The impact of the number of add/drop ports in wavelength routing all-optical networks

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ABSTRACT

The study of wavelength-routing optical networks is an exciting research topic that has been attracting a lot of attention recently. For the design and operation of these networks, it would be important to study the way network performance is affected by factors such as wavelength number, wavelength conversion capability and the number of usable add/drop ports at the optical switches. We study the performance of wavelength-routing all-optical networks with both limited number of link capacities (i.e. wavelengths) and limited number of node add/drop ports (i.e. transmitters and receivers). The analytical models for both virtual wavelength path and wavelength path networks are presented. Based on the simulation and analytical results obtained for various kinds of networks, we have evaluated the impact of the number of add/drop ports in each node. We find that only a limited number of add/drop ports are required in each node to achieve a performance very close to that of a network where each node is equipped with the full number of full-range-tuneable add/drop ports.

1 Introduction

Wavelength Division Multiplexing (WDM) [1-9] is expected to be a popular technique for constructing large optical networks interconnecting a large number of nodes. With suitable optical cross- connects (OXC) [10-12] at the nodes, such a network will allow wavelengths and light-paths to be switched in a very flexible fashion between the active source-destination pairs. This flexibility in routing will make these networks easy to configure and operate and will also improve the reliability of the network by providing easy-to-set-up alternate paths in case of node and link failures [13-15].

In a network with dynamic traffic loading, light-path requirements will vary with time. This will lead to new light-path requests being generated and older light-paths getting terminated as the traffic pattern and the offered loads change over time. Analytical models for WDM networks with dynamic traffic loading will be of use in studying this performance [16-19]. Such a model is proposed in [16] assuming independent link loads and wavelength occupancies over the network; a recursive procedure is subsequently proposed for computations. A model accounting for the correlation between two neighboring links on a light path has also been proposed in [17]. The model proposed in [18] can also give good results for WDM networks with short light-paths.

For simplicity, a common assumption has been made in all the above-mentioned analytical models and other similar approaches. These models do take into account the link capacity limitations (i.e. the maximum available number of wavelengths on each link), but ignore the possible impact of having only a limited number of add/drop ports (i.e., transmitters and receivers) at each node. From a practical point of view, this assumption may not be true for a realistic optical transport network (OTN) [20]. An OXC node in a real OTN, as illustrated as Fig. 1, may only be equipped with a limited number of add/drop ports. This could be because it may be too costly to provide one add/drop port for each inlet/outlet wavelength. Moreover, deploying one add/drop port per inlet/outlet wavelength would not even be efficient, as a number of light-paths (wavelengths) may only transit through the OXC node; these wavelengths would not actually need an add/drop process at the OXC. Some initial studies have been made on the impact of the number of add/drop ports available at the nodes of the network. For example, in [21], an integrated network design scheme has been developed which does consider the limitations on the number of usable add/drop ports; however, this has been done only for a network where the traffic requirements are known a priori. An all-to-all connection scheduling method taking into account the impact of the number add/drop ports at the nodes has been designed for a ring network in [22]. Also for a ring network, [33] looked into the benefit of reconfigurability for a network with limited ports per node. However, similar investigations for a network with general topology and dynamic light-path requirements have not been reported in the literature. From a practical standpoint, there is also a need for studying networks with dynamic light-path requirements, where both the number of wavelengths on each link and the number of add/drop ports in each node are limited. The goal of this paper is to examine analytically the impact of the number of add/drop ports on the performance of wavelength routing optical networks. We study how the performance (in terms of blocking probability) of the network depends both on the number of wavelengths available per link and the number of add/drop ports in each node [23]. These studies have been conducted based both on our analytical models and on simulations. A related simulation based study on the impact of the number of transceivers and their *tuneability* has also been reported by us in [24].

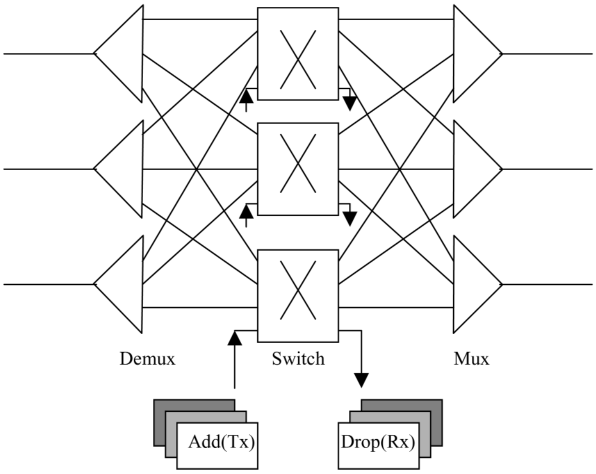

Figure 1: The architecture of a typical optical cross-connect (Demux: Demultiplexer; Mux: Multiplexer).

The rest of this paper is organized as follows. In Section II, we briefly introduce the concepts of wavelength path (WP) and virtual wavelength path (VWP) WDM networks. In Section III, we present the traffic model used for the wavelength routing optical network and describe some of the related assumptions that we have made. Section IV presents our approximate analytical models for both VWP and WP networks. Section V evaluates the accuracy of the proposed models and also studies the impact of having a limited number of node add/drop ports at the nodes of the network. Section VI concludes the paper.

2 Wavelength Path (WP), Virtual Wavelength Path (VWP)

Consider a WDM network where different source-destination node pairs communicate with each other using the network's optical links with appropriate routing. The route between a particular source-destination node pair is typically referred to as its *light-path*. This light-path will be set up between the end nodes following the optical links along the specific route being used. An important issue that needs to be considered in this case is whether the system will have the flexibility of changing the wavelength that is being used as we traverse the route of the light-path from its source to its destination (and vice versa). Depending on whether the system has no flexibility or full flexibility, WDM optical networks may be configured as *wavelength path* (WP) or *virtual wavelength path* (VWP) networks [23]. Networks with *partial wavelength conversion* (PWC) [25-27] have also been suggested but will not be considered in this paper.

A WP network [10,23] is one where no wavelength conversion is allowed along the light-path, i.e. the same wavelength must be used in all the links going from the source to the destination along the selected light-path. A WP network must therefore satisfy the *wavelength continuity* constraint requiring that a unique and identical wavelength must be used everywhere on any particular light-path in the system. A WP-WDM network is simple to design and operate but will not offer any operational flexibility in wavelength conversion.

A VWP [10,23] network will provide the maximum flexibility in wavelength conversion. Each node in the network has a sufficient number of wavelength converters so that any wavelength on any incoming link may be switched to any wavelength on any outgoing link – this is of course conditional on the fact that the same wavelength on an outgoing link cannot be used more than once. These wavelength converters would then permit different wavelengths to be used on different links of a particular light-path making these VWP networks very similar to what one encounters in traditional circuit switched telephone networks. The techniques used to analyze circuit switched networks may also be useful in analyzing VWP-WDM networks.

3 Network Traffic Model

Consider an *N*-node WDM network such as the one shown in Fig. 2 [28]. We make the simplifying assumptions that:

1. Every node is reachable from every other node.
2. Each link has a pair of fibres, one for each direction, and the maximum number of available wavelengths on each fibre is the same value *W*.
3. Each node is equipped with a limited number of add/drop ports. The number of such ports in each node is assumed to be the same. Each of these ports is assumed to be capable of emitting any one of the wavelengths in the *W*-wavelength band. [Note that this may possibly be achieved by using a *W*-wavelength laser array or by a wide-tuneable-range laser at each port.]

A *light-path generator* G_{ij} is used to model the light-path requirement for traffic between the end nodes *i* and *j*. Light-path requests between the end nodes *i* and *j* will be generated by this generator and will be representative of the traffic requirement between these end nodes. If a light-path request can be satisfied then the route and wavelengths to be used for this are provided; otherwise the light-path request fails. The light-path is terminated when its holding time expires and the corresponding wavelength is released for subsequent use by another light-path. We make the following assumptions in this regard:

1. Light-path generators are independent of each other.
2. Light-path generators are bi-directional, $G_{ij} = G_{ji}$ for $i \neq j$, and $G_{ii} = 0$. This assumption is appropriate as network communication is often bi-directional in nature.
3. Each generator generates light-path requests following a Poisson arrival process model, and the holding time of each light-path is assumed to follow a negative exponential distribution. The Poisson arrival process and the negative exponential service time would be suitable for a light-path because a light-path in the WDM network is similar to a circuit in traditional circuit switching networks[1].
4. The routing procedures for all the light-paths follow fixed Dijkstra's shortest-path algorithm. Other alternative routing approaches may also be applied, which will, however, increase the complexity of the model.
5. In a WP network, a wavelength is randomly assigned to a new light-path from the ones that are available for use. Other strategies like the *first-fit wavelength assignment* method may also be used to select a wavelength for a new light-path, but its analysis will be more complicated.
6. For simplicity, the traffic on different links is assumed to be independent. This assumption has been found to be suitable when the network is not too sparsely connected [16].

The actual functions of light-path routing and wavelength assignment for a successful light-path request and wavelength release on light-path termination may be done in either a centralised or distributed fashion [29-30]. This issue of network management has not been addressed in this paper.

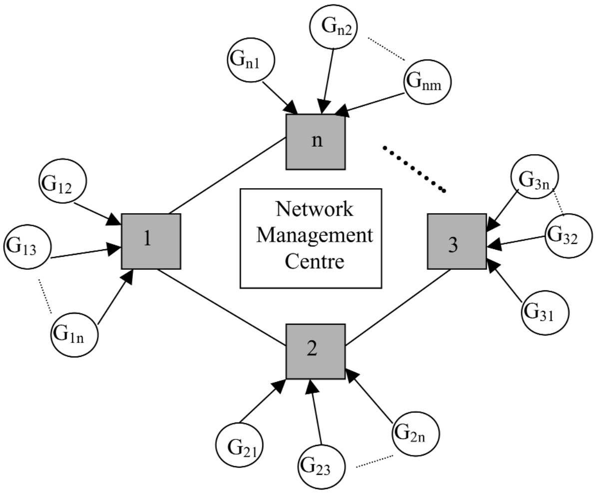

Figure 2: Network traffic model for dynamic traffic loading.

4 Analytical Models

In this section, we present the analytical models for both VWP and WP networks. For VWP networks, we propose the model based on the one widely used in the traditional telephone circuit-switching network. For WP networks, an approximate model, which requires low computational complexity, is developed with the assumption of link traffic independence.

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[1] *Note that other alternative traffic models could also have been selected. However, Poisson-based traffic models have been widely adopted as in [10,16-18], which led us to use this model here. As for the choice of traffic model more suitable for optical networks, this would be outside the scope of this paper.*

4.1 Analytical model for VWP networks

Consider a VWP-WDM network with dynamic traffic loading. Let $\lambda(s,d)$ be the call arrival rate of the light-path between the node pair (s,d) for the traffic generator G_{sd} and let $1/\mu$ be the average holding time of a light path. To simplify our notations, we normalise time such that the average service time is unity (i.e. $1/\mu = 1$). We also assume $\lambda_l(i)$ to be the corresponding total light-path request arrival rate on the i^{th} link of the path, and similarly, $\lambda_n(i)$ to be the total light-path request arrival rate on node i.

Given T to be the number of add/drop ports in node i, we have the blocking probability $B_n(i)$ at node i due to the limited number of add/drop ports given by the Erlang loss formula as

$$B_n(i) = E(\lambda_n(i),T) = \frac{\dfrac{\lambda_n(i)^T}{T!}}{\displaystyle\sum_{j=0}^{T}\frac{\lambda_n(i)^j}{j!}} \qquad (1)$$

Similarly, the blocking probability $B_l(i)$ at link i due to its limited link capacity of W, is given by the Erlang loss formula as

$$B_l(i) = E(\lambda_l(i),W) = \frac{\dfrac{\lambda_l(i)^W}{T!}}{\displaystyle\sum_{j=0}^{T}\frac{\lambda_l(i)^j}{j!}}$$

To establish a light-path between a node pair successfully, apart from enough link capacity, a pair of free add/drop ports in the source and destination nodes are also required. Therefore, the blocking probability $p_b(s,d)$ of the light-path between nodes s and d has to consider the constraints both from limited number of link capacities and from limited number of node add/drop ports. This may be computed as

$$\begin{aligned} p_b(s,d) &= 1-(1-B_n(s))(1-B_n(d)) \prod_{i\in path\,(s,d)} (1-B_l(i)) \\ &= 1-(1-E(\lambda_n(s),T)) \\ &\qquad (1-E(\lambda_n(d),T)) \prod_{i\in path\,(s,d)} (1-E(\lambda_l(i),W)) \quad (2) \end{aligned}$$

Here, $path\,(s,\ d)$ is a set of concatenated optical links that makes up the lightpath, the term $(1 - E(\lambda_n(s),T))$ $(1 - E(\lambda_n(d),T))$ is the probability that both source and destination nodes can provide free add/drop port(s), and the term $\prod_{i\in path\,(s,d)}(1 - E(\lambda_l(i),W))$ is the probability that all the links on the light-path can offer free capacities (i.e., wavelengths).

The traffic matrix representing the offered load $\lambda(s,d)$ between any pair of stations s and d in the network will normally be given. It is shown in [16] that a good approximation for the offered load on link i in the network with wavelength conversion is

$$\lambda_l(i) = \sum_{s,d} a(i,s,d)\,\lambda(s,d)\,\frac{1-p_b(s,d)}{1-B_l(i)} \qquad (3)$$

Here $a(i,s,d)$ is the link-path incidence matrix defined as

$$a(i,s,d) = \begin{cases} 1, & link\ i \in path\,(s,d) \\ 0, & otherwise \end{cases}$$

Therefore, the term $\sum_{s,d} a(i,s,d)\lambda(s,d)(1-p_b(s,d))$ represents the load carried by link i, and it is smaller than the offered load by factor $1 - B_l(i)$.

Similarly, with assumption (3) of Section 3, we can get the arrival-rate-relationship between a node and the corresponding traffic generators. The approximate offered load on node i may be expressed as

$$\lambda_n(i) = \sum_{j} \lambda(i,j)\,\frac{1-p_b(i,j)}{1-B_n(i)} \qquad (4)$$

Here the term $\sum_j \lambda(i,j)(1-p_b(i,j))$ denotes the load carried by node i, which is smaller than the offered load by factor $1 - B_n(i)$.

With equations (3) and (4), to compute the final light-path blocking probability, we need to solve the Erlang fixed-point equations [16,31] for both links and nodes. These are given as

$$\begin{aligned} B_l(i) &= E(\lambda_l(i),W) \\ &= E\left(\sum_{s,d} a(i,s,d)\lambda(s,d)\,\frac{1-p_b(s,d)}{1-B_l(i)},W\right) \qquad (5) \end{aligned}$$

$$B_n(s) = E(\lambda_n(s),T) = E(\sum_i \left(\lambda(s,i)\,\frac{1-p_b(s,i)}{1-B_n(s)}\right),T) \qquad (6)$$

$$B_n(d) = E(\lambda_n(d),T) = E(\sum_i \left(\lambda(i,d)\,\frac{1-p_b(i,d)}{1-B_n(d)}\right),T) \qquad (7)$$

The average light-path blocking probability of the network may then be calculated as

$$P_B = \frac{\displaystyle\sum_{s,d} p_b(s,d)\lambda(s,d)}{\displaystyle\sum_{s,d}\lambda(s,d)} \qquad (8)$$

The *relaxation method* [31] is a good approach to use to solve (5)-(7) with the definitions that $\lambda_l^n(i)$, $\lambda_n^n(i)$, $B_l^n(i)$, $B_n^n(i)$, $p_b^n(s,d)$ and P_B^n are the values obtained for $\lambda_l(i)$, $\lambda_n(i)$, $B_l(i)$, $B_n(i)$, $p_b(s,d)$ and P_B in the nth iteration. The detailed steps for this are given below:

1. Let $p_b^0(s,d)$, P_B^0, $B_n^0(i)$ and $B_l^0(i)$ be 0; let $\lambda_l^0(i)$ and $\lambda_n^0(i)$ be arbitrary values.
2. Let $n = 1$
3. Calculate $\lambda_l^n(i)$ using (3) and $\lambda_n^n(i)$ using (4).

4. Calculate $B_l^n(i)$, $B_n^n(i)$ using (5), (6) and (7).
5. Calculate $p_b^n(s,d)$ using (2).
6. Find P_B^n using (8).
7. If the difference between P_B^n and P_B^{n-1} is smaller than a threshold value, stop. Otherwise, set $n = n + 1$ and go to Step 3.

4.2 Analytical model for WP networks

This part considers the model for WP networks. In contrast to VWP networks, WP networks have to guarantee the *wavelength continuity* constraint for each light-path. This means that the same wavelength is required on all the links of the light-path. Following this constraint, we present our WP model as follows.

Let $X_l(i)$ be the random variable denoting the number of idle wavelengths on link i in equilibrium. Let $q_i(\omega) = \Pr[X_l(i) = \omega]$ $(\omega = 0,\ldots,W)$ be the idle capacity distribution on link i. We make the following additional assumptions:

1. The random variables $X_l(i)$ are mutually independent.
2. When there are ω idle wavelengths on link i, the time until next call is set up on link i is exponentially distributed with parameter $\alpha_i(\omega)$. This conditional parameter is the call setup rate on link i when ω wavelengths are free on that link.

We follow the birth-and-death process suggested in [18,32]. This gives us

$$q_i(\omega) = \frac{W(W-1)\ldots(W-\omega+1)}{\alpha_i(1)\alpha_i(2)\ldots\alpha_i(\omega)}\,q_i(0) \qquad \omega = 1,\ldots,W \tag{9}$$

where

$$q_i(0) = \left[1 + \sum_{\omega=1}^{W} \frac{W(W-1)\ldots(W-\omega+1)}{\alpha_i(1)\alpha_i(2)\ldots\alpha_i(\omega)}\right]^{-1} \tag{10}$$

The call set up rate on link i when there are ω idle wavelengths on link $i,\alpha_i(\omega)$, is obtained by combining the contributions from the light-path request streams to routes of which link j is a member.

$$\begin{cases} \alpha_i(\omega) = 0, & \text{if } \omega = 0, \\ \displaystyle\sum_{s,d:i\in path(s,d)} \lambda(s,d)P\{X_p(s,d) > 0 \mid X_l(i) = \omega\}, & \text{if } \omega = 1,\ldots,W \end{cases} \tag{11}$$

Here, $\lambda(s,d)$ is the traffic load of light-path between s and d and $X_p(s,d)$ is the random variable denoting the number of idle wavelengths along this light-path. Note that the holding time of each light-path is assumed to be exponentially distributed with a mean of unity as before.

Let $f_l(i)$ denote the probability that a particular wavelength (say λ) is free on link i where

$$\begin{aligned} f_l(i) &= q_i(1)\frac{1}{W} + q_i(2)\frac{2}{W} + \cdots + q_i(W) \\ &= \sum_{k=1}^{W} q_i(k)\frac{k}{W} \end{aligned} \tag{12}$$

Here the term $q_i(k)\dfrac{k}{W}$ denotes the probability that a particular wavelength (say λ) is free on link i when there are k free wavelengths on this link.

Let $\{\lambda_1,\lambda_2,\ldots,\lambda_\omega\}$ be the set of idle wavelengths on link i. In order to establish a light-path between a node pair, we must guarantee both the enough free link capacity and free add/drop ports at the source and destination nodes. Therefore, with the equations (1), (4), (6) and (7) in section 4 and the assumption of traffic link-independence, for $\omega \neq 0$, we have

$$\begin{aligned} &\Pr[X_p(s,d) > 0 \mid X_l(i) = \omega] = (1-E(\lambda_n(s),T)) \\ &\quad (1-E(\lambda_n(d),T))(1-\prod_{j=1}^{\omega}(1-\prod_{\substack{k\in path(s,d)\\ k\neq i}} f_l(k))) \\ &\quad = (1-E(\lambda_n(s),T))(1-E(\lambda_n(d),T)) \\ &\quad (1-(1-\prod_{\substack{k\in path(s,d)\\ k\neq i}} f_l(k))^{\omega}) \end{aligned} \tag{13}$$

Here, the term $1-(1-\prod_{\substack{k\in path(s,d)\\ k\neq i}} f_l(k))^{\omega}$ is the probability that there are free wavelength(s) on the light-path between s and d, and the term $(1 - E(\lambda_n(s),T))(1 - E(\lambda_n(d),T))$ is the probability that both source and destination nodes have free add/drop ports.

Additionally, with the assumption of the traffic link-independence, the blocking probability of the light-path (s,d) can be expressed as

$$\begin{aligned} p_b(s,d) = 1-(1-E(\lambda_n(s),T))(1-E(\lambda_n(d),T)) \\ (1-(1-\prod_{i\in path(s,d)} f_l(i))^{W}) \end{aligned} \tag{14}$$

Thus, the blocking probability of the network P_B may be computed as the weighted average of the blocking probabilities of the individual light-paths. This gives -

$$P_B = \frac{\sum_{s,d} p_b(s,d)\lambda(s,d)}{\sum_{s,d}\lambda(s,d)} \tag{15}$$

In order to calculate the total blocking probability, we can use the relaxation method [31] again. During the iterative process, let $f_l^n(i)$, $\alpha_i^n(\omega)$, $\lambda_n^n(i)$, $B_n^n(i)$, $q^n{}_i(\omega)$, $p_b^n(s,d)$, P_B^n be the values obtained for $f_l(i)$, $\alpha_i(\omega)$, $\lambda_n(i)$,

$B_n(i)$, $q_i(\omega)$, $p_b(s,d)$ and P_B at the end of n^{th} iteration. The iterative process will proceed as follows:

1. Let P_B^0, $p_b^0(s,d)$ and $B_n^0(i)$ be 0; let $\alpha_i^0(0)$ and $f_l^0(i)$ be arbitrary values between 0 and 1
2. $n = 1$
3. Calculate $\lambda_n^n(i)$ using (4) and $B_n^n(i)$ using (1).
4. Calculate $\alpha_i^n(\omega)$ using (13) and (11).
5. Calculate $q_i^n(\omega)$ using (9) and (10).
6. Calculate $f_l^n(i)$ using (12).
7. Calculate $p_b^n(s,d)$ using (14).
8. Find P_B^n using (15). If $|P_B^n - P_B^{n-1}| < \varepsilon$, then stop; otherwise, $n = n + 1$ and go to Step (3).

We have applied the relaxation method [31] for both VWP and WP analytical models to solve their individual equations. However, convergence of the iterative procedures for these models cannot be guaranteed. Other numerical methods that are guaranteed to converge (such as the Newton method of [31]) may also be used instead. However, all our numerical experiments show that the results converge rapidly for all realistic values of the system parameters.

5 Performance Results

We have evaluated the impact of the number of node add/drop ports on the performance of WDM network with dynamic traffic loading and shortest-path routing using both simulations and analytical approaches given above. Various kinds of networks including regular and irregular topologies have been studied. These include

1. 14-node NSFNET backbone network (irregular topology), which is shown in Fig. 3.
2. 16-node grid – mesh network (regular topology), which is shown in Fig. 4.
3. 10-node ring network (regular topology).

Data communications may exist between any pair of nodes, so we assume each node pair in the network has a light-path generator. Thus, the 14-node NSFNET backbone network would have (14 × 13)/2 light-path generators, the 16-node grid-mesh network would have 120 light-path generators, and the 10-node ring would have 45 light-path generators. In addition, we assume that each generator has the same traffic load and distribution as described in Section 3. To guarantee simulation accuracy, we run each simulation with 10^6 light-path arrival requests.

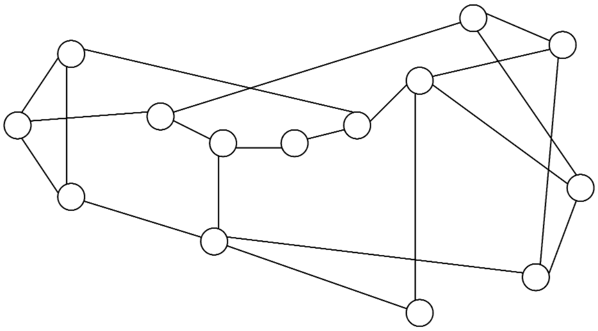

Figure 3: 14-node NSFNET backbone network.

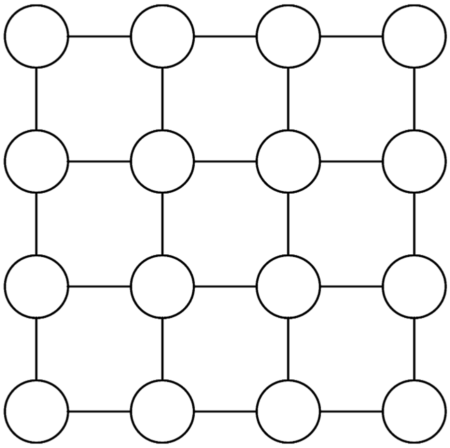

Figure 4: 16-node grid-mesh network.

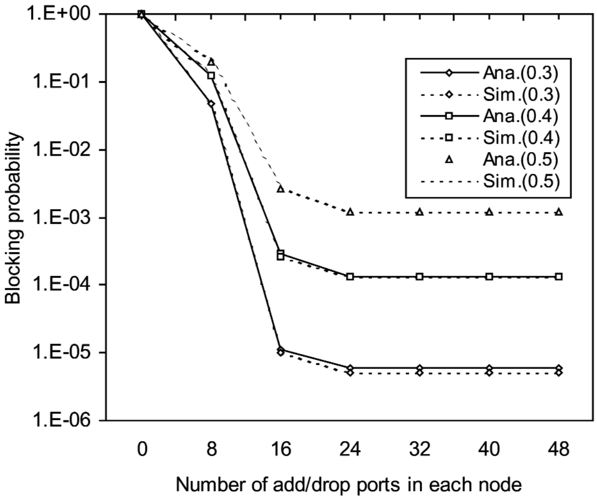

Figure 5: The blocking probability of NSFNET VWP network with limited number of node add/drop ports and 16 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

Figures 5-7 show the blocking probabilities of NSFNET, the grid-mesh, and the ring VWP networks under the condition that there are T add/drop ports in each node. Note that this T is assumed to be identical in all the nodes. Both NSFNET and the grid-mesh networks have 16 wavelengths available on each link, and the ring network has 8 wavelengths available on each link. Each curve in the figures is plotted corresponding to a certain generator traffic load, which has been assumed to be the same for all the node pairs (i.e. traffic generators) in the network. As expected, the blocking probabilities of networks decrease with the increase of number of add/drop ports. However, this trend slows down when each node is

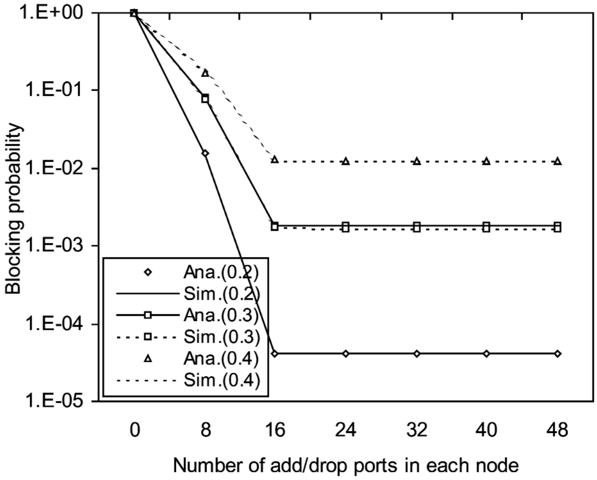

Figure 6: The blocking probability of 16-node grid-mesh VWP network with limited number of node add/drop ports and 16 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

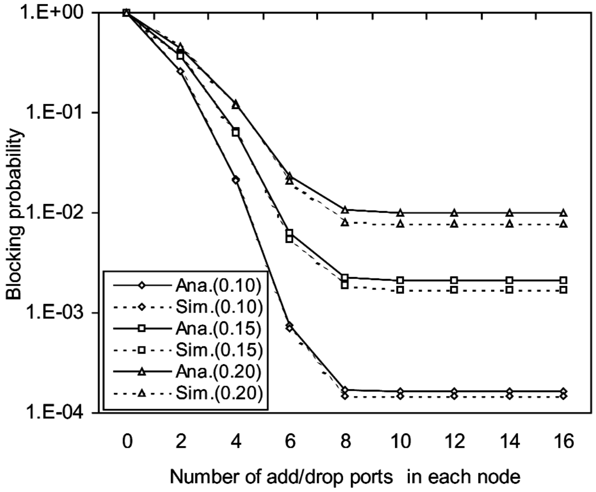

Figure 7: The blocking probability of 10-node ring VWP network with limited number of node add/drop ports and 8 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

equipped with more add/drop ports. We observe that there is a threshold between the blocking probability and the number of add/drop ports in each node. Typically, for the 21-edge 14-node NSFNET network, the average number of add/drop ports in each node is $(21 \times 2 \times 16)/14 = 48$ if each wavelength is assigned an add/drop port. However, in Fig. 5 we find that only around 16 ~ 24 add/drop ports are required in each node to achieve a performance close to that of the network with the full number of add/drop ports (i.e. average 48 add/drop ports in each node). Therefore, only around 30~50% number of add/drop ports are required in the NSFNET network to obtain almost the same performance as that of the network equipped with full number of add/drop ports. Similar results have been obtained for the other two networks, i.e. the grid-mesh network and the ring network as shown in Fig. 6 and 7, respectively; their thresholds are also around 30% and 50%, respectively. Interestingly, these results are similar to those obtained for the partial wavelength conversion network, where only few wavelength converters are required to achieve the performance close to that of VWP networks [17]. We can ascribe this result to the fact that, in an optical network, a number of light-paths (wavelengths) only transit through OXC nodes, but do not actually need an add/drop process at each OXC. This therefore leads to some network situations where although there are still some available free add/drop ports at a node, the corresponding inlet/outlet wavelengths have been occupied by other light-paths transiting the node. From these results, we can conclude that in a wavelength routing VWP-WDM network, assigning one add/drop port for each wavelength at nodes may be not necessary. It would be sufficient and equally efficient to equip only a suitable number (e.g. 30%-50% for NSFNET) of add/drop ports in each node.

In addition, we have also examined the accuracy of our VWP analytical model by comparing against simulations. Figures 5-7 also show the results obtained from simulations for the networks considered. We find that our analytical model is accurate enough to match the simulation results very well for each of the three networks considered, both for irregular and regular topologies.

We have also investigated the impact of the number of add/drop ports on the network performance for WP networks. As for VWP networks, the number of add/drop ports in each node is assumed to be constant around the whole network. The maximum number of wavelengths on each link is assumed to be 16 in NSFNET and the grid-mesh networks, and 8 in the ring network. Figures 8-10 show the blocking probabilities of NSFNET, the

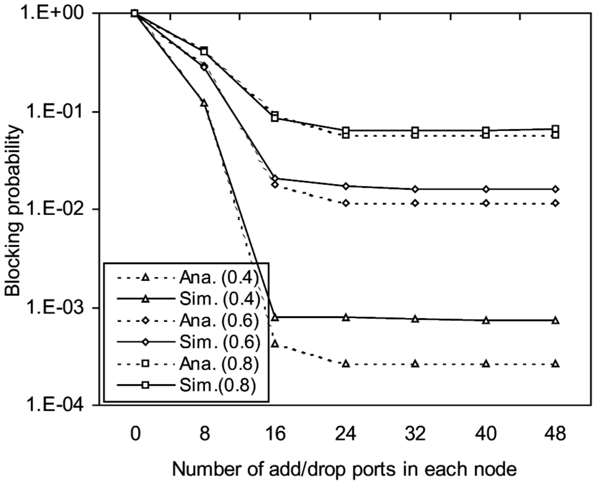

Figure 8: The blocking probability of NSFNET WP network with limited number of node add/drop ports and 16 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

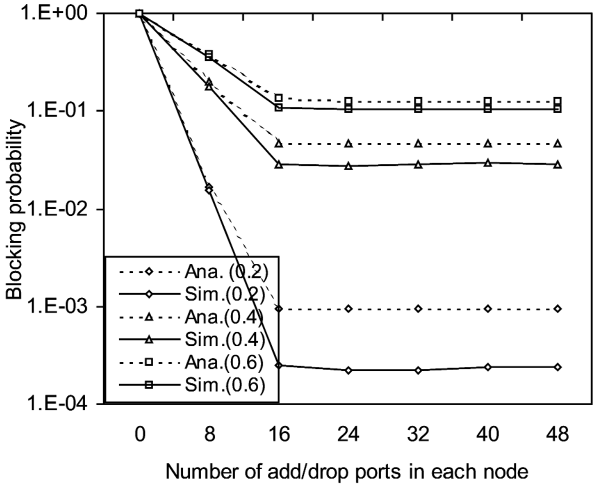

Figure 9: The blocking probability of 16-node grid-mesh WP network with limited number of node add/drop ports and 16 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

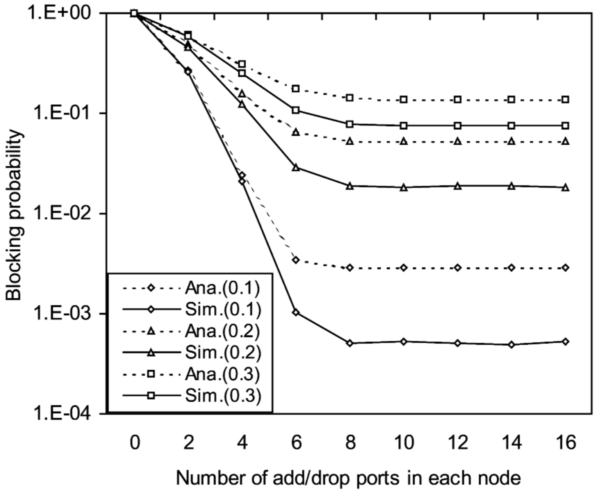

Figure 10: The blocking probability of 10-node ring VWP network with limited number of node add/drop ports and 8 wavelengths on each link (Ana: Analysis result; Sim: Simulation result).

grid-mesh and the ring networks, respectively, versus the number of add/drop ports in each node[2]. As in the case of VWP networks, we find that for the WP-WDM networks there is also a threshold between the light-path blocking probability and the number of add/drop ports in each node. These thresholds are around 30~50% for NSFNET network, 30% for the grid-mesh network, and 50% for the ring network.

With regard to the accuracy of our WP analytical model, we observe that the results obtained from our WP analytical model can basically match the simulation results well enough to predict the changing trend of blocking probabilities versus the number of add/drop ports in each node. However, the numerical results are not very accurate when the traffic load is light. This can be explained by the fact that, under light loading, the traffic density on each link/node is such that the independence assumption may not be expected to hold well. Since this is a key assumption of our analytical model, the accuracy of our model will be poor under these conditions. Alternatively, the accuracy of our model may be improved by modifying it to take into account the traffic correlations between the neighbouring links along the lines of the approach given in [6]. This would however lead to a considerably more complicated model and will require a much higher computational effort.

Finally, we compare the performances of VWP and WP networks with a limited number of add/drop ports at nodes. From Figs. 5-10, we find that the wavelength conversion capability does not change the trend of the results obtained – even the threshold values remain roughly the same for WP and VWP WDM networks.

6 Conclusion

We have studied the impact of the number of add/drop ports in each OXC node on network performance. Analytical models for both VWP and WP networks are presented and evaluated and simulations are also done for network topologies of various kinds. Based on the results obtained, we found that fully equipping a node with add/drop ports, i.e. one add/drop port per wavelength, for a wavelength routing WDM network is not necessary. Only a limited number of add/drop ports are required in each node to achieve a performance comparable to that of a network with a full number of add/drop ports at its nodes. In addition, by comparing the results from simulations and analyses, we can also conclude that our analytical models are accurate and effective enough to deal with various kinds of network scenarios.

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[2] *It may be observed that different traffic loads were used for studies of WP and VWP networks. We have done this to present the results of WP networks as clearly as possible. For WP networks, using the same traffic loads as for VWP networks, leads to figures which do not present the results as clearly as the current ones. Moreover, using different traffic loads for WP networks also verify the overall effectiveness of the conclusion made in the paper.*

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