Wavelength Conversion Placement in WDM Mesh Optical Networks*

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Abstract. Wavelength conversion helps improve the performance of wavelength division multiplexed (WDM) optical networks that employ wavelength routing. In this paper, we address the problem of optimally placing a limited number of wavelength converters in mesh topologies. Two objective functions, namely, minimizing the average blocking probability and minimizing the maximum blocking probability over all routes, are considered. In the first part of the paper, we extend an earlier analytical model to compute the blocking probability on an arbitrary route in a mesh topology, given the traffic and locations of converters. We then propose heuristic algorithms to place wavelength converters, and evaluate the performance of the proposed heuristics using the analytical model. Results suggest that simple heuristics are sufficient to give near-optimal performance.

Keywords: wavelength-routing, wavelength converters, circuit switching, blocking probability, converter placement

1 Introduction

All-optical wavelength-routing networks hold out great promise as possible candidates for wide-area backbone networks. The performance of wavelength routing networks is critically dependent on the capability of routing nodes to perform wavelength conversion. Since all-optical wavelength converters are expensive, recent work has focused on networks with sparse or limited wavelength conversion [2–8]. Networks with sparse wavelength conversion have a small fraction of routing nodes equipped with full wavelength conversion capability [4]. Analytical models were presented in Subramaniam et al. [4] for evaluating the blocking performance of networks under dynamic Poisson traffic for a given conversion density (the fraction of nodes with full wavelength conversion capability). The performance obtained in Subramaniam et al. [4] was the average blocking probability when a binomially distributed number of converters with a given expected value was randomly placed in the network.

We focus on networks with sparse wavelength conversion in this paper and look at the interesting and practical problem of optimally placing wavelength converters. Given a network topology, a certain number of converters, and traffic statistics between the nodes, how do we place converters such that an appropriate objective function is optimized? A dynamic programming approach to place full wavelength converters on a single path such that the average blocking probability is minimized was presented in Subramaniam et al. [9]. The approach was also extended to obtain optimal placements for the bus and ring topologies. However, the converter placement problem is hard in mesh topologies.1 For an N-node network, a brute force approach to place K converters would evaluate the performance for each of the possible \( \binom{N}{K} \) placement configurations, and choose the configuration that yields the optimal

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performance. This approach can be improved upon as shown in [10], but the time complexity of the improved algorithm is still $O(N^k)$.

In this paper, we assume a dynamic traffic model in which lightpath requests (calls) arrive to the network according to a Poisson process, and each call requires an exponentially distributed holding time. The routing is assumed to be fixed, and the Erlang load on each route is assumed to be given. The goal is to place wavelength converters such that an objective function is minimized. We consider two objective functions in our study: the average blocking probability and the maximum blocking probability over all paths. Some heuristics have been proposed recently for placing converters to minimize average blocking probability in mesh topologies [11–13]. In Harai et al. [11] and Iness [13], a heuristic that places the converters one by one sequentially is proposed, while a heuristic for the placement of limited range wavelength converters is presented in Venugopal et al. [12]. In this paper, we propose a class of heuristic algorithms for the converter placement problem, and evaluate the performance of some algorithms in that class. As we will see later, some of the heuristics require the knowledge of the blocking performance for a given placement configuration. Instead of obtaining the performance by using time-consuming simulations, we extend a previously presented analytical model [4] to obtain the blocking performance of an arbitrary mesh topology with given traffic loads and converter locations.

The rest of this paper is organized as follows. In Section 2, we present a brief description of the model in Subramaniam et al. [4], and modify it to obtain the blocking performance of topologies with given traffic loads and given converter locations. Converter placement heuristics for minimizing average blocking probability and their performance are presented in Section 3. A heuristic for minimizing the maximum blocking probability is evaluated in Section 4, and the paper is concluded in Section 5.

2 Analytical Computation of Blocking Performance

In this section, we present an analytical approach to compute the blocking probabilities ($P_b$) on a mesh topology with given traffic loads and converter locations. The approach is based on the work in Subramaniam et al. [4], where a model for computing $P_b$ under uniform Poisson traffic was given. The effects of wavelength conversion on blocking performance was analyzed in Subramaniam et al. [4] by assuming that each node has a converter with probability $q$ (called the conversion density of the network). Correlation between wavelength usages on various links was modeled by assuming Markovian spatial correlation, i.e., the wavelength usage on a link is dependent only on the usage on an adjacent link. In the following, we present a modification of that model to compute the blocking probability on an arbitrary route for a given converter placement configuration.

2.1 Network Model and Assumptions

The following assumptions are used in the model.

- A network of $N$ nodes, numbered $1, 2, \ldots, N$, is given. The links are directed, and each link corresponds to a single fiber oriented in the direction of the link. The number of wavelengths is given, and is assumed to be the same on each link. It is denoted by $F$. The constant wavelength assumption can be easily relaxed, and is used here only for simplicity.

- For $m$ converters, the placement vector denoted as $a^{(m)}$ is an $N$-vector, and the $i$-th element $a_i$ is 1 if node $i$ has a converter, and 0 otherwise.

- The route used by a call is independent of the network state. Note that this does not imply that a single fixed route is always used for a lightpath request between a given source and destination. It is possible to have several different routes, but the choice of which route to use is not dependent on the network state. An example of such routing is the random selection of a route from a fixed set of routes for the given source and destination.

- Upon arrival of a lightpath request, a suitable route is chosen as above. Between two consecutive converter nodes on the route, the wavelength is chosen from the set of wavelengths available on all of the links between those two nodes. This assignment scheme is called as random wavelength assignment. If no such wavelength is available, the call is not retried on another route, and is considered to be blocked. This model of routing and wavelength assignment is used chiefly for analytical tractability.