Analysis of Multi-Rate Traffic in WDM Grooming Networks

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***Abstract*— Traffic grooming in optical networks employing wavelength division multiplexing has gained prominence due to the prevailing sub-wavelength capacity requirements of users. One approach to achieving wavelength sharing is through time division multiplexing. Connection requests can have varying number of time slot requirements. Analytical modeling for computing blocking performance of establishing multi-rate connections in WDM grooming networks involves extensive combinatorial complexity thus requires prohibitively large state-space for solution. In this paper, we develop an analytical model that employs an approximation to the exact distribution of number of calls of a certain bandwidth requirement on a wavelength. We validate the approximation through simulation results for two different networks that have high and low link-load correlation. It is observed that up to an order of magnitude performance improvement is obtained by improving the grooming capability in the network for calls that require two time slots.**

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 and has been steadily increasing from OC-48 (2.5 Gbps) to OC-192 (10 Gbps), and is expected to increase up to OC-768 (40 Gbps) in the near future. However, this large granularity of wavelength capacity 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/demultiplexing lower rate traffic onto a wavelength and switching them from one *lightpath* to another, where a lightpath is defined as an all-optical connection between two nodes. Optical processing and storage technologies are currently 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, the source-destination pairs are connected by *lightpaths*. Connections between a source and destination are multiplexed onto the lightpath. If the bandwidth required by a new request at a node is not available on any of the existing lightpaths to the destination, a new lightpath to the destination is established. On the other hand, in SWG networks, if a request cannot be accommodated on an existing lightpath to the destination, it is multiplexed onto an existing lightpath to an intermediate node. The connection is then switched at the intermediate node to the final destination either directly or through other nodes. The performance of WDM grooming networks depends on the efficient merging of the fractional wavelength requirements of the requests into full or almost-full wavelength requirements.

Traffic grooming in SWG networks can be either static or dynamic. 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.

In [1], a single-fiber multi-wavelength TDM-switched network has been analyzed for blocking performance, as an extension of the link-independence model proposed for wavelength-routed network in [2] and [3]. The equivalence of single-fiber multi-wavelength TDM-switched network to multi-fiber multi-wavelength wavelength-routed networks has been shown in [4]. A wavelength-routed network is a special case of WDM-TDM switched network when every wavelength has one time slot. The blocking performance of grooming networks for multi-rate traffic with shortest-path routing has been studied in [5] by analyzing path blocking performance for one wavelength and extending it for multiple wavelengths. The analytical model results in higher estimates for blocking probability than the simulation values. In [6], an analytical model is developed for evaluating blocking performance of establishing dual-rate calls assuming statistical independence of link loads.

Nodes in a WDM grooming network can be classified into various categories depending on the level of grooming capability available [7]. If a node can switch connections across different lightpaths but cannot convert from one wavelength to another, it is termed as a *wavelength-level grooming* (WG) node. WG 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 channels across all dimensions (fiber, wavelength, and time slot), then it is referred to as full-grooming network.

In this paper, an analytical model for evaluating the blocking performance of establishing multi-rate traffic in wavelength-

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level grooming networks is developed assuming link load correlation. The wavelength-level grooming network considered in this paper is modeled as a homogeneous Trunk Switched Network (TSN) [8]. An analytical model for multi-rate analysis is developed. The analytical model is shown to be accurate by comparing the values with the simulation results. The rest of the paper is organized as follows: Section II describes WDM grooming networks. The analytical model for multi-rate traffic is developed in Section III. The blocking performance of establishing multi-rate connections is evaluated on two different networks and the results are compared with the simulation studies in Section IV. Section V concludes the paper.

II. Network model

We consider a WDM grooming network with wavelength-level grooming nodes. The nodes in the network are connected using links. Each link is assumed to carry F fibers, each fiber carrying W wavelengths. Each wavelength is divided into frames which are further sub-divided into T time slots. Every slot within a frame is denoted by a 4-tuple, (l, f, w, t), where $1 \leq l \leq L$, $1 \leq f \leq F$, $1 \leq w \leq W$, and $1 \leq t \leq T$. For example, the tuple $(1, 1, 2, 1)$ (read from right to left) denotes first time slot in a frame on the second wavelength of the first fiber on the first link. A *channel* on a link is defined as a collection of a particular time slot across successive frames. Hence, the number of channels in a link is the same as the number of slots in a frame, $F \times W \times T$. Each channel is also represented by a 4-tuple, (l, f, w, t), similar to the representation of a slot.

A. Node architecture

A WDM grooming network with wavelength-level grooming nodes is modeled as a homogeneous Trunk Switched Network (TSN) [8]. A TSN is a two-level network model in which every link in the network is viewed as multiple channels.

A node in a TSN groups the channels with similar characteristics in a link into groups called *trunks*. Fig. 1 shows the node architecture in a TSN. The node in the figure is assumed to have three links attached to it and views each link as a set of four trunks. The trunks are first de-multiplexed from the link. The trunks from different links are then sent to their respective trunk switches where the channels are switched. We impose trunk-continuity constraint at a node, i.e., a channel in a trunk on a link can be switched to a channel that falls within the same trunk on another link. Such a restriction stems from the architectural point of view. The complexity of having a switch architecture that would switch the channels across all the links is very high. Therefore, switch design for the near future are likely to be based on simple architectures that would work on a restricted set of channels from every incoming link. In this paper, it is assumed that a full-permutation switch is employed for every trunk in a node, i.e., a free channel of a trunk at the input of the switch can be switched to any free channel of the same trunk at its output. In case of a homogeneous network with wavelength-level grooming nodes, every wavelength is treated as a trunk.

Consider a trunk on a two-link path. The trunk is said to be *available* on the two-link path for a call with capacity requirement b if there are at least b free channels in the trunk on the first link that can be switched by the node to b free channels in the second link, subjected to the constraints of the switch. For a full-permutation switch, if a trunk is available on a two-link path if the trunk is free at the input and the output of the switch.

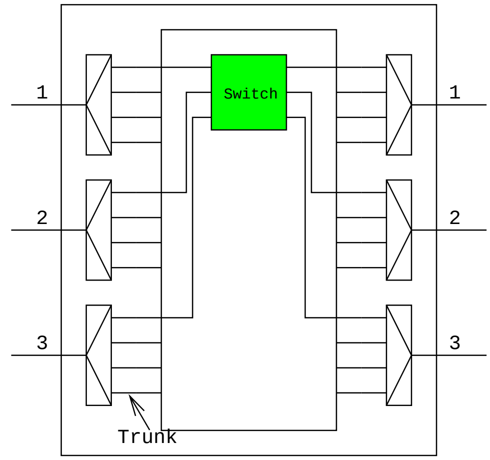

Fig. 1. Node architecture in a Trunk Switched Network.

III. Analysis

We develop an analytical model for wavelength-level grooming networks by viewing them as a homogeneous TSN where every wavelength is a trunk. The analytical model is based on the following assumptions:

- The call arrival at every node follows a Poisson process with rate λ_n and is equally likely to be destined to any other node. The choice of Poisson traffic is to keep the analysis tractable.
- The probability that a call requires for capacity b (as integral number of time-slots) is assumed to be f_b. Hence, the arrival rate of a call request for bandwidth b at a node is $\lambda_n f_b$.
- The holding time of every call follows an exponential distribution with mean $\frac{1}{\mu}$.
- The path selection is pre-determined (fixed-path routing), eg: shortest-path.
- Blocked calls are not re-attempted.
- A call is assigned a channel randomly from a set of available channels.

The call arrival rate at nodes are converted into link arrival rates as described in [9]. This approach is similar to the one employed in [8] but accounts for multiple capacity requirements of the requests. The analysis is developed in three steps: **Step 1:** The channel distribution on a two link path that describes the number of busy channels on the two links of the path is computed with the knowledge of the link arrival rates . **Step 2:** The channel distribution is translated into trunk distribution that describes if a trunk is available on a two-link path for a call with a capacity requirement of b time slots. The information regarding the exact number of calls that require a certain bandwidth is neglected in this step, thus leading to an approximation in the trunk distribution. **Step 3:** The blocking probability on a z-link path is computed recursively from that of the two-link path. Each of these steps are described in detail in the following subsections.

Consider a two-link path model as shown in Fig. 2. Let $\lambda_p^{(b)}$, $\lambda_l^{(b)}$, and $\lambda_c^{(b)}$ denote the arrival rate for calls that request for capacity b to the first link, the second link, and those that continue from the first link to the second. Note that $\lambda_c^{(b)} \leq min(\lambda_p^{(b)}, \lambda_l^{(b)})$. The Erlang loads corresponding to the calls that occupy the first link, second link, and that which continue from the first to the second can be written as, $\rho_p^{(b)} = \frac{\lambda_p^{(b)}}{\mu}$, $\rho_l^{(b)} = \frac{\lambda_l^{(b)}}{\mu}$, and $\rho_c^{(b)} = \frac{\lambda_c^{(b)}}{\mu}$, respectively.

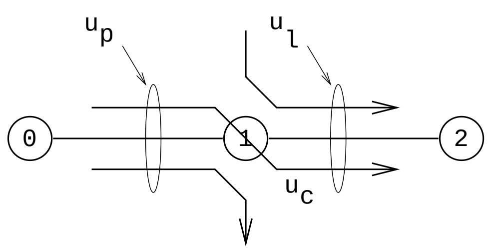

Fig. 2. A two-link path model.

A. Channel distribution

Let u_p, u_l, and u_c denote the number of channels busy on the first link, number of channels busy on second link, and number of channels occupied by calls that continue from the first link to the second, respectively. Note that $u_c \leq min(u_p, u_l)$.

The channel distribution on a two-link path can be characterized to a limited extent as a 3-dimensional Markov chain. The state-space is denoted by the 3-tuple (u_p, u_l, u_c). Note that such a representation of the state of the two-links does not take into account the number of calls that require a certain specified bandwidth. The steady-state probability for the states is computed recursively by considering the number of calls that require a certain capacity, C, as:

$$\Pi(u_p, u_l, u_c) = \frac{1}{G}\xi_B(u_p, u_l, u_c)$$

where $0 \leq u_p \leq KS$, $0 \leq u_l \leq KS$, and $0 \leq u_c \leq min(u_p, u_l)$. G is the normalization constant and is defined as:

$$G = \sum_{u_p=0}^{KS}\sum_{u_l=0}^{KS}\sum_{u_c=0}^{\min(u_p,u_l)} \xi_B(u_p, u_l, u_c)$$

$\xi_b(u_p, u_l, u_c)$ is recursively computed as shown in Fig. 3.

B. Trunk distribution

From the channel distribution, the trunk distribution is computed. This computation could be carried out by considering the exact number of calls of a certain bandwidth requirement that is present on a two-link path. However, this computation would require a large state-space. In this paper, it is assumed that the total number of channels occupied by calls are known and the exact distribution is neglected. With this assumption, the trunk distribution is computed as described in [8] with necessary modifications to accommodate multi-rate connections. Recall that a trunk on a path is said to be busy if the number of channels available on the trunk on the path is less than that required by the call request. The equations that are described below are for call requests that have a requirement of b time slots.

Let V_p, V_l, and V_c denote the number of trunks busy on the first link, number of trunks busy on the second link, and number of trunks that are busy on both the first and second links, respectively. It can be observed that $V_c \leq min(V_p, V_l)$. The number of trunks free on both the links is given by, $T_a = K - (V_p + V_l - V_c)$. Note that with the assumption of full-permutation switching employed per trunk, T_a trunks are available for establishing the connection on the two-link path. The state-space of the trunk distribution is captured by the 3-tuple (V_p, V_l, V_c) whose steady-state probability is computed by conditioning on the channel distribution as:

$$\psi(V_p, V_l, V_c) = \sum_{u_p=0}^{KS}\sum_{u_l=0}^{KS}\sum_{u_c=0}^{min(u_p,u_l)} P(V_p, V_l, V_c|u_p, u_l, u_c)\,\Pi(u_p, u_l, u_c)$$

where $P(V_p, V_l, V_c|u_p, u_l, u_c)$ denotes the probability that the trunk distribution is in state (V_p, V_l, V_c) given that the channel distribution is (u_p, u_l).

The trunk occupancy probability for a given a channel distribution, is computed as:

$$P(V_p, V_l, V_c|u_p, u_l) = \frac{N_{k=K}(V_p, V_l, V_c, K - (V_p + V_l - V_c)|u_p, u_l, u_c)}{A_{k=K}(u_p, u_l, u_c)}$$

where $N_k(V_p, V_l, V_c, T_a|u_p, u_l, u_c)$ denotes the number of ways of arranging across k trunks, u_p busy channels on the first link, u_l busy channels on the second link, with u_c channels among them being occupied by calls that continue from the first link to second, such that V_p trunks are busy on the first link, V_l trunks are busy on the second link with V_c among them busy on both the links, and T_a trunks being available on the two-link path. As the switching at every node is assumed to be full-permutation, the number of available trunks T_a is expressed as $T_a = K - (V_p + V_l - V_c)$. The additional information of T_a is employed to compute the number of combinations of busy channel arrangements that would result in an available trunk. If the switches employed per trunk at nodes are not full-permutation switches, then T_a can be smaller than $K - (V_p + V_l - V_c)$, as a trunk can be free on both the links but the free channels at the input cannot be switched to the free channels at the output due to the blocking nature of the switch.

$A_k(u_p, u_l, u_c)$ denotes all possible ways of arranging across k trunks, u_p busy channels on the first link, u_l busy channels on the second link. $A_k(u_p, u_l)$ is recursively computed as:

$$A_k(u_p, u_l, u_c) = \sum_{z=0}^{\min(S,u_c)}\sum_{x=z}^{min(S,u_p)}\sum_{y=z}^{min(S,u_l)} A_1(x, y, z)\; A_{k-1}(u_p - x, u_l - y, u_c - z)$$

$$\xi_b(u_p,u_l,u_c) = \begin{cases} \sum_{z=0}^{\lfloor \frac{u_c}{b} \rfloor} \sum_{x=z}^{\lfloor \frac{u_p}{b} \rfloor} \sum_{y=z}^{\lfloor \frac{u_l}{b} \rfloor} \left[\frac{(\rho_p^{(b)}-\rho_c^{(b)})^{x-z}}{(x-z)!} \frac{(\rho_c^{(b)})^z}{z!} \frac{(\rho_p^{(b)}-\rho_c^{(b)})^{y-z}}{(y-z)!} \xi_{b-1}(u_p-bx, u_l-by, u_c-bz) \right] & \text{if } b>1 \\ \frac{(\rho_p^{(b)}-\rho_c^{(b)})^{u_p-u_c}}{(u_p-u_c)!} \frac{(\rho_c^{(b)})^{u_c}}{u_c!} \frac{(\rho_p^{(b)}-\rho_c^{(b)})^{u_l-u_c}}{(u_l-u_c)!} & \text{if } b=1 \\ 0 & \text{otherwise} \end{cases}$$

Fig. 3. Equation to compute $\xi_b(u_p,u_l,u_c)$.

where $0 \le u_p \le kS$, $0 \le u_l \le kS$, and $0 \le u_c \le \min(u_p,u_l)$. The definition of $A_1(x,y,z)$ depends on the nature of switch.

$N_k(V_p,V_l,V_c,T_a|u_p,u_l,u_c)$ (written as $N_k(.)$ for short due to space constraints) is computed recursively under one of the following four cases assuming that the bandwidth requirement of the call is b. Note that a trunk has S channels in total, hence the trunk is available on a link only when there are at least b channels free.

Case 1: If $V_c > 0$
The required probability is obtained by conditioning on a trunk being busy on both the links.

$$N_k(.) = \frac{k}{V_c} \sum_{z=0}^{\min(S,u_c)} \sum_{x=max(z,S-b+1)}^{\min(S,u_p)} \sum_{y=max(z,S-b+1)}^{\min(S,u_l)} [\, A_1(x,y,z) \times N_{k-1}(V_p-1,V_l-1,V_c-1,T_a|u_p-x,u_l-y,u_c-z)\,]$$

Case 2: If $V_c = 0, V_p > 0$
The required probability is obtained by conditioning on a trunk being busy on the first link but free on the second link.

$$N_k(.) = \frac{k}{V_p} \sum_{z=0}^{\min(S-b,u_c)} \sum_{x=S-b+1}^{\min(S,u_p)} \sum_{y=z}^{min(S-b,u_l)} [\, A_1(x,y,z) \times N_{k-1}(V_p-1,V_l,V_c,T_a|u_p-x,u_l-y,u_c-z)\,]$$

Case 3: If $V_c = 0, V_p = 0, V_l > 0$
The required probability is obtained by conditioning on a trunk being free on the first link but busy on the second link.

$$N_k(.) = \frac{k}{V_l} \sum_{z=0}^{\min(S-b,u_c)} \sum_{x=z}^{min(S-b,u_p)} \sum_{y=S-b+1}^{\min(S,u_l)} [\, A_1(x,y,z) \times N_{k-1}(V_p,V_l-1,V_c,T_a|u_p-x,u_l-y,u_c-z)\,]$$

Case 4: If $V_c = 0, V_p = 0, V_l = 0$
In this case, a trunk can be made available with different possible arrangements for the busy channel distribution. The required probability is obtained on the condition that a trunk is free on both the links, considering one at a time.

$$N_k(.) = \sum_{z=0}^{\min(S-b,u_c)} \sum_{x=z}^{\min(S-b,u_p)} \sum_{y=z}^{\min(S-b,u_l)} [\, A_1(x,y,z) \times N_{k-1}(V_p,V_l,V_c,T_a-1|u_p-x,u_l-y,u_c-z)\,]$$

The starting point of the recursion (for $k=1$), denoted by $N_1(V_p,V_l,V_c,T_a|u_p,u_l,u_c)$ is computed as:

$$N_1(.) = \begin{cases} A_1(u_p,u_l,u_c) & \text{if } T_a = 1, max(u_p,u_l) \le S-b \\ 0 & \text{otherwise.} \end{cases}$$

For a full-permutation switch, a trunk busy on a two-link path if either the trunk at the input or at the output has less than C capacity available. Therefore, a full-permutation switch can be described as:

$$A_1(u_p,u_l,u_c) = \begin{cases} \binom{S}{u_p}\binom{S}{u_l} & \text{if } 0 \le u_p,u_l \le S \text{ and } u_c \le \min(u_p,u_l) \\ 0 & \text{otherwise.} \end{cases}$$

C. Path blocking performance

The blocking probability of establishing a call requesting for capacity b over a z-link is evaluated with the trunk distributions computed in the earlier section as the basis. A z-link path is treated as a two-hop path with the first $z-1$ links in the first hop and the last two links as the second hop as shown in Fig. 4.

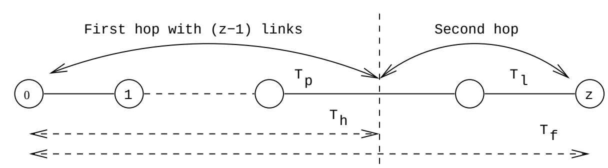

Fig. 4. A z-link path model.

Let $P_z(T_f)$ denote the probability of T_f trunks being available on a z-link path as viewed by the last node on the path[1] (node z). The definition of the trunk is as viewed by the node denoted by the suffix for P. $P_z(T_f=0)$ denotes the blocking probability over the z-link path. The ensemble average of the network blocking probability, denoted by P_b, is obtained as:

$$P_b = \sum_{z=1}^{N-1} P_z(T_f=0)P(z)$$

where $P(z)$ denotes the probability of selecting a z-link path. $P(z)$ depends on the network topology and routing strategy employed in the network, and can be easily computed for most regular network topologies and routing strategies.

[1]The destination is not considered as the last node in the path.

Let $P_z(T_f, T_l)$ denote the probability of T_f trunks being available on a z-link path with T_l trunks free on the last link. It can be seen that the last link should have at-least T_f trunks free, therefore $T_l \geq T_f$. $P_z(T_f)$ can then be written as:

$$P_z(T_f) = \sum_{T_l=T_f}^{K_z} P_z(T_f, T_l)$$

where K_z denotes the number trunks in the link as viewed by node z.

A z-link path is analyzed as a two-hop path by considering the first $z-1$ links as the first hop and the last two links as the second hop, as shown in Fig. 4. Let T_h and T_p denote the number of trunks available on the first hop and that which are free on the last link of the first hop (link $z-1$), respectively, as viewed by the last node on the first hop (node $z-1$). Let T_1 and T_2 denote the number of trunks free on the first hop and number of trunks free on the last link of the first hop as seen by the node in the second hop (node z). $P_z(T_f, T_l)$ can then be recursively computed as:

$$P_z(T_f, T_l) = \sum_{T_h=T_f}^{K} \sum_{T_p=T_h}^{K} P_{z-1}(T_h, T_p)\ P(T_f, T_l | T_h, T_p)$$

where K denotes the number of trunks in a link as viewed by the nodes in the network. The computation of $P(T_1, T_2 | T_h, T_p)$ for different trunk definitions is being studied by the authors. Hence, the scope of the analysis presented in this paper is limited to homogeneous TSN's.

The starting point of the recursion, for $z = 1$, is defined as:

$$P_1(T_f, T_l) = \begin{cases} P(T_l) & \text{if } T_f = T_l \\ 0 & \text{otherwise.} \end{cases}$$

where $P(T_l)$ denotes the probability of T_l trunks being free on a link. The computation of $P(T_l)$ is discussed in Section III-A.

$P(T_f, T_l | T_h, T_p)$ is computed by conditioning on the number of trunks free on the last link. The number of trunks free on the last link depends on the number of trunks free on the previous links. The correlation of traffic on a link is assumed to be only due to its previous link, referred to as the *Markovian correlation*. With the assumption of Markovian correlation, $P(T_f, T_l | T_h, T_p)$ is written as:

$$P(T_f, T_l | T_h, T_p) = \begin{cases} P(T_f | T_h, T_p, T_l)\ P(T_l | T_p) & \text{if } T_h \geq T_f \\ 0 & \text{otherwise} \end{cases}$$

$P(T_f | T_h, T_p, T_l)$ is computed as given below for a full-permutation switch to grooming traffic on a wavelength.

$$P(T_f | T_h, T_p, T_l) = \frac{\binom{T_h}{T_f}\binom{K-T_h}{T_l-T_f}}{\binom{K}{T_l}}$$

For other kinds of wavelength-level switch architectures, space switch for example, one could use the framework in [8] to consider generic trunk mappings.

The variables that remain to be computed are $P(T_l | T_p)$ and $P(T_l)$. These are computed from the steady state trunk distribution as defined below:

$$P(T_l | T_p) = \frac{\sum_{v_c=max(0,K-T_p-T_l)}^{min(K-T_p,K-T_l)} \psi(K-T_p, K-T_l, v_c)}{\sum_{t_l=0}^{KS} \sum_{v_c=max(0,K-T_p-T_l)}^{min(K-T_p,K-T_l)} \psi(K-T_p, K-t_l, v_c)}$$

$$P(T_l) = \sum_{t_p=0}^{K} \sum_{v_c=max(0,K-t_p-T_l)}^{min(K-t_p,K-T_l)} \psi(K-t_p, K-T_l, v_c)$$

IV. Performance Evaluation

The blocking performance of establishing multi-rate traffic connections are evaluated on 25-node bi-directional ring and 5×5 bi-directional mesh-torus networks. The choice of these two networks are due to the high and low link correlation, hence the accuracy of the model can be established at both extremes. A 25-node bi-directional ring network has a correlation ratio of 0.84 while a 5×5 bi-directional mesh-torus network has a correlation ratio of 0.20 when shortest path routing is employed.

The calls are generated at a node according to Poisson distribution and are equally likely to be destined to any other node in the network. The bandwidth requirement of a call is assumed to be either 1 or 2 timeslots with equal probability. Every link is assumed to have a capacity of 20 timeslots with three different wavelength and time-slot combinations: (1) 4 wavelengths with 5 timeslots each; (2) 2 wavelengths with 10 timeslots each; and (3) one wavelength with 20 timeslots. Each node has a full-permutation switch for every wavelength.

Figs. 5 and 6 show the blocking performance for establishing calls that require one time slot on ring and mesh networks, respectively, with different wavelength and timeslot combinations. The blocking performance for establishing calls requiring two timeslots are shown in Figs. 7 and 8 for ring and mesh-torus networks, respectively. It is observed from the figures that the analytical model closely approximates the simulation. Note that the approximation employed in the analytical model affects networks with more wavelengths.

It is observed that blocking performance of establishing calls requesting for one time slot decreases in the simulation results with increase in the number of wavelengths, i.e., decreasing grooming capability. This phenomenon is due to the increased blocking of calls that require two timeslots. It is intuitive that as the grooming capability is decreased, the blocking probability of higher capacity calls increase. As a result, networks that block more of higher capacity calls have lower blocking probability for lower capacity calls. This behavior can be obtained from the analytical model to some extent through iterative computation of blocking probabilities of calls of different rates.

It is observed that increasing the grooming capability in the network results in an order of magnitude improvement in the blocking performance of two time slot requests. This improvement is expected to be even more pronounced for higher capacity requests. However, it is an expensive solution to implement full grooming at all the nodes in the network. Hence, other

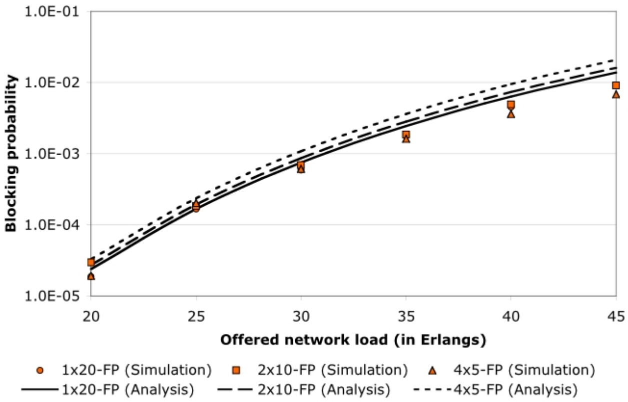

Fig. 5. Blocking probability of connections requiring 1 timeslot in a 25-node bi-directional ring network.

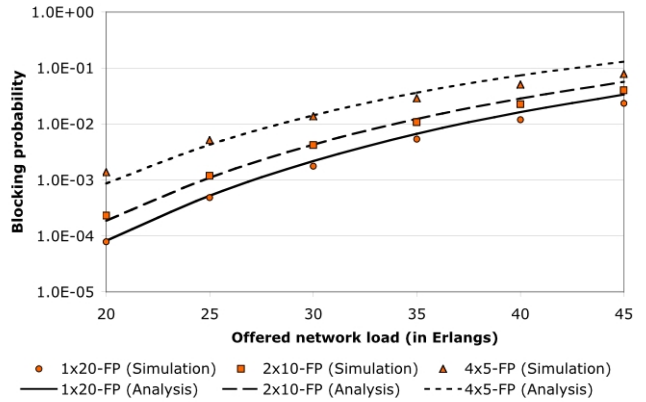

Fig. 7. Blocking probability of connections requiring 2 timeslot in a 25-node bi-directional ring network.

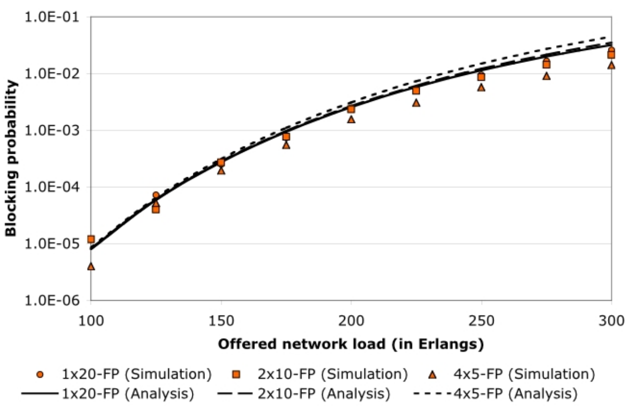

Fig. 6. Blocking probability of connections requiring 1 timeslot in a 5x5 bi-directional mesh-torus network.

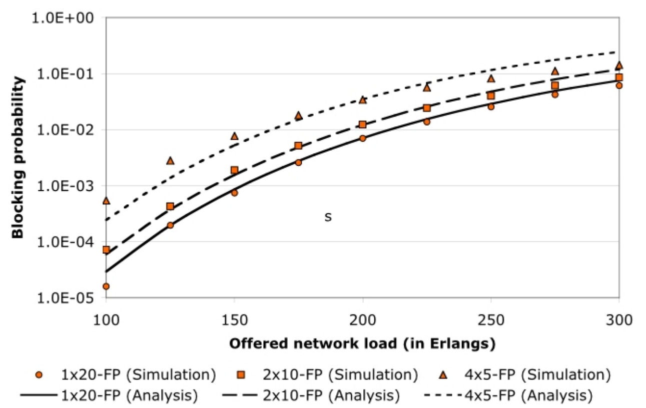

Fig. 8. Blocking probability of connections requiring 2 timeslot in a 5x5 bi-directional mesh-torus network.

approaches such as splitting higher capacity connections into multiple lower capacity connections, referred to as *dispersity routing*, could be considered as cost-effective alternatives.

V. Conclusion

In this paper, we develop an analytical model to evaluate the blocking performance of establishing multi-rate traffic in WDM grooming networks. The analysis presented in this paper is based on our earlier work on a generalized analytical framework for evaluating blocking performance in WDM grooming networks [8]. Exact analytical model of multi-rate traffic requires extensive combinatorics requiring prohibitively large computational time, hence necessitating the need for developing approximate solutions. The analytical model developed in this paper employs an approximation to the exact distribution of the number of calls of a certain bandwidth requirement. We validate our approximation through simulation ring and mesh networks.

It is observed that improving grooming capability results in significant improvement in blocking performance, up to an order of magnitude for two-timeslot requests. As grooming is an expensive solution, it is necessary to devise other mechanisms, such as dynamic routing and dispersity routing, through which such improvements could be obtained.

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