Importantly, observe that, to realize load balancing and grooming interests, the constants a and b in the cost function must be greater than 1.

Case 2. If the residual capacity of λ' on link (u, v) is less than β_i, then $\Psi_{u,v}^{\lambda'} = \infty$, which means it cannot be used to establish the routing path.

Note that, from Equation (5), if λ' is not being used by any existing connection request on link (u, v) (i.e. full wavelength capacity of λ' is available on link (u, v)), then the cost assigned to it represents the change in its relative load that would occur if it were to be used by the new connection request [38]. From Equation (6), if the residual capacity of λ' on link (u, v) is less than Ω, but is no less than the requested bandwidth β_i, then the cost of λ' on this link is expressed as a function of the change in its relative load and the residual capacity of λ'. In other words, load balancing is realized by increasing the cost of using wavelengths on heavily loaded links, thus discouraging them from being used by new connection requests. To encourage grooming new connection requests onto the *wavelengths that are already being used* by existing traffic, the costs of these wavelengths are *further decreased* by a factor of their residual capacities. Therefore, among the wavelengths that are currently being used on a link, we encourage grooming on the wavelength that has the highest residual capacity. This minimizes the logical disconnection of nodes from the network and achieves our objective.

Algorithm

We are now ready to introduce the detailed algorithm as follows. Once a new connection request arrives, the algorithm is executed to determine whether the request is accepted.

Algorithm OTGA$(s_i, d_i, \beta_i, D_i, \varepsilon)$
begin
$\mathbb{C}_{\text{MAX}} \leftarrow \infty, \lambda \leftarrow nil, P_i^{\lambda} \leftarrow nil,$
/* $\mathbb{C}_{\text{MAX}}$ is the total cost to establish request i, λ is the resulting wavelength on which */
/* to route request i, P_i^{λ} is the routing path for request i, Ω is the total capacity per */
/* wavelength, Num_Hops (P_i^{λ}) returns the number of hops in P_i^{λ} */
Step 1. Tear down and free the wavelength resources used by all the connection requests
that terminate before the arrival of connection request i.
$\forall (u, v) \in E : \hat{\beta}_i(u, v) \leftarrow \frac{\beta_i}{\mu_{u,v}}$
Step 2. for each wavelength $\lambda' \in W$ **do**
Step 3. Compute $RC\ (u, v, \lambda')$, the residual capacity of λ' on link $(u, v) \in E$
Step 4. **if** $RC\ (u, v, \lambda') = \Omega$
then $\Psi_{u,v}^{\lambda'} \leftarrow$ cost from (5)
else if $\beta_i \le RC\ (u, v, \lambda') < \Omega$
then $\Psi_{u,v}^{\lambda'} \leftarrow$ cost from (6)
else $\Psi_{u,v}^{\lambda'} \leftarrow \infty$
endif;
endif;
Step 5. Using Dijkstra's algorithm, find a shortest path $P_{(\lambda',i)}$ from s_i to d_i w.r.t costs $\Psi_{u,v}^{\lambda'}$. Let c_i be the sum of the cost of all the links in $P_{(\lambda',i)}$.
Step 6. **if** $c_i < \mathbb{C}_{\text{MAX}}$ **then**
$\mathbb{C}_{\text{MAX}} \leftarrow c_i$; $\lambda \leftarrow \lambda'$; $P_i^{\lambda} \leftarrow P_{(\lambda',i)}$
endif;
endfor;
Step 7. if $\mathbb{C}_{\text{MAX}} \neq \infty$ **then**
if Num_Hops$(P_i^{\lambda}) \le (D_i + \varepsilon)$ **then**
for each link $(u, v) \in P_i^{\lambda}$ **do**
$RC\ (u, v, \lambda) \leftarrow RC\ (u, v, \lambda) - \beta_i$
$RC\ (v, u, \lambda) \leftarrow RC\ (v, u, \lambda) - \beta_i$
endfor;
return P_i^{λ}
endif;
endif;
Step 8. return "request blocked"
end.

The computational complexity of the proposed algorithm can be analyzed as follows. The shortest path from the source node to the destination node can be found using Dijkstra's algorithm, which can be implemented in $O\,(m + n \log n)$

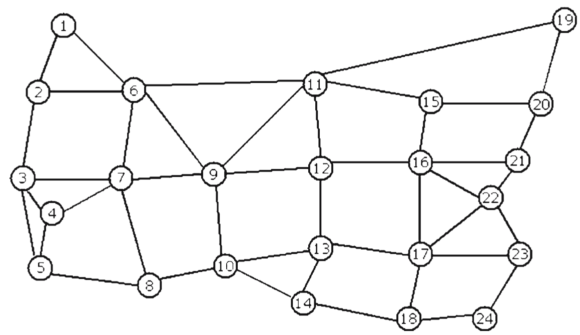


Fig. 5 Experimental telecommunications network topology

time using Fibonacci heaps. Therefore, the time complexity of the algorithm is $O(w(m + n \log n))$ as it is run once for each $\lambda' \in W$ with $w = |W|$.

Simulation study

In this section, we first introduce the simulation environment and then present the experimental results. We analyze the performance of OTGA using various network performance metrics and compare the results with the other existing algorithms.

Simulation environment

To evaluate the performance of the proposed algorithm, we conducted experiments on a representative sized mesh network shown in Fig. 5, which consists of 24 nodes and 43-fiber links. Each fiber link carries 16 wavelengths. All the nodes in the network have the architecture shown in Fig. 2. We further assume that the wavelength continuity constraint is imposed.

The bandwidth required by connection requests is uniformly distributed between one OC-3 and sixteen OC-3s. The request arrival is a Poisson process with the traffic uniformly distributed between all node pairs. The connection holding time is exponentially distributed. The load (in Erlangs) on the network is varied by increasing the average connection holding time. We simulate 200,000 connection requests to obtain the network performance under a certain network load. The simulations were performed on a Linux PC with a 2.8 GHz Pentium IV processor and 512 MB of memory. The average running time to simulate 200,000 connection requests is about 20 min. In all our experiments, the constants a, b and ε are fixed at 4, 2 and 2, respectively. We also experimented with other set of values and found the above combination to give consistently good network performance across all loads.

Experimental results

We compared the performance of OTGA with the other existing algorithms—WSP, SWP and ASP. The metrics used to measure the performance of the algorithms are (i) bandwidth blocking ratio, (ii) network utilization, (iii) average capacity of accepted requests (fairness) and (iv) normalized revenue.

(i) Bandwidth blocking ratio. Figure 6 compares the bandwidth blocking ratio of different routing algorithms. It represents the percentage of the amount of blocked traffic over the total amount of bandwidth required by all the connection requests during the entire simulation period. As bandwidth requirements of different connection requests are different, just comparing the overall request blocking probability does not reflect the effectiveness of the routing algorithms. Instead, bandwidth blocking ratio is a more suitable metric to compare the network performance and throughput.

It can be observed from the figure that, at low network loads (in Erlang), the percentage of bandwidth blocked by OTGA and ASP is similar. This is because, at low loads, the average connection holding time is less. The costs assigned to all the links derived from the cost function are nearly identical. Therefore, the performance of OTGA and ASP are similar.

With the increase in the average connection holding time, the network load also increases. The exponential nature of the cost functions in Equations (5) and (6) prevent the depletion of wavelengths on heavily loaded links by assigning to it, costs, that are significantly higher than the costs assigned to lightly loaded links. This in turn leads to the creation of routing paths that are distributed among the links evenly. From the figure it can be seen that, as the network load increases, the bandwidth blocking ratio increases as well. However, the percentage of total bandwidth blocked by OTGA is lower than that of the other three heuristics. OTGA delivers higher network throughput, and thus offers better performance.

(ii) Average network utilization. The average network utilization is determined as follows. Consider a connection request i between nodes s_i and d_i with the capacity requirement β_i. Let the distance between them be D_i. Now, if connection request i is to be established, then irrespective of the routing algorithm used, the minimum capacity required in the network is $\beta_i \times D_i$. This is called the *effective capacity requirement* of the request. Depending on the routing algorithm employed, the number of hops taken by it to establish the connection request may be greater than D_i.

Denote by ENC, the effective network capacity utilized at any instant of time. ENC is defined as the sum of the effective capacity requirement of all the connection requests that are active at that instant. The total network capacity is defined as $m \times |W| \times \Omega$. The network utilization is then determined as the ratio of the effective network capacity utilized to the total network capacity as $\frac{ENC}{m \times |W| \times \Omega}$. We compute the network utilization at intervals of every 250 incoming requests, and

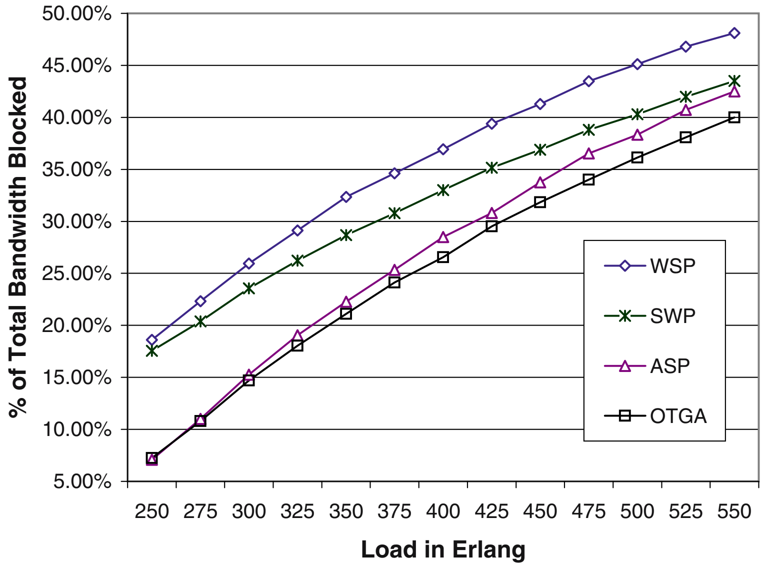


Fig. 6 Bandwidth blocking ratio versus load in Erlang

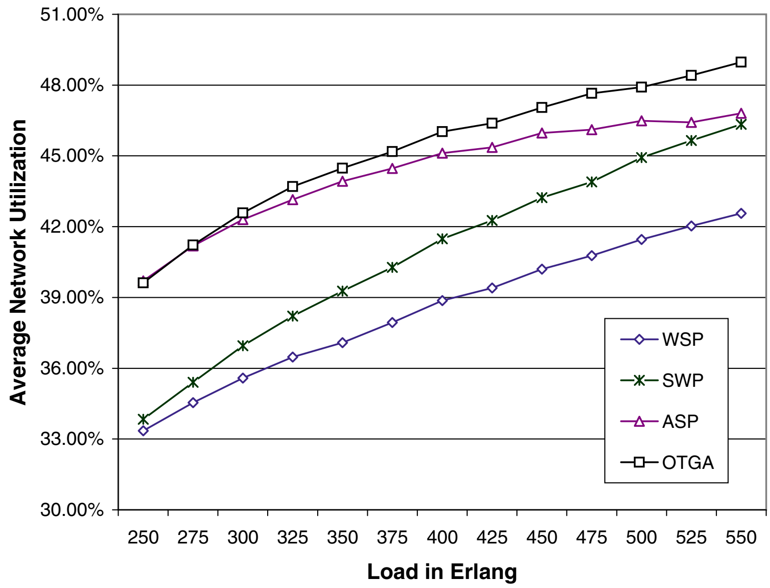


Fig. 7 Average network utilization by different routing algorithms

average it over 200, 000 connection requests. The resulting curves are plotted in Fig. 7.

WSP achieves the least network utilization because it routes connection requests over longer paths. This results in over usage of wavelength resources. The connection admission policy introduced in OTGA leads to effective utilization of bandwidth, thereby achieving the maximum network utilization.

(iii) Average capacity of accepted requests. Figure 8 shows the average capacity of accepted connection requests in terms of the number of OC-3 channels. With the increase in the network load, routing algorithms exhibit a bias in favor of connection requests that require smaller capacities. Larger capacity requests experience higher blocking than requests requiring smaller capacities.

An ideal routing algorithm will have a constant value for this metric at all network loads. Since the bandwidth requirement is uniformly distributed between 1 OC-3 and 16 OC-3s, an ideal routing algorithm in our simulation environment will establish an equal number of connection requests requiring 1 OC-3, 2 OC-3s, 3 OC-3s, . . . , 16 OC-3s of bandwidth. That is, the average capacity of connection requests accepted by an ideal routing algorithm will be 8.5 OC-3s. A routing algorithm demonstrates better fairness over another one if it has a higher value with respect to this metric. The closer the value is to 8.5 OC-3s, the better is its performance. Figure 8 compares the average capacity of accepted connection requests. It can be seen that OTGA realizes more higher capacity requests than the other three routing algorithms. This shows that OTGA provides improved fairness and reduces the bias

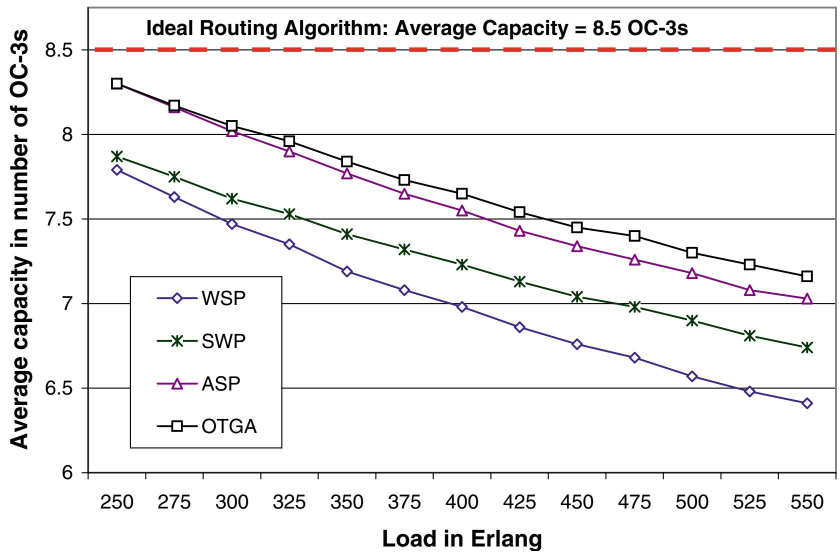


Fig. 8 Average capacity of accepted connection requests

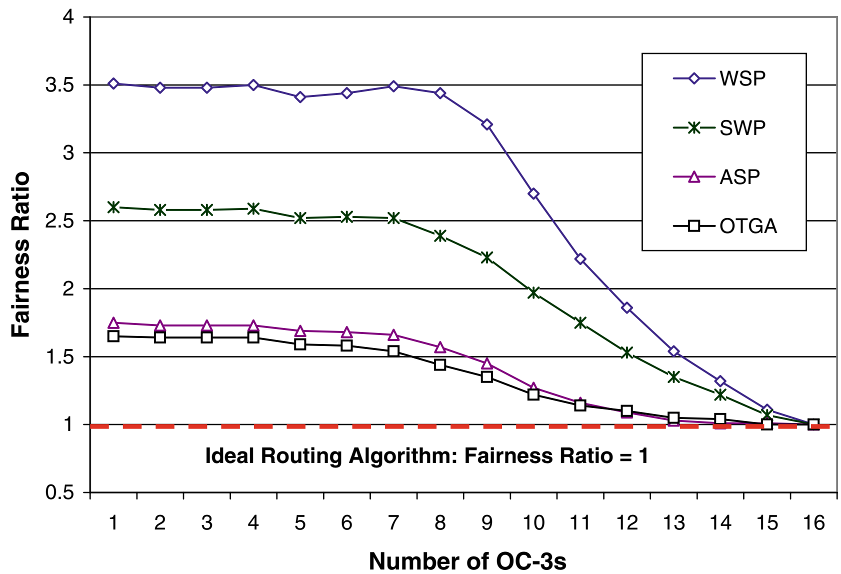


Fig. 9 Fairness ratio of different routing algorithms at 400 Erlang

in favor of establishing connection requests requiring smaller capacities.

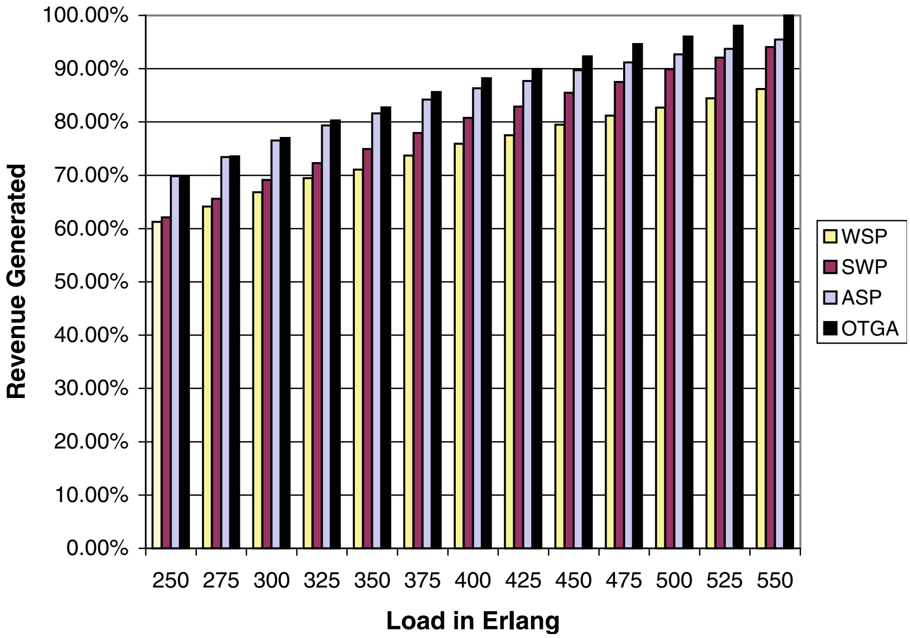
In Fig. 9, we plot the *fairness ratio* of the routing algorithms when the network load is fixed at 400 Erlang. We compute the fairness ratio as follows. At the end of the simulation, we calculate the number of established connection requests that required 1 OC-3, 2 OC-3s, 3 OC-3s, 4 OC-3s, ..., 16 OC-3s of bandwidth. Let $A = \{a_1, a_2, \ldots, a_{16}\}$, where $a_j \in A$ denotes the number of established connection requests that required j OC-3s of bandwidth. The fairness ratio is then expressed as $\frac{a_j}{a_{16}}$ for all $a_j \in A$. An ideal routing algorithm will have a constant value of 1 for this metric as it will establish an equal number of connection requests of varying capacity requirements. It can be observed that WSP and SWP algorithms favor more smaller capacity requests, while OTGA outperforms all the other algorithms.

(iv) Revenue generated. Let b_i be a 0 / 1 variable, which takes the value 1 if connection request i is established, otherwise 0. Then the revenue generated, R, is proportional to the bandwidth utilized by a connection request times the duration for which the request is active. Therefore, we have

$$R \propto \sum_{i=1}^{2\cdot 10^5} b_i \cdot (\beta_i \cdot \Delta_i)\,. \tag{8}$$

Figure 10 shows the normalized revenue generated at different network loads. The efficiency of constructing the routing paths using the cost function is observed as the network load is increased. OTGA generates more revenue in comparison to ASP, SWP and WSP routing schemes.

Fig. 10 Normalized revenue generated by the routing algorithms



Conclusion

In this paper, on-line traffic grooming in a WDM–TDM switched optical mesh network without wavelength conversion capability was investigated. Using a novel exponential cost function, we proposed a routing algorithm for the concerned problem. We compared and analyzed the performance of the proposed algorithm with the other known heuristics. The experimental results showed that the proposed algorithm outperforms the existing algorithms — ASP, SWP and WSP in terms of bandwidth blocking ratio, network utilization, fairness and revenue.

Acknowledgements It is acknowledged that the work by the authors was supported by research grant No: DP0449431, funded by the Australian Research Council under its Discovery Schemes.

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