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Online traffic grooming using timing information in WDM–TDM networks

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Abstract In this paper, the effect of holding time awareness on the process of time slot assignment in WDM–TDM is considered. Use has been made of Markov model in order to predict the wavelength congestion. A routing algorithm is developed based on the Markov modeling. The results are compared with existing algorithms—ASP, WSP and OTGA. Validation results have shown that the performance of the system is significantly improved in terms of bandwidth blocking ratio, network utilization and fairness.

1. Introduction

With traffic demands continuing to increase rapidly, wavelength-division multiplexing (WDM) has emerged as an attractive solution for increasing capacity in optical networks. Conventional WDM allows multiple data streams to be carried using the same fiber link, as long as each data stream occupies different wavelengths [1]. As WDM technology matures, there exists a large gap between the capacity of a WDM channel (e.g., OC-48/OC-192/OC-768) and the bandwidth requirements of a typical connection request (e.g., STS-1, STS-3, STS-12, etc.). Traffic grooming is an important and practical approach for designing WDM networks which refers to the technique of efficiently multiplexing a set of low-speed connection requests onto high-capacity optical circuits and intelligently switching them at intermediate nodes. For example, time-division multiplexing (TDM) divides the bandwidth's time domain into repeated time-slots of fixed bandwidth. Therefore, with TDM, multiple signals can share a given wavelength if they are non-overlapping in time [2–6]. The resulting multi-wavelength optical time division multiplexed network is referred to as WDM–TDM network. In our work we consider all-optical wavelength-routed WDM–TDM networks with fiber delay lines as time slot interchangers OTSIs [7].

Due to the evolution of services and applications over optical networks, traffic is becoming more dynamic. In a dynamic environment, a sequence of sub-wavelength requests arrives

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over time and each request has a random holding time. These requests need to be set up dynamically by determining a route across the network connecting the source to the destination and assigning it to a suitable time-slots on a suitable wavelength along the path. We exploit the knowledge of connection holding time to devise an efficient algorithm for dynamic traffic grooming of sub-wavelength requests in optical WDM mesh networks. A proper utilization of connection durations allows us to minimize resource occupation and hence to achieve lower blocking probability for incoming request.

2. Related work

This section provides a brief overview of traffic grooming in optical WDM mesh networks: The problem of traffic grooming in optical networks is to determine how to efficiently route traffic demands and at the same time to combine lower-rate (sub-wavelength) connections onto a single wavelength [8–13]. In a dynamic environment, the connection requests arrive one at a time with different starting time and holding period. In [14–16] dynamic traffic grooming algorithms that jointly employs knowledge of holding-times and the network bandwidth availability are developed in order to balance the traffic loading and avoid creation of bottlenecks. Consequently, this has improved bandwidth blocking probability for WDM networks. On the other hand, the authors in [17,18] incorporated holding time in energy-aware traffic grooming and solved both the static and dynamic traffic grooming problems in a wavelength routing network, the objective has been to minimize the total energy consumption of the core network based on holding time awareness. For the static traffic problem, they proposed an Integer Linear Programming (ILP). On the other hand, for the dynamic traffic problem, they used the shortest path(s) in an auxiliary graph with specific weights. Their algorithms are compared to the routing algorithms in [19] based on "minimum lightpaths" that tries to minimize the number of newly established lightpaths and "minimum hops" that tries to minimize the number of lightpath hops. Simulation results have indicated that the algorithm discussed in [17] performs best under low traffic, but performs worst under high traffic.

3. Our contributions

In this paper, we develop on the work presented in [15]. Here we consider the case in which holding time awareness is used to control the time slot assignments rather than the wavelengths. In this respect, an estimate of the close-future congestion probability of network wavelengths is developed based on knowledge of the connection's durations. The estimation is, then, used to apply a holding-time-aware Time-slot/Wavelength assignment for on-line routing algorithm in a WDM–TDM mesh network. As can be seen, we have effectively combined path selection, wavelength selection as well as time-slot assignments rather than performing each of them separately [13]. This approach, which we call Online Traffic Grooming Based on Time-slot/Wavelength Congestion (TGTSWC) is expected to outperforms the existing dynamic routing (DR) approaches discussed and analyzed in [3,4]. In particular, our approach is seen to achieve a significantly better blocking probability.

The rest of the paper is organized as follows. The node architecture and network modeling are introduced in Section 4. In Section 5, an overview of the dynamic routing model is presented. In Section 6, the holding time for traffic grooming problem is formulated. Section 7, presents a statistical model to the Time-slot/Wavelength Congestion probability. This model is, then, used to devise a computationally tractable, efficient algorithm called TGTSWC for the DR problem. The findings in this paper are evaluates by simulations in Section 8. Section 9 draws some conclusions.

4. Notations

4.1. Node architecture

A WDM–TDM switched mesh network consists of switching nodes with fiber communication links interconnecting the nodes. Each fiber link carries a certain number of wavelengths and each wavelength is divided into a number of time slots. The node architecture for sub-wavelength traffic grooming in such a WDM–TDM mesh network is shown in Fig. 1. The figure represents a node supporting M links ($e_1, e_2, \ldots, e_M$), and W wavelengths per link ($w_1, w_2, \ldots, w_W$) and each wavelength is divided into TS time-slots ($t_1, t_2, ..., t_{TS}$). The data carried on an incoming time slot can be delayed using Optical Time Slot Interchangers (OTSIs). Therefore, time slots occupied by data on an incoming wavelength at an input port can be mapped on to different time slots on the same outgoing wavelength at any output port. That is, wavelength conversion is not incorporated in this architecture.

4.2. Network model

The physical topology of a WDM–TDM mesh network can be 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. $W = \{w_1, w_2, \ldots, w_W\}$ is the set of available wavelengths in the network. Each wavelength is divided into number of repeated time-slots (TS) of fixed bandwidth. We denote the set of existing sub-wavelength connections on any wavelength $w' \in W$ in the network at any time by $L_{w'} = \{(s^{i,w'}, d^{i,w'}, l^{i,w'}, t_a^{i,w'}, t_h^{i,w'})\}$ where the quintuple $(s^{i,w'}, d^{i,w'}, l^{i,w'}, t_a^{i,w'}, t_h^{i,w'})$ specifies, respectively, the source node, the destination node, the route, the arrival time and the holding time for the ith connection on a wavelength w'. We associate a wavelength utilization level descriptor $v_{w'}$ to each wavelength $w' \in W$ in each link $(u, v) \in E$ in the network. Therefore, the occupation of time-slots on a wavelength can be represented as an integer set $\{v_{w'} | \forall w' \in W, 0 \leq v_{w'} \leq \mathrm{TS}\}$. Using $v_{w'}$, the on-line traffic grooming objective is to find minimum cost and bandwidth path(s) $P_i^{w'}$ on wavelength(s) $w' \in W$ between a source node $s^{i,w'}$ to its destination $d^{i,w'}$ at *a given* arrival time $t_a^{i,w'}$ for a duration $t_h^{i,w'}$. The overall aim is to maximize the network throughput such that the established requests must not be interrupted.

5. Dynamic routing model

In this section, an overview on dynamic routing approaches in optical networks is presented. In these approaches, bandwidth requirements for connection requests are expressed in terms of the number of time-slots. In this respect, we assume that a

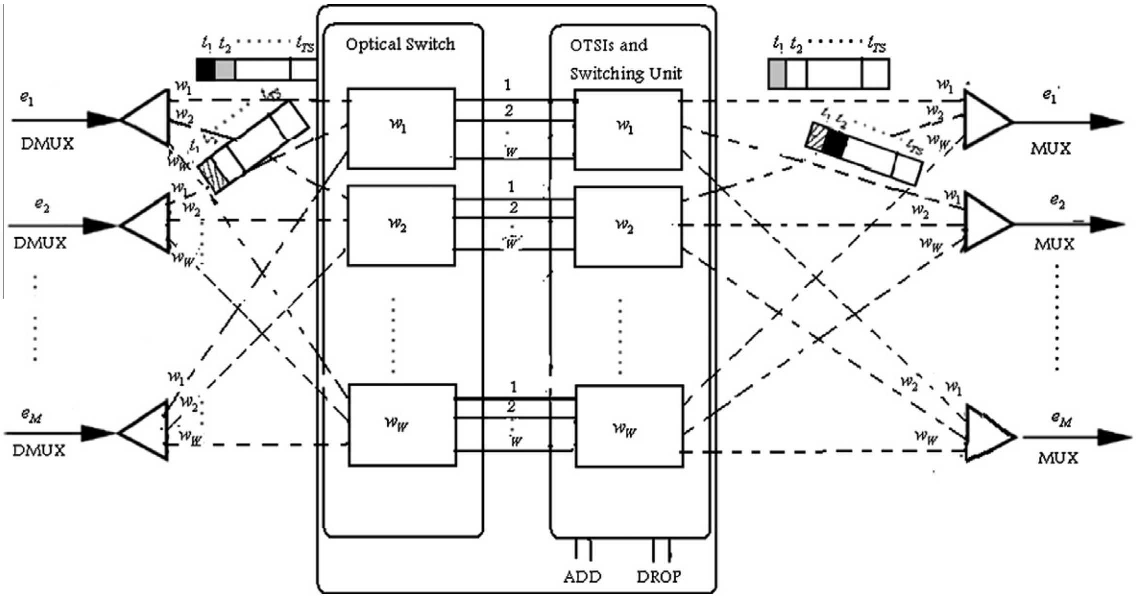

Figure 1 Node architecture for sub-wavelength demand traffic grooming with all-optical switches and OTSIs.

wavelength is divided into 16 time-slots; each has a fixed bandwidth equivalent to one OC-3 channel. Therefore, the total available bandwidth per-wavelength Ω is equivalent to an OC-48 channel, hence, Ω = 16 OC-3s.

In general terms, only links with sufficient bandwidth capacities to accommodate the requests are considered and the Dijkstra's algorithm is adopted in order to find the least-cost C_l, path between each source – destination nodes:

$$C_{u,v}^{w'} = \begin{cases} \infty & v_{w'} = \Omega \\ 1 & \text{Otherwise} \end{cases} \tag{1}$$

Such that

$$C_l = \sum_{(u,v)\in l} C_{u,v}^{w'} \quad \text{is minimized} \tag{2}$$

where $v_{w'}$ is the number of OC-3 channels being used on a wavelength $w' \in W$ on link $(u, v) \in E$, $C_{u,v}^{w'}$ refers to Cost of using this wavelength on the link and C_l is the total cost of the route between the source and the destination nodes. When two or more paths are having equal costs, the one with minimum hop count is selected. If two paths have the same hop count, then the tie is broken by using the first-fit wavelength assignment policy [3,4]. For purpose of completion, the following cost function model [20] is outlined.

Let $\mu_{u,v}$ represents the total available bandwidth on a given link (u, v). Therefore, we have

$$\mu_{u,v} = W \times \Omega \quad \forall (u,v) \in E \tag{3}$$

where W is the total number of wavelengths carried by each link (u, v). For convenience, the requested bandwidth B_i, is normalized to the total available bandwidth on a link (u, v). Therefore,

$$\widehat{B}_i(u,v) = \frac{B_i}{\mu_{u,v}}, \tag{4}$$

and the load on a link $(u, v) \in E$ after considering a request k is defined as,

$$l_{u,v}^{K} = \sum_{\substack{j=1 \\ (u,v)\in P_j}}^{K} \widehat{B}_j(u,v) \tag{5}$$

Now, let $R_{w'}(u, v)$ be the residual capacity on wavelength w' on link (u, v) after considering the first K requests is given by,

$$R_{w'} = 1 - \frac{v_{w'}}{\Omega} \tag{6}$$

By checking $RC(u, v, w')$ the residual capacity of w' on link (u, v) in terms of the number of OC-3 channel, the Cost $C_{u,v}^{w'}$ of using the number of time-slots (OC-3 channels) requested for a connection i on a wavelength w' is represented by:

$$C_{u,v}^{w'} = \begin{cases} a^{l_{u,v}^{k}}\left(a^{\widehat{B_i(u,v)}} - 1\right) & RC(u,v,w') = \Omega \\ \frac{a^{l_{u,v}^{k}}\left(a^{\widehat{B_i(u,v)}}-1\right)}{b^{R_{W'}(u,v)}} & B_i \le RC(u,v,w') < \Omega \\ \infty & \text{Otherwise} \end{cases} \tag{7}$$

where a and b are constant >1. Later in this paper, we shall present our Time-slot/Wavelength cost assignment that evaluates Future Wavelength Utilization $FWU^{w'}$ probability based on the results of Markov modeling of time-slots occupation on wavelength w', as described in Eq. (15).

6. Holding-time aware dynamic traffic grooming

Most of traffic grooming strategies is developed to reduce the blocking probability of arriving connections without knowledge of connection's-holding-time in advance. However, it can be seen that, wavelength congestion level changes during the holding time of incoming connections whenever some of existing connections depart or new connections arrive. This means that, we can exploit the information about the connection departure events, which is retrievable from the knowledge of the connection's holding time. Hence, we could modify the Time-slot/Wavelength cost assignment to capture the future degree of utilization of a given wavelength in terms of requested number of time slots as well as the estimated occupation time. More specifically, we can determine the residual lifetime $h_{i,w'}$ of an existing connection i on a wavelength w' by the largest ending time of a connection as follows,

$$h_{i,w'} := \begin{cases} t_a^{i,w'} + t_h^{i,w'} - T_a & \text{if } (t_a^{i,w'} + t_h^{i,w'} \leq T_a + T_h) \\ T_h & \text{Otherwise} \end{cases} \tag{8}$$

where $\langle t_a^{i,w'}, t_h^{i,w'} \rangle$ and $\langle T_a, T_h \rangle$ are the pairs ⟨arrival time, holding time⟩ of the existing connections on wavelength w' and of the incoming connections, respectively. We introduce the symbols $v_{w'}(\Delta\tau_{k,w'})$ and $C_{u,v}^{w'}(\Delta\tau_{k,w'})$, which express the values of wavelength utilization $v_{w'}$ and wavelength cost in a link $(u, v) \in E$ (respectively), in the time interval $\Delta\tau_{k,w'}$ which is obtained according to values of ending life time of existing connections as given by Eq. (8) above.

The values of $h_{i,w'}$'s are then ordered as $h_{i,w'} \leq h_{i+1,w'}, i = 1, 2, \ldots, |L|$. As a consequence, $\tau_{w'} = \{\tau_{0,w'}, \tau_{1,w'}, \ldots, \tau_{|L|,w'}\} = \{0, h_{1,w'}, h_{2.w'}, \ldots, h_{|L|,w'}\}$ indicate the departure events in the interval T_h of incoming connection request on a wavelength w' and $\Delta\tau_{k.w'} = \tau_{k,w'} - \tau_{k-1,w'}$ express the time interval between two departures on a wavelength w'. Wavelength utilization $v_{w'}(\Delta\tau_{k,w'})$ and associated cost $C_{u,v}^{w'}(\Delta\tau_{k,w'})$ will be updated according to the kth connection departure. In other words, we have divided the interval T_h of incoming connection request into a series of time intervals $\Delta\tau_{w'}$ which express the distance between two departures for each wavelength $w' \in W$.

7. Occupation time estimation

In this section, we adopt the time-dependent model [15] in order to estimate the future occupation of the requested number of time-slots on a given wavelength w' when the duration of existing connections are given. To obtain this estimation, the time-slots occupation process can be modeled as a Markov chain describing the relationship between arrival and departure times of calls as described in Fig. 2.

Let $X = \{X(t){:}t \geqslant 0\}$ be the homogeneous continuous-time Markov chain describing the time-slot occupation process on a given wavelength w', with transition matrix $Q^{w'}$. Let $q_{ij}^{w'}$ be the (i, j)th element of $Q^{w'}$, and $q_i^{w'} = \sum_{i \neq j} q_{ij}^{w'}$, be the rate of state i.

Now, let $Z = \{Z_n{:}n = 0, 1, \ldots\}$ be discrete time version of the Markov chain with the same state space but with transition probability matrix $P_{u,v}^{w'} = I + Q^{w'}/\Lambda_{w'}$ for each wavelength $w' \in W$ on each link $(u, v) \in E$, where $\Lambda_{w'} = \max_i\{q_i^{w'}\}$.

$$P_{u,v}^{w'} = \begin{bmatrix} 1 - \frac{\lambda_{u,v}}{\Lambda_{w'}} & \frac{\lambda_{u,v}}{\Lambda_{w'}} & 0 & \ldots & 0 & \\ \frac{\mu}{\Lambda_{w'}} & 1 - \frac{\mu+\lambda_{u,v}}{\Lambda_{w'}} & \frac{\lambda_{u,v}}{\Lambda_{w'}} & \ldots & 0 & \\ \vdots & \ldots & \ldots & \ldots & \vdots & .. \\ \vdots & \ldots & \ldots & \ldots & \vdots & \\ 0 & \ldots & 0 & \frac{(\mathrm{TS})\mu}{\Lambda_{w'}} & 1 - \frac{(\mathrm{TS})\mu}{\Lambda_{w'}} & \end{bmatrix}$$

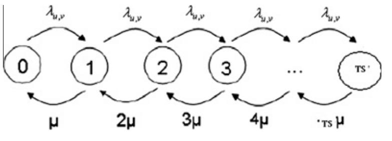

Figure 2 State transition diagram of connections' arrivals/departures on a Single wavelength where TS is the number of time-slots per wavelength.

Assume $N = \{N(t){:}t \geqslant 0\}$ is a Poisson process with rate Λ independent of Z. Then, if the time between transitions for the chain Z is exponentially distributed with rate $\Lambda_{w'}$, then the residence time spent in a visit to state i is exponential with mean $1/q_i^{w'}$. Since the total residence time in i is identical in both of the continuous and discrete processes as well as the probability of moving from i to j We may consider that $\mathbf{X}$ and $\mathbf{Z}$ to be equivalent processes.

Now, let $\Pi^{w'}(t)$ be a vector such that the jth element equals to the probability that $\mathbf{X}$ is in state (time-slot) j at time t, given an initial distribution of the states. After n transitions, $\mathbf{Z}$ will be in state j with probability $v_j^{w'}(n)$, where $v_j^{w'}(n)$ is the jth entry of the vector $v^{w'}(n) = v^{w'}(0)P_{w'}^n$ and $v^{w'}(0)$ is the initial state probability vector. Independent of the number of transitions in the interval $(0, t)$, we obtain

$$\Pi^{w'}(t) = \sum_{n=0}^{\infty} e^{-\Lambda_{w'} t} \frac{(\Lambda_{w'} t)^n}{n!} V^{w'}(n) \tag{9}$$

where $P_{w'}^n$ is the TS's transition probability matrix on wavelength w'. If we truncate Eq. (9) for a given values of N-TS, the error $\varepsilon(N)$ of any entry of the vector $\Pi^{w'}(t)$ is given by:

$$\varepsilon(N) \leq 1 - \sum_{n=0}^{N} e^{-\Lambda_{w'} t} \frac{(\Lambda_{w'} t)}{n!} \tag{10}$$

As can be seen, for a relatively large N, the truncation error can be neglected [21].

7.1. *Time slot mean transient probability*

In general, the mean transient probability in a given state can be obtained if we consider the time interval $\Delta\tau_{w'}$. Hence, the mean values of each element in the vector $\Pi^{w'}(t)$ is given by,

$$\begin{aligned} \overline{\Pi_j^{w'}(\Delta\tau_{w'})} &= \frac{\int_{\Delta\tau_{w'}} \sum_{n=0}^{\infty} e^{-\Lambda_{w'} t} \frac{(\Lambda_{w'} t)^n}{n!} v^{w'}(n) dt}{\Delta\tau_{w'}} \\ &= \frac{\sum_{n=0}^{\infty} \frac{v^{w'}(n)}{n!} \int_{\Delta\tau_{w'}} e^{-\Lambda_{w'} t} (\Lambda_{w'} t)^n dt}{\Delta\tau} \\ &= \frac{\sum_{n=0}^{\infty} \frac{v_{w'}(n)}{n!} (1 - e^{-\Lambda_{w'} t} \sum_{i=0}^{n} \frac{(\Lambda_{w'} \Delta\tau_{w'})^{n-i}}{(n-i)!})}{\Delta\tau_{w'}} \end{aligned} \tag{11}$$

Eq. (11) can easily be computed recursively. Details are skipped for the sake of brevity.

7.2. *Wavelength transient-state expected value*

Since $\sum_j \Pi_j^{w'}(t) = 1$ at each time instant t, and that the $\overline{\Pi_j^{w'}(\Delta\tau_{w'})}$ defines the mean transient probability of the jth time slot during the time interval $\Delta\tau_{w'}$, we can express the expected value of $\Delta\tau_{w'}$ in a wavelength w' by:

$$E_v^{w'}(\Delta\tau_{w'}) = \frac{\sum_{j=0}^{\mathrm{TS}} \overline{\Pi_j^{w'}(\Delta\tau_{w'})} * j}{\mathrm{TS}} \tag{12}$$

7.3. *Transient probability during a connection's holding-time*

Now we can define the expected-mean occupation of a time slots in a given wavelength w', over a time interval T_h starting from the arrival time T_a of an incoming connection. For sake of illustrations, we focus on the example in Fig. 3 where we draw the time persistence of two existing connections r_1 and

r_2 each of which reserves one time-slot on a wavelength $w'(\mathrm{TS}=4)$, while connection r_3 is requesting one time-slot. Let us suppose that $\lambda_{u,v}$ is the mean value of the connection arrival rate to link (u, v) and μ its mean holding time. If r_3 arrives to the network with holding time $T_h = 20$, r_1 has to linger on wavelength w' other 10 time units.

Therefore, its lifetime on that wavelength will be set $h_{1,w'} = 10$. As for r_2, even if r_2 has to be operated other 30 time units, in our analysis its lifetime on the same wavelength w' is bounded to $h_{2,w'} = 20$ according to Eq. (8). Thus, the holding time T_h is split into two time intervals $\Delta\tau_{1,w'}$ and $\Delta\tau_{2,w'}$ (in the present example). Let us set $\tau_{0,w'} = T_a$, for each time interval $\Delta\tau_{k,w'}$ we compute: an auxiliary transition probability matrix $\widehat{P}^{w',k}_{u,v}$ with initial state probability vector $v^{w'}_k(0)$, the final state probability vector $\Pi^{w'}(\Delta\tau_{k,w'})$ and the expected value $E^{w'}_v(\Delta\tau_{k,w'})$. From which the auxiliary probability matrix $\widehat{P}^{w',k}_{u,v}$ of the kth time interval is defined as $\widehat{P}^{w',k}_{u,v} = \widehat{I}_k + \widehat{Q}^{w'}_k/\widehat{\Lambda}_k$, where $\widehat{I}_k$ and $\widehat{Q}^{w'}_k$ are given by the Hadamard product of the following matrices:

$$\widehat{Q}^{w'}_k = Q^{w'} \cdot H_k \quad \widehat{I}_k = I \cdot H_k \tag{13}$$

where H_k functions as a filter function: H_k is composed by 0s or 1s: the (i,j)th element will be set to 1 if and only if i and j are strictly greater than the minimum number of time-slot in a certain wavelength, certainly occupied in the time interval $\Delta\tau_{k,w'}$, otherwise it will be set to 0. Let $\hat{q}^{w'}_{ij}$ be the (i,j)th element of $\widehat{Q}^{w'}_k$, and $\hat{q}^{k,w'}_i = \sum_{i \neq j} \hat{q}^{k,w'}_{ij}$, designates the exponential rate out of state i. Moreover, $\Lambda_{k,w'} = \max_i\{\hat{q}^{k,w'}_i\}$. The auxiliary probability matrix $\widehat{P}^{w',k}_{u,v}$ is utilized in place of $P^{w'}_{u,v}$ to obtain the truncated Markov chain corresponding to the minimum number of time slots reserved by the existing connections that are certainly supported by the wavelength during the time interval $\Delta\tau_{k,w'}$ as follows:

- $\Delta\tau_{1,w'}$ (from time 0 to 10): the minimum number of occupied time-slot in a wavelength w', is 3 (we assume that the incoming connection r_3 is routed on the same wavelength w' on the same link (u, v). Therefore

$$\widehat{P}^{w',1}_{u,v}(\Delta\tau_{1,w'}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\frac{\lambda_{u,v}}{\widehat{\Lambda}_1} & \frac{\lambda_{u,v}}{\widehat{\Lambda}_1} \\ 0 & 0 & 0 & \frac{4\mu}{\widehat{\Lambda}_1} & 1-\frac{4\mu}{\widehat{\Lambda}_1} \end{bmatrix}$$

  where $\widehat{\Lambda}_{1,w'} = \max\{\lambda_{u,v}, 4\mu\}$.

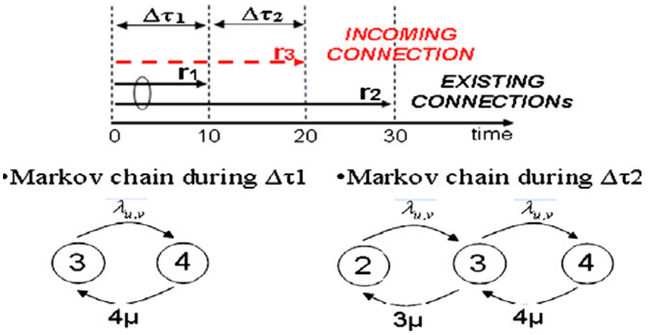

Figure 3 Example of transient analysis on a generic wavelength w'.

- $\Delta\tau_{2,w'}$ (from time 10 to 20): the minimum number of occupied time-slots is 2, since r_1 departs from wavelength w' and leaves the network at time 10. Therefore,

$$\widehat{P}^{w',2}_{u,v}(\Delta\tau_{2,w'}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-\frac{\lambda_{u,v}}{\widehat{\Lambda}_2} & \frac{\lambda_{u,v}}{\widehat{\Lambda}_2} & 0 \\ 0 & 0 & \frac{3\mu}{\widehat{\Lambda}_2} & 1-\frac{3\mu+\lambda_{u,v}}{\widehat{\Lambda}_2} & \frac{\lambda_{u,v}}{\widehat{\Lambda}_2} \\ 0 & 0 & 0 & \frac{4\mu}{\widehat{\Lambda}_2} & 1-\frac{4\mu}{\widehat{\Lambda}_2} \end{bmatrix}$$

where $\widehat{\Lambda}_{2,w'} = \max\{3\mu + \lambda_{u,v}, 4\mu\}$. In Table 1 below, we report the transient state probabilities of the initial and final vectors during the time intervals $\Delta\tau_{1,w'}$ and $\Delta\tau_{2,w'}$.

Note that, since connection r_1 departs (deterministically) from the wavelength w' and leaves the network at time $\tau_{1,w'} = 10$, the initial vector $V_{2,_{w'}}$ of the interval $\Delta\tau_{2,w'}$ is obtained by a cyclic-left-unitary shift of the previous final state vector $\Pi^{w'}(10)$. Then, by Eqs. (9) and (12), we can compute the final state probability $\Pi^{w'}(\tau_{k,w'})$ and the expected value $E^{w'}_v(\Delta\tau_k)$ for the wavelength w' for each time interval $\Delta\tau_{k,w'}$. Finally, we can define the close Future Wavelength Utilization $FWU^{w'}$ of wavelength w' as the average of the expected value $E^{w'}_v(\Delta\tau_{k,w'})$ within the holding time of the incoming connection T_h:

$$FWU^{w'} = \frac{\sum_{K=1}^{|L|} E^{w'}_v(\Delta\tau_{k,w'}) \times \Delta\tau_{k,w'}}{T_h} \tag{14}$$

7.4. TGTSWC approach

In order to minimize the blocking probability while considering both the close-future occupation of time slots on each wavelength on link $(u, v) \in E$ and the current occupation of that link. The routing algorithm is executed iteratively on per wavelength $w' \in W$ basis. The aim is to determine the best possible time slot and wavelength assignments over the best available route for a given request. The way this is achieved is based on the time-dependent model which estimates the future occupation $FWU^{w'}$ of the requested time slots (TS) on each wavelength w' given the duration of connection.

In the following, the cost of using a number of time slots (TS) on a wavelength w' on a given link (u, v) for a connection request T_h is given by:

Since the load on each link is described by Eq. (5)

$$l^K_{u,v} = \sum_{\substack{j=1 \\ (u,v) \in P_j}}^{K} \widehat{B}_j(u,v),$$

when a new connection request i arrives, we check $RC(u, v, w')$ the residual capacity of w' on link (u, v) in terms of the number

Table 1 Initial and final vectors during $\Delta\tau_{1,w'}$ and $\Delta\tau_{2,w'}$.

	0	1	2	3	4
$V^{w'}_1(0)$	0	0	0	1	0
$\Pi^{w'}(\tau_{1,w'})$	0	0	0	$\Pi^{w'}_3(10)$	$\Pi^{w'}_4(10)$
$V^{w'}_2(0)$	0	0	$\Pi^{w'}_3(10)$	$\Pi^{w'}_4(10)$	0
$\Pi^{w'}(\tau_{2,w'})$	0	0	$\Pi^{w'}_2(20)$	$\Pi^{w'}_3(20)$	$\Pi^{w'}_4(20)$

of OC-3 channels and then assign the cost of using the requested number of time slots (TS) on each wavelength $w' \in W$ on each link $(u, v) \in E$ as follows:

$$C^{w'}_{u,v}(T_h) = \begin{cases} \infty & RC(u,v,w') < B_i \\ \alpha FWU^{w'} + \beta(l^{k}_{u,v} + 1) & \text{Otherwise} \end{cases} \tag{15}$$

Such that

$$C_l = \sum_{(u,v)\in l} C^{w'}_{u,v}(T_h) \quad \text{is minimized} \tag{16}$$

where $\alpha \geqslant 0$ and $\beta \geqslant 0$ are the weights associated with future time slot (TS) occupation on wavelength w' on link $(u, v) \in E$ and the current load on that link respectively. As can be seen, this new cost function considers the future time slot (TS) usage $FWU^{w'}$ of each wavelength $w' \in W$ along the entire connection's-holding time. The new Time-slot/Wavelength-cost assignment in Eq. (15) will be referred to as statistical Online Traffic Grooming Based On Time-slot/Wavelength Congestion, i.e. (TGTSWC). Dijkstra's algorithm is then used to determine the shortest path between each source and destination nodes with minimum route cost C_l (Eq. (16)). If two or more paths can accommodate the request, then the path with the minimum hop count is chosen. If two paths have the same hop count, then the tie is broken by using the first-fit wavelength assignment policy.

Now, let us define a 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, the number of hops in the shortest path between the two endpoints in $G = (V, E)$ without considering the availability of wavelengths on links.

As the number of the hops on a route increases, chances of finding an available time-slots on wavelength on all the intermediate links decreases. Due to this, we introduce the following connection admission policy to minimize the utilization of additional Time-slot/Wavelength resources. 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 TGTSWC needed to establish the connection request between the nodes s_i and d_i. This implies that, even if sufficient time-slots to accommodate the requested bandwidth are available on wavelength $w' \in W$ to route request i, the request is blocked if the total number of hops in the resulting 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.

To evaluate the performance of the proposed algorithm, we conducted experiments on the representative sized mesh network shown in Fig. 4, which consists of 24 nodes and 43-fiber links. Each fiber link carries 16 wavelengths and each wavelength is divided into 16 time-slots. The bandwidth available on each time-slot is 1 OC-3. All the nodes in the network have the architecture shown in Fig. 1. We further assume that the wavelength continuity constraint is imposed. The bandwidth required by connection requests is uniformly distributed between 1 OC-3 and 16 OC-3s.

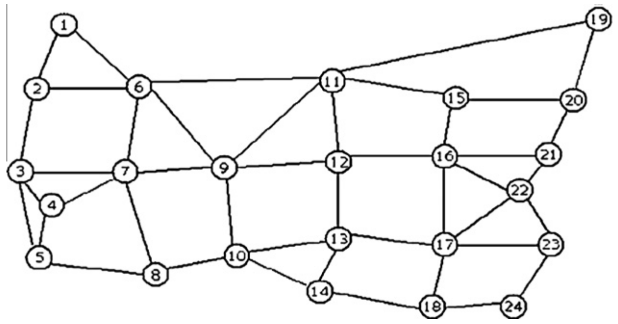

Figure 4 Experimental telecommunications network topology.

8. Experimental results

In this section, we compare the performance of (TGTSWC) with other existing algorithms—WSP (Widest Shortest Path), ASP (Available Shortest Path) and OTGA (Online Traffic Grooming Algorithm) [20]. Results have indicated that, being a holding time aware scheme. Its occupation awareness has improved the performance over that presented in the OTGA system. The metrics used to measure the performance of the algorithms are (i) bandwidth blocking ratio, (ii) network utilization, (iii) average capacity of accepted requests, (iv) fairness (defined below)

In the following, we explain the findings of the results obtained:

(i) *Bandwidth blocking ratio*: Fig. 5 compares the bandwidth blocking ratio for 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. The percentage of total bandwidth blocked by TGTSWC is lower than that of the other three heuristics. TGTSWC 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 capacity requirement B_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 $B_i \times D_i$. 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 $\frac{ENC}{m \times |W| \times \Omega}$. WSP achieves the least network utilization because it routes connection requests over longer paths. This results in an over usage of wavelength resources Fig. 6. The connection admission policy introduced in TGTSWC leads to effective utilization of bandwidth, thereby achieving the maximum network utilization.

(iii) *Average capacity of accepted requests*: Fig. 7 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

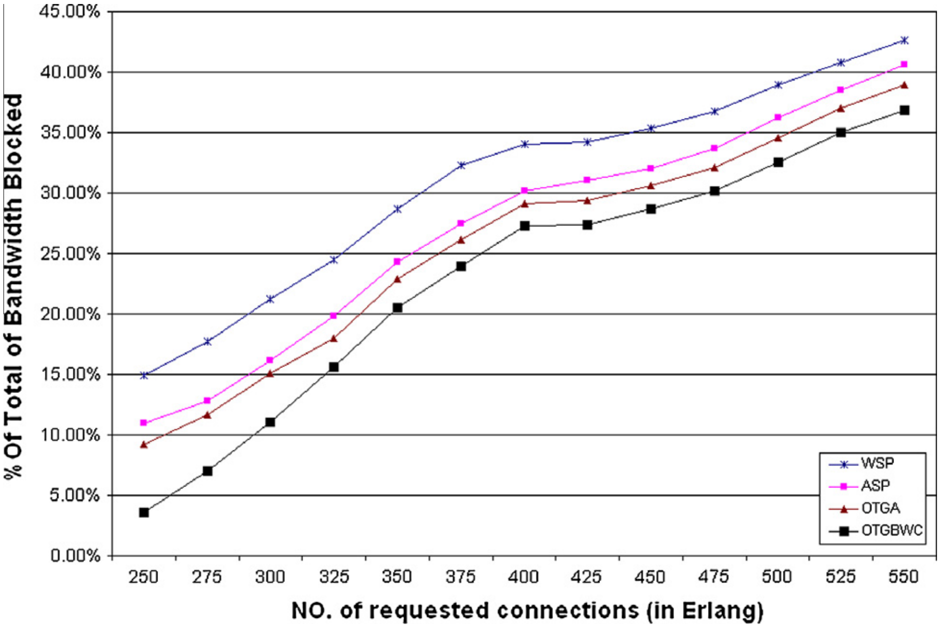

Figure 5 Bandwidth blocking ratio versus load.

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 values of 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 is 85 OC-3s. Hence, our routing algorithm demonstrates a better fairness over others especially if it has a higher value of this metric. The closer the value to 85 OC-3s, the better is its performance. Fig. 8 compares the average capacity of accepted connection requests. It can be seen that TGTSWC realizes higher capacity requests than the other three routing algorithms. This shows that TGTSWC provides improved fairness.

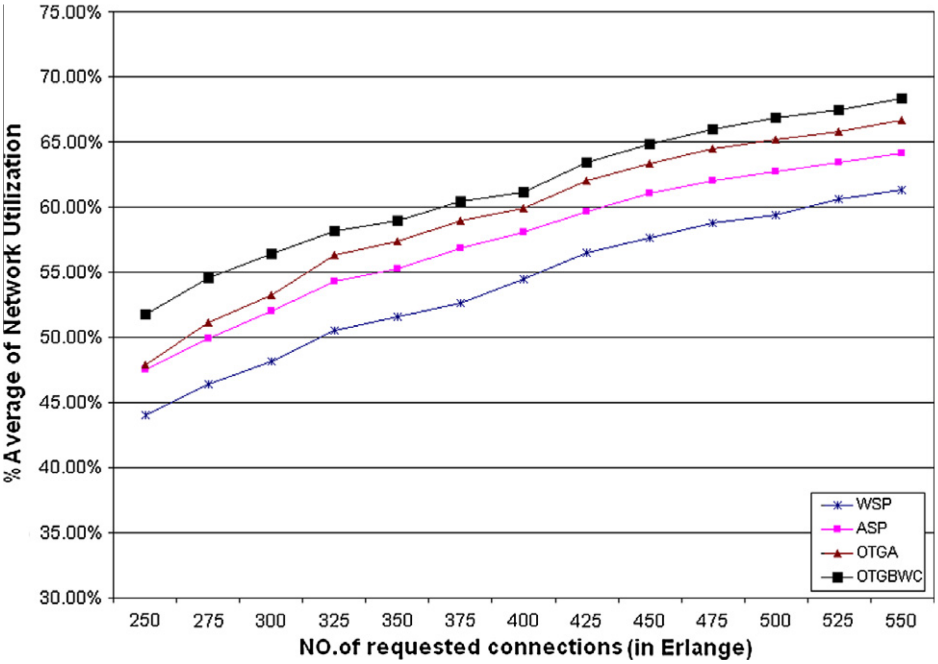

Figure 6 Average network utilization by different routing algorithms.

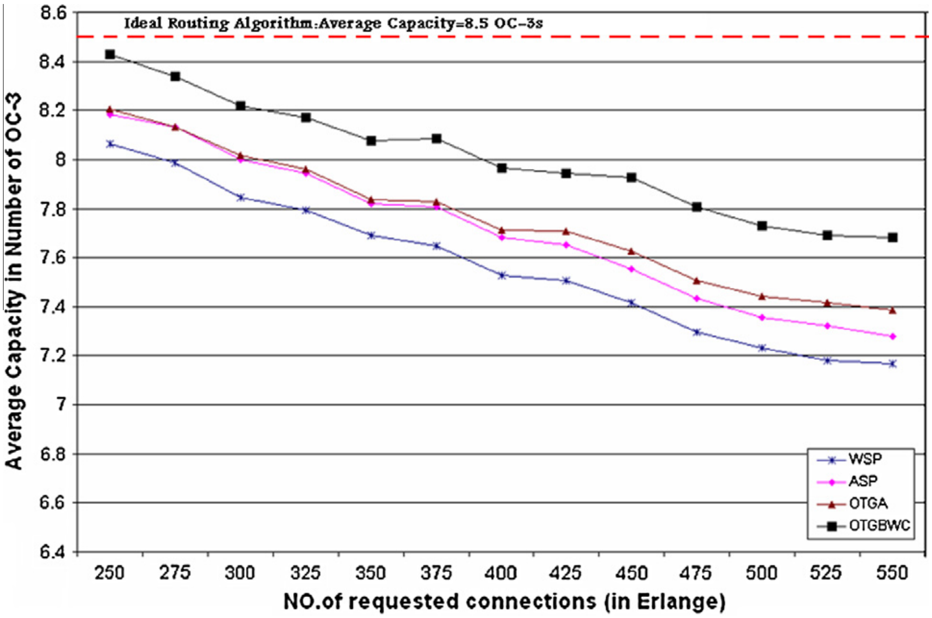

Figure 7 Average capacity of accepted connection requests.

(iv) In Fig. 8, we plot the *fairness ratio* of the routing algorithms when the network load is fixed at 400 request/s given $\mu = 1$ (normalized Erlang at $\mu = 1$). 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, and 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 TGTSWC outperforms all the other algorithms.

9. Summary and conclusion

In this paper, on-line traffic grooming in a WDM–TDM optical mesh network without wavelength conversion capability is investigated. A novel, intelligent approach to dynamic routing

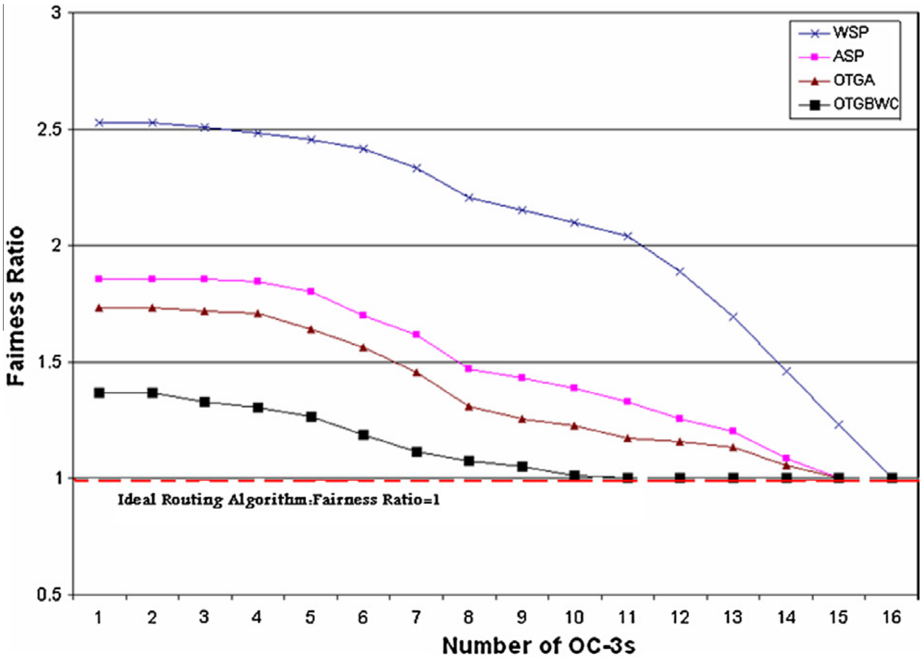

Figure 8 Fairness ratio of different routing algorithms at 400 request/s.

based on knowledge of the connection's-holding time is formulated and its performance is validated. Results are compared with that presented in [20]. The following observations conclude the validation results:

1. A better blocking probability of about 5% is achieved over OTGA while utilizing the same system architecture (no extra hardware is needed).
2. Higher network utilization.
3. Fairness results indicated that our holding time aware system is seen to be quite close to the ideal case

As a result, we claim that the proposed algorithm outperforms the existing algorithms—ASP, WSP as well as the OTGA.

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