

Operation of WDM Networks With Different Wavelength Conversion Capabilities

Gangxiang Shen, *Student Member, IEEE*, Sanjay K. Bose, *Senior Member, IEEE*, Tee Hiang Cheng, *Member, IEEE*, Chao Lu, *Member, IEEE*, and Teck Yoong Chai

Abstract—We study the impact of wavelength conversion capability on wavelength routing WDM networks with fixed shortest-path routing. We propose a method for implementing wavelength routing in a WDM network with partial wavelength conversion capability. Simulation results show that such partial wavelength conversion networks provide a performance in between that of wavelength continuous networks and those with full conversion capability. In addition, it can be seen that only limited wavelength conversion capability is enough to provide a performance close to that of a network with full conversion. Analytical and simulation bounding results for the full and no conversion cases have also been provided.

Index Terms—Blocking probability, first-fit, NWC, PWC, wavelength conversion, wavelength routing, WC.

I. INTRODUCTION

THE impact of wavelength conversion capability on WDM networks with dynamic traffic loading has been considered in [1]–[5]. In [1] and [2], the approximate analytical models both for nonwavelength continuous (NWC) and wavelength continuous (WC) WDM networks were proposed. An analytical model on the effects of path length, switch size, and interference length on blocking probability and performance improvement using wavelength changers (i.e. converters) was studied in [3]. This is based on the parameter of *achievable utilization* for a given blocking probability. Assuming that only few wavelength converters are equipped at each node, “*share per node*” and “*share per link*” partial wavelength conversion (PWC) networks have been suggested in [4]. The issue of partial wavelength conversion based on “*sparse-converter placement*” is studied in [5]. These use an “*auxiliary graph*” approach, which significantly increases the complexity of the network and the process of wavelength and route assignment. The heuristic algorithm proposed in Section II for wavelength and converter assignment in a PWC network can achieve good performance much more efficiently and are simple enough to be used in real-time network operation. We propose this for use with “*share per link*” conversion. We do not consider “*sparse-converter placement*” here but the proposed algorithm is also fit for use in such case.

The corresponding WC and NWC systems will provide the bounds on the performance of our proposed PWC algorithm.

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The authors are with Network Technology Research Center, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore.

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For the NWC case, the analytical approach of [1] was found to be adequate. However, the WC-WDM analysis of [2] is computationally difficult for large networks. We propose a new analytical approximation for this in Section III, which gives good results with faster computations even for large networks.

We consider in this paper a WDM network where the maximum available wavelength numbers on each link has the same value W . The light-path traffic loads on different node pairs are bidirectional, independent and identically distributed. We assume that light-path requests for each node-pair are generated from identical Poisson processes and have independent holding times having unity mean exponential distributions. In this paper, we assume that the shortest-path between the node pair is always used for light-path routing. However, the heuristic algorithm proposed by us for PWC networks may also be adapted for use with other path routing methods. More details and other associated research results may be found in [6].

II. HEURISTIC ALGORITHM FOR WAVELENGTH AND CONVERTER ASSIGNMENT

Consider a network where the converters in each node are shared by all the wavelengths on the corresponding outgoing links. During network operations with dynamic traffic loading, the converters for some links in some of the nodes may be currently in use and will be unavailable for new assignments; other unused wavelengths and converters will still be available. The objective of our proposed algorithm is to utilize efficiently the currently remaining wavelength and converter resources in the network.

For this, consider a new light-path request between node s and node d . For the given network topology, let the shortest path between nodes s and d be one with n intermediate nodes (labeled 1 to n in sequence) and $n + 1$ links ($n \geq 0$). This new light-path request can be accepted if wavelengths and converters for its use may be provided along this path; otherwise the light-path request is blocked and discarded. Our heuristic algorithm for converter usage and wavelength assignment for this request is as follows:

- Step 1) Check if any common wavelength is available on all the links of the route. If any such wavelength exists, assign one with the smallest index (i.e. *first fit wavelength assignment*) to the light-path and terminate; else continue.
- Step 2) Find the first node i (as per the node order 1 to n) with free converters available for use. If there is no

such node with free wavelength converters, then this light-path is blocked and the algorithm terminates; otherwise, continue.

Step 3) Find a common wavelength, which is free on all the links up to node i . If we cannot find any such wavelength, then this light-path will be blocked and the algorithm terminates; otherwise, assign the common wavelength to all the links up to node i and continue. (If there are more than one such wavelength, the one with smallest index is selected.)

Step 4) Consider node i to become the new source node s and repeat the procedure from Step 1. This continues until either (a) the process terminates with a failure, in which the corresponding light-path is blocked or (b) it succeeds with a choice of converters and wavelengths as indicated by the algorithm itself.

We have shown in Fig. 1, the performance results obtained through simulations for this algorithm for the NSFNET backbone (14-node, 21-link) [7]. We assume that the wavelength number W is 16 for each link and that the number of converters at each node varies from 0 (WC) to 16 (NWC). The value of *Load* indicated in Fig. 1 corresponds to the light-path request traffic for one node pair in the network where all node pairs are assumed to contribute identically distributed loads.

As can be seen from Fig. 1, for a given value of the offered *light-path load*, the network has the lowest light-path blocking probability for $\text{CON} = W$ corresponding to the NWC case. The blocking probability is highest for $\text{CON} = 0$ corresponding to a WC system. The results for PWC-WDM can be seen for CON values ranging between these limits. These results show that the blocking probability drops rapidly at first going from $\text{CON} = 0$ to $\text{CON} = 2$ but then quickly saturates for higher values of CON. We can hence conclude that whereas substantial performance improvement is possible with a few wavelength converters at each node, not too many of these are actually needed to get near-NWC performance. In the NSFNET example, we only need around 25% wavelength conversion capability to achieve performances close to that of NWC. Since the NWC case represents the best performance that can possibly be achieved, the results of Fig. 2 also imply that our proposed algorithm for handling wavelength and converter choice for partial wavelength conversion yields results that are very close to being optimal. Its simplicity also makes it suitable to handle wavelength and converter assignment, even under real-time conditions. We have also applied our heuristic algorithm to other networks. As reported in [6], similar results were obtained in these cases as well.

We have not yet been able to get analytical results for the PWC algorithm. Since the limiting cases of PWC are WC and NWC, we wanted to verify these simulation results using analytical models as these results would correspond to the limits of what can be achieved by a PWC system. For the NWC-WDM network, we used [1] for obtaining analytical results and these were found to be in close agreement with our simulations. For the WC-WDM case, the approach of [2] was considered. Even though this approach is feasible for small networks, its computational complexity quickly becomes excessive for larger ones. For this case, we developed the following simpler approximate model, which still gives good results.

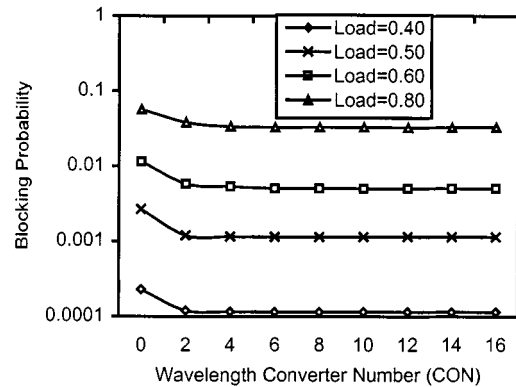


Fig. 1. Blocking Probability in NSFNET for Different Wavelength Converter Numbers (CON) per Node and Varying Load ($W = 16$; First-Fit Assignment).

III. ANALYTICAL MODEL FOR WC-WDM NETWORK

Consider a WC-WDM network and let X_j be the random variable denoting the number of idle wavelengths on link j . We assume that the random variables X_j are mutually independent as in [2] with the probability distribution:

$$q_j(\omega) = \Pr[X_j = \omega], \quad \omega = 0, \dots, W$$

denoting the idle capacity distribution on link j . We also assume that when there are ω idle wavelengths on link j , the time until when the next call is set up on link j is exponentially distributed with parameter $\alpha_j(\omega)$. Assuming that the number of idle wavelengths on link j as arising from a "birth-and-death process," we get

$$q_j(\omega) = \frac{W(W-1)\cdots(W-\omega+1)}{\alpha_j(1)\alpha_j(2)\cdots\alpha_j(\omega)} q_j(0), \quad \omega = 1, \dots, W$$

Applying the normalization condition for this yields

$$q_j(0) = \left[1 + \sum_{\omega=1}^W \frac{W(W-1)\cdots(W-\omega+1)}{\alpha_j(1)\alpha_j(2)\cdots\alpha_j(\omega)} \right]^{-1}$$

The call setup rate $\alpha_j(\omega)$ on link j , when there are ω idle wavelengths on link j , is obtained by combining the contributions from the light-path request streams for routes of which link j is a member. We get

$$\begin{aligned} \alpha_j(\omega) &= 0, \quad \text{if } \omega = 0, \\ &= \sum_{R:j \in R} \alpha_R P\{X_R > 0 \mid X_j = \omega\}, \quad \text{if } \omega = 1, \dots, W \end{aligned}$$

Here, α_R is the traffic load of light-path R and X_R is the random variable denoting the number of idle wavelengths along this light-path.

Let f_j denote the probability that a particular wavelength (say λ) is free on link j where

$$f_j = q_j(1) \frac{1}{W} + q_j(2) \frac{2}{W} + \cdots + q_j(W) = \sum_{k=1}^W q_j(k) \frac{k}{W}$$

Let $\{\lambda_1, \lambda_2, \dots, \lambda_\omega\}$ be the set of idle wavelengths on link j . We make the simplifying assumption that the light-path traffic on a particular link is independent of the traffic on the other

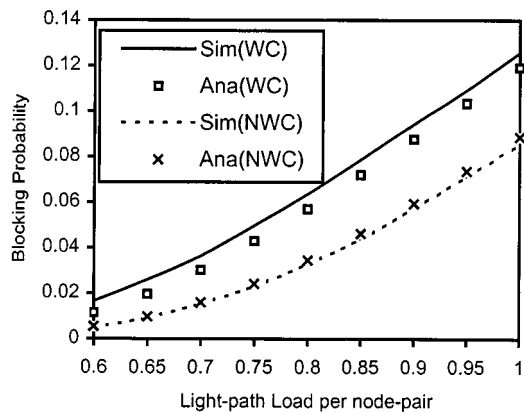


Fig. 2. Blocking Probability for NSFNET ($W = 16$) [Sim: Simulation; Ana: Analysis].

links. Using this assumption of traffic link-independence, we get that

$$\begin{aligned} \Pr[X_R > 0 | X_j = \omega] &= 1 - \prod_{i=1}^{\omega} \left(1 - \prod_{\substack{k \in R \\ k \neq j}} f_k \right) \\ &= 1 - \left(1 - \prod_{\substack{k \in R \\ k \neq j}} f_k \right)^{\omega}, \quad \text{for } \omega \neq 0. \end{aligned}$$

Under the assumption of the traffic link-independence, the blocking probability of the light-path R , given that we know f_j , can be expressed as

$$p_b(R) = \left(1 - \prod_{j \in R} f_j \right)^W.$$

The average blocking probability P_B of the entire network may then be computed as

$$P_B = \frac{\sum_R p_b(R) \alpha_R}{\sum_R \alpha_R}.$$

To obtain the blocking probability P_B for WC-WDM network using the above formulae, we use an iterative procedure following the *relaxation method* of [1], [2] and [8]. The convergence of this cannot be guaranteed but we observed that results converge rapidly in all cases examined by us.

In Fig. 2, we compare the results between the simulations and analytical models for WC-WDM networks. For purposes of comparison, we also show in this figure the corresponding analytical and simulation results for the NWC-WDM case. It can be seen that the results match closely indicating that the analytical models are quite accurate in estimating the blocking probability for NWC and WC networks. The PWC-WDM heuristic algorithm's results will lie between the limiting WC and NWC values.

Our approximate WC-WDM analytical model may be applied to large networks avoiding the computational difficulties of [2]. This is primarily because, unlike [2], our method does not need a recursive process in doing this analysis. Instead, we rely on simple assumptions of link traffic independence, which will tend to be easily satisfied in networks where the traffic flows from a large ensemble of sources. We have also compared our results with that of [1], which also assumes link traffic independence. The accuracies of the two approaches are found to be similar. However, the advantage of our model is that it does not need a recursive computation. It should be noted that a model taking into account the traffic correlation between the links has been proposed in [9]. Even though this would more accurately model the traffic flows in the links, it would still require more computational effort than proposed method.

IV. CONCLUSION

We study the impact of wavelength conversion capability on a wavelength routing WDM network with fixed shortest-path routing and dynamic traffic loading. In order to use the network's conversion resources efficiently, we propose a simple, heuristic algorithm for wavelength and converter assignment in a WDM network with partial wavelength conversion capabilities. The performance of this algorithm has been studied through simulations and we find that only a few converters (roughly 25%) are really required to give a performance close to that obtainable in a full conversion (NWC) model. We have also presented an approximate analytical model for WC-WDM networks, which can be used to study reasonably large networks without excessive computational complexity. Analytical results on WC and NWC WDM networks are useful to verify the accuracy of our simulations and establish performance bounds on the PWC-WDM algorithm.

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