Wavelength Converter Placement Under Different RWA Algorithms in Wavelength-Routed All-Optical Networks

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***Abstract*—Sparse wavelength conversion and appropriate routing and wavelength assignment (RWA) algorithms are the two key factors in improving the blocking performance in wavelength-routed all-optical networks. It has been shown that the optimal placement of a limited number of wavelength converters in an arbitrary mesh network is an NP-complete problem. There have been various heuristic algorithms proposed in the literature, in which most of them assume that a static routing and random-wavelength assignment RWA algorithm is employed. However, the existing work shows that fixed-alternate routing and dynamic routing RWA algorithms can achieve much better blocking performance. Our study further demonstrates that the wavelength converter placement and RWA algorithms are closely related in the sense that a well-designed wavelength converter placement mechanism for a particular RWA algorithm might not work well with a different RWA algorithm. Therefore, the wavelength converter placement and the RWA have to be considered jointly. The objective of this paper is to investigate the wavelength converter placement problem under the *fixed-alternate routing* (FAR) algorithm and *least-loaded routing* (LLR) algorithm. Under the FAR algorithm, we propose a heuristic algorithm called *minimum blocking probability first* for wavelength converter placement. Under the LLR algorithm, we propose another heuristic algorithm called *weighted maximum segment length*. The objective of the converter placement algorithms is to minimize the overall blocking probability. Extensive simulation studies have been carried out over three typical mesh networks, including the 14-node NSFNET, 19-node EON, and 38-node CTNET. We observe that the proposed algorithms not only outperform existing wavelength converter placement algorithms by a large margin, but they also can achieve almost the same performance compared with full wavelength conversion under the same RWA algorithm.**

***Index Terms*—Routing and wavelength assignment (RWA), wavelength converter placement, wavelength-division multiplexing (WDM), wavelength routing.**

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I. Introduction

WAVELENGTH-ROUTED all-optical networks are considered to be candidates for the next generation wide-area backbone networks [4], [14]. In such networks, wavelength conversion (or translation) plays an important role in improving the fiber link utilization and reducing the call blocking probability [10]. Since the wavelength converters[1] are still very expensive nowadays, much research work focuses on *sparse wavelength conversion*, which means that only part of the network nodes have the capability of wavelength conversion, while others have no conversion capability [15]. If all the network nodes are capable of wavelength conversion, this is referred to as *full wavelength conversion*.

It has been shown in [15] that, by using sparse wavelength conversion, a relatively small number of converters can achieve satisfactory performance. However, the problem of wavelength converter placement was not considered. That is, given a network topology, a certain number of wavelength converters, and traffic statistics, how can the wavelength converters be placed into the network in order to minimize the overall blocking probability? Usually, this is addressed as a separate issue that is solved by converter placement algorithms. The algorithms for optimal converter placement in simple topologies, such as bus and ring, have been provided in [16]. However, optimal converter placement for more realistic topologies such as arbitrary mesh is considered to be very hard. Hence, a number of heuristic algorithms have been proposed [1], [9], [11], [18]. All of them assume that the static routing and random wavelength assignment (RWA) algorithm is employed.

Nevertheless, the literature results show that the blocking probabilities of wavelength-routed networks are heavily dependent on the RWA algorithms [5], [8], [12]. Our studies also demonstrate that a well-designed wavelength converter placement mechanism for the static RWA algorithm does not work well under a different RWA algorithm. Therefore, we argue that wavelength converter placement and RWA algorithms should be considered jointly.

In this paper, we investigate the problem of wavelength converter placement under two RWA algorithms, both of which have exhibited that better blocking performance can be obtained. The first one is the *fixed-alternate routing* and *first-fit wavelength assignment* (FAR-FF RWA) algorithm. The second

[1]In this paper, wavelength converter means a wavelength router with the capability of wavelength conversion.

one is the *least-loaded routing* and *first-fit wavelength assignment* (LLR-FF RWA) algorithm. The FAR algorithm has been shown to outperform the static routing algorithm significantly [8]. The LLR algorithm is a commonly used dynamic routing algorithm, which can usually achieve better performance than the FAR algorithm, at the expense of longer setup delays and higher control overheads [12]. The FF wavelength assignment algorithm can achieve almost the same performance as the most-used wavelength assignment algorithm [19] and is very simple for implementation. For the FAR-FF RWA algorithm, we first present an approximate analytical model that can derive the overall blocking probability of wavelength-routed all-optical networks that employ the FAR algorithm. Based on the analytical model, we propose a heuristic algorithm, called *minimum blocking probability first* (MBPF), for placing a limited number of wavelength converters in an arbitrary mesh network. For the LLR-FF RWA algorithm, we propose another efficient heuristic converter placement algorithm, called the *weighted maximum segment length* (WMSL) algorithm.

In our network model, the connection calls arrive at the network according to a Poisson process and the connection holding time is exponentially distributed. The proposed MBPF and WMSL algorithms can place any number of wavelength converters in an arbitrary mesh network efficiently. We first evaluate the benefit and significance of sparse wavelength conversion through simulations on an 8-node ring network and a 25-node mesh-torus network. After that, we evaluate the performance of the MBPF and WMSL algorithms using extensive simulations on three typical mesh network topologies, including 14-node NSFNET, 19-node European optical network (EON), and 38-node China Telecom network (CTNET). The simulation results show that, with the appropriate RWA algorithms, our heuristic converter placement algorithms outperform existing algorithms significantly. Moreover, our heuristic algorithms for a limited number of wavelength converters can achieve almost the same performance comparing with full wavelength conversion under the same RWA algorithm.

The rest of the paper is organized as follows. In Section II, an analytical model for calculating the overall blocking probabilities of wavelength-routed networks with FAR and sparse wavelength conversion is first presented. Then, we present the MBPF algorithm for converter placement in an arbitrary mesh network that employs the FAR-FF RWA algorithm. In Section III, we present the WMSL algorithm for converter placement in an arbitrary mesh network that employs the LLR-FF RWA algorithm. In Section IV, we evaluate the performance of the proposed MBPF and WMSL algorithms and compare them with existing algorithms. Finally, Section V concludes the paper and presents some possible future work.

II. Converter Placement Under FAR Algorithm

An analytical model which incorporates FAR and wavelength conversion has been proposed in [13]. However, this model is too complicated because it considers limited-range wavelength conversion capabilities. In this section, we modify that model to the case of sparse wavelength conversion with full-range wavelength conversion capability. This new analytical model will be used in our heuristic MBPF algorithm of wavelength converter placement.

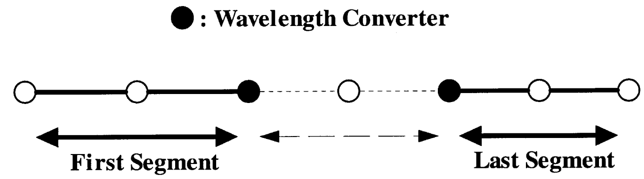

Fig. 1. Path and its segments.

A. System Parameters and Assumptions

In this section, we make the following assumptions.

1) The network consists of N nodes and J fiber links. Each link has W wavelengths that are labeled from 1 to W.
2) We assume that call requests arrive at end-to-end node pair a following a Poisson distribution. The call-holding times are assumed to be exponentially distributed with a unit time.
3) The number of wavelength converters is denoted by M. Our objective is to minimize the overall blocking probability by placing these converters appropriately.
4) A path (or route) R is a subset of the whole link set $\{1, 2, \ldots, J\}$. The number of hop counts for path R is denoted by $h(R)$.
5) There are M_a number of edge-disjoint paths provided for node pair a, denoted by $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$, in sequence. The FAR algorithm is used for route selection, i.e., when a call request for node pair a arrives, paths are tried sequentially from $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$, until a path with an available wavelength assignment is found. It is possible for multiple lightpaths to be set up simultaneously on different paths between node pair a, as long as there are free wavelength resources.
6) If there are w_a^t wavelength converters on the path $R_a^{(t)}$ (excluding the two end nodes, i.e., node pair a), we can divide this path into $w_a^t + 1$ segments, as illustrated in Fig. 1. Each segment suffers the wavelength continuity constraint. The kth segment is denoted by $R_a^{(t,k)}$, and the number of hop counts of segment $R_a^{(t,k)}$ is represented by $h(R_a^{(t,k)})$. Notice that the integer k starts from 1.
7) The term "offered traffic" denotes the traffic (or call requests) that arrive, and "carried traffic" denotes the traffic that actually can be set up successfully. The traffic is measured in Erlang load, i.e., the number of call requests per unit call-holding time.
8) A^a is the offered traffic for node pair a, which is given in advance. $\overline{A^a}$ is the carried traffic for node pair a.
9) $B_{R_a^{(t)}}$ is the blocking probability of the path $R_a^{(t)}$.

B. Analytical Model

Our analytical model includes link-traffic analysis and path-blocking analysis. The link-traffic analysis consists of a set of equations that determine the traffic offered to each link (so-called link-offered traffic) from the path-blocking probabilities.

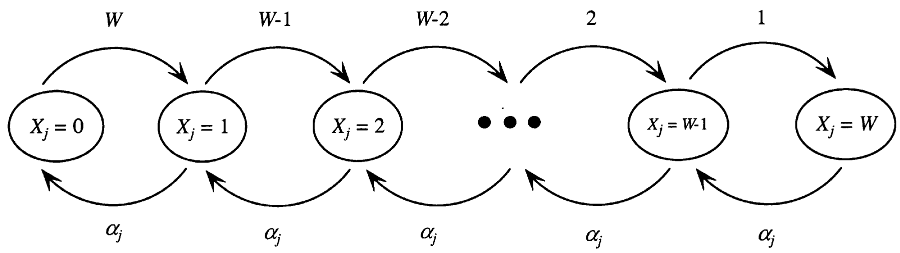

Fig. 2. Markov chain for free wavelength distribution on link j.

On the other hand, the path-blocking analysis consists of a set of equations that determine the path-blocking probabilities from the link-offered traffic. These two parts of analysis lead to a set of fixed-point nonlinear equations, and they can be solved by iterative substitutions.

The overall blocking probability P is the ratio of blocked traffic to the offered traffic. That is

$$P = \frac{\sum_a (A^a - \overline{A^a})}{\sum_a A^a}. \quad (1)$$

The traffic for node pair a can be carried on any of its provided paths. And the connection will be blocked if and only if it is blocked on all the M_a number of paths. Given the assumption that these paths are link disjoint, we can consider the blocking events on these paths to be independent from each other. So we can have

$$\overline{A^a} = A^a \left(1 - \prod_{t=1}^{M_a} B_{R_a^{(t)}}\right). \quad (2)$$

From (1) and (2), we can simplify the overall blocking probability as

$$P = \frac{\sum_a A^a \prod_{t=1}^{M_a} B_{R_a^{(t)}}}{\sum_a A^a}. \quad (3)$$

To obtain the steady-state probability of the number of available wavelengths on each link, we use the reduced-load approximation method presented in [3]. Let X_j denote the random variable standing for the number of free wavelengths on link j. We assume that the random variables $X_j, j \in \{l, \ldots, J\}$ are independent, and the call requests arrive at link j following a Poisson distribution with rate α_j. Let $q_j(m_j)$ denote the probability that m_j wavelengths are free on link j. According to our assumption, the arriving and serving behavior on the link forms an M/M/C/C system and the corresponding Markov chain is illustrated in Fig. 2. By solving the Markov chain, we can derive

$$q_j(m_j) = P(X_j = m_j)$$
$$= \frac{\prod_{i=1}^{m_j}(W - i + 1)}{\alpha_j^{m_j}} P(X_j = 0), \qquad m_j \geq 1 \quad (4)$$

$$q_j(0) = P(X_j = 0) = \left[1 + \sum_{m_j=1}^{W} \frac{\prod_{i=t}^{m_j}(W-i+1)}{\alpha_j^{m_j}}\right]^{-1}. \quad (5)$$

Following the assumption made in [10], we have the following equation by considering the carried traffic on link j:

$$\alpha_j\,(1-q_j(0)) = \sum_a \sum_{\substack{1\leq t\leq M_a \\ j\in R_a^{(t)}}} A^a B_{R_a^{(1)}}, \ldots, B_{R_a^{(t-1)}} \left(1 - B_{R_a^{(t)}}\right). \quad (6)$$

From the above three equations, we can see that the values of $q_j(m_j)$ depend on the path-blocking probabilities $B_{R_a^{(t)}}$. However, in the following analysis, we will show that the path-blocking probabilities $B_{R_a^t}$ also depend on the values of $q_j(m_j)$.

First of all, we introduce a term $u_i(m_j, R_a^{(t,k)})$ to represent the probability that when m_j wavelengths are idle on link j, i wavelengths are available on segment $R_a^{(t,k)}$ that includes link j. It is obvious that $u_0(m_j, R_a^{(t,k)})$ is the probability that when m_j wavelengths are idle on link j, there is no common free wavelength on segment $R_a^{(t,k)}$. Thus, the probability that the segment $R_a^{(t,k)}$ has free wavelengths can be calculated by $1 - \sum_{m_j=0}^{W} q_j(m_j)u_0(m_j, R_a^{(t,k)})$. A path can be set up if each segment of that path has its own free wavelengths. With an approximate assumption that the blocking events on all the segments are independent, we can derive the blocking probability of any path R as

$$B_{R_a^{(t)}} = 1 - \prod_{k=1}^{w_a^t+1} \left[1 - \sum_{m_j=0}^{W} q_j(m_j) u_0\left(m_j, R_a^{(t,k)}\right)\right]. \quad (7)$$

By letting the link set of segment $R_a^{(t,k)}$ be $\{j, j_1, j_2, \cdots, j_{h(R_a^{(t,k)})-1}\}$, the probability $u_i(m_j, R_a^{(t,k)})$ is given by the following equation if we use h to denote $h(R_a^{(t,k)})$, i.e., the length of the segment:

$$u_i\left(m_j, R_a^{(t,k)}\right) = \sum_{m_{j_1}=0}^{W} \sum_{m_{j_2}=0}^{W} \cdots \sum_{m_{j_{h-1}}=0}^{W}$$
$$\times \left\{\prod_{l=1}^{h-1} q_{j_l}(m_{j_l}) \times p_i^h(m_j, m_{j_1}, m_{j_2}, \cdots, m_{j_{h-1}})\right\} \quad (8)$$

where $p_i^h(\cdot)$ denotes the probability that there exist i available wavelengths on the h-hop segment. Specifically, the term $p_i^2(k, m_{j_h})$ is defined as the probability that there exist i common free wavelengths on a two-hop segment, given that one hop has k available wavelengths and the other m_{j_h} has available wavelengths. By decomposition, a h-hop segment can be regarded as a "two-hop" segment: the first hop is the $(h-1)$-hop segment (consisting of $(h-1)$ links $j_1, j_2, \ldots, j_{h-1}$), and the second hop is the last link j_h. The probability that there are k free wavelengths in the $(h-1)$-hop segment can be presented by $p_k^{h-1}(m_{j_1}, m_{j_2}, \ldots, m_{j_{h-1}})$. Therefore, $p_i^h(\cdot)$ can be determined by the following recursive formula:[2]

$$p_i^h(m_{j_1}, m_{j_2}, m_{j_3}, \ldots, m_{j_h}) = \sum_{k=0}^{W} p_i^2(k, m_{j_h}) p_k^{h-1}(m_{j_1}, m_{j_2}, \ldots, m_{j_{h-1}}) \tag{9}$$

$$p_i^2(x,y) = \begin{cases} \beta(x,y,i), & x \geq y \geq i; x+y-i \leq W; 1 \leq x, y \leq W \\ \beta(y,x,i), & y \geq x \geq i; x+y-i \leq W; 1 \leq x, y \leq W \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

The conditional probability $\beta(x,y,i)$ is the probability that there exist i available wavelengths under the condition that x and y wavelengths are available on successive two links. From [3], $\beta(x,y,i)$ is given by

$$\beta(x,y,i) = \binom{y}{i} \cdot \left(\prod_{k=1}^{i} \frac{x-k+1}{W-k+1} \right) \cdot \left(\prod_{k=1}^{y-i} \frac{W-x-k+1}{W-i-k+1} \right). \tag{11}$$

C. Numerical Algorithm

In summary, we can determine the overall blocking probability as follows.

1) Initialize $B_{R_a^{(t)}}$ as 0 for all paths. $q_j(0)$ is initialized as 0 for all links.
2) Determine α_j using (6) for all links.
3) Determine $q_j(m_j)$ using (4) and (5) for all links.
4) Calculate $B_{R_a^{(t)}}$ for all paths using (7)–(11). If new values of $B_{R_a^{(t)}}$ are converged[3] to the older ones, the iteration is terminated and we can go to Step 5). Otherwise go to Step 2) for next iteration.
5) Finally, determine the overall blocking probability using (3).

In our practice, the convergence time of the iteration process depends on the network topology. In most cases, the algorithm will converge within 20 iterations with the error tolerance of 10^{-6}.

D. Heuristic of Wavelength Converter Placement

Our objective of wavelength converter placement is to minimize the overall blocking probability. This problem is particularly challenging under mesh topologies. In this section, we first extend the FAR-FF RWA algorithm for the environment of sparse wavelength conversion. We then propose a heuristic algorithm named MBPF for converter placement in a mesh network that employs the FAR-FF RWA algorithm.

1) FAR-FF RWA Algorithm With Sparse Wavelength Conversion: We assume that there are M wavelength converters placed in the network. When a call request for node pair a arrives, we should select a path from the M_a number of provided paths, and assign wavelength(s) to that path. The FAR-FF algorithm attempts paths in sequence from $R_a^{(1)}$ to $R_a^{(M_a)}$, until a path with a valid wavelength assignment is found. If no wavelength is available on any of the paths, the call request is blocked. Once a call is set up, the FF wavelength-assignment scheme will be employed on each segment along the selected path, i.e., for each segment, the free wavelength with the smallest label will be assigned to all the links in that segment.

2) MBPF Algorithm for Wavelength Converter Placement: An exhaustive approach by enumerating all the possible means of converter placement and choosing the best one is not practical for large networks. In this subsection, we propose a heuristic algorithm of wavelength converter placement in an arbitrary mesh network that employs the FAR-FF RWA algorithm. The algorithm places the converters one by one, sequentially. Each time we are trying to find the most important node from the candidate nodes such that if we put a converter on that node, the overall blocking probability can be decreased most significantly. The algorithm is the so-called MBPF.

The MBPF algorithm works as follows.

1) Find the paths $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$ for each node pair a according to the FAR algorithm. We will place M converters into the network one by one.
2) The term "candidate node" means the node that has no converter yet. For each candidate node v, we first assume that a wavelength converter has been placed at that node, and then we can calculate the corresponding overall blocking probability using the analytical model presented in Section II. After the calculation of all candidate nodes, we place a wavelength converter at the node that can result in the minimum overall blocking probability.
3) If there are still wavelength converters left, go to Step 2).

The MBPF algorithm will use the numerical algorithm $O(MN)$ times. This is very efficient compared to the exhaustive searching of all the $(N!)/(M!(N-M)!)$ combinations of converter placement schemes.

III. Converter Placement Under LLR Algorithm

It has been shown that the LLR-FF RWA algorithm can achieve much better blocking performance than static RWA algorithms. Therefore, it is also desirable to find a converter placement mechanism that works well under the LLR-FF RWA algorithm. In this section, we first modify the LLR-FF RWA algorithm for the case of sparse wavelength conversion. Then we propose a heuristic algorithm named WMSL for converter placement in an arbitrary mesh network that employs the LLR-FF RWA algorithm. The rationale of the heuristic algorithm is presented as well.

A. System Parameters and Assumptions

1) The mesh network consists of N nodes and J fiber links. Each link has W wavelengths that are labeled from 1 to W.
2) We assume that call requests arrive between a node pair a following a Poisson distribution with rate A^a. The call-

[2] This recursion formula has also been used in [3], [8], and [10].

[3] The convergence here means that the difference between the new value and old value is less than some predefined small value.

holding time is exponentially distributed with one unit time. So the traffic load for node pair a is exactly A^a.

3) We further assume that the LLR-FF RWA algorithm is used for lightpaths set up.
4) The number of wavelength converters is denoted by M. Our objective is to minimize the overall blocking probability by placing these converters appropriately.

B. LLR-FF RWA Algorithm With Sparse Wavelength Conversion

This subsection presents the LLR-FF RWA algorithm with sparse wavelength conversion.

We assume that there are M_a routes provided for node pair a, denoted by $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$, in order, and M wavelength converters have been placed in the network. The definition and notation of segment are the same as those in Section II. Furthermore, the number of free wavelengths of segment $R_a^{(t,k)}$ is presented by $f(R_a^{(t,k)})$. For each path $R_a^{(t)}$, we define the maximum segment length as the largest value of $h(R_a^{(t,k)})$ among the $w_a^t + 1$ segments, and denoted it as $s_{R_a^{(t)}}$. The number of free wavelengths of path $R_a^{(t)}$ is defined as the smallest value of $f(R_a^{(t,k)})$ among all the segments in path $R_a^{(t)}$.

Once a call request for node pair a arrives, we should select a path and assign wavelength(s) to that path. The states of the number of free wavelengths on the M_a paths between node pair a are examined at the same time. The path with the maximum number of free wavelengths is selected to set up the connection. If no wavelength is available on any of the paths, the call request will be blocked. If two or more paths have the same maximum number of free wavelengths, the path with the smallest label is selected. Once a call connection is set up, the FF wavelength assignment scheme will be employed on each segment in the selected path, i.e., for each segment, the free wavelength with the smallest label will be assigned to all the links in that segment.

C. WMSL Algorithm for Wavelength Converter Placement

In this subsection, we propose a heuristic algorithm of wavelength converter placement in an arbitrary mesh network that employs the LLR-FF RWA algorithm. The WMSL algorithm places the converters one by one sequentially. Each time we want to find the most important node from the candidate nodes, such that if we put a converter on that node, the average blocking probability can be decreased most significantly. Our approach is to assign a weight value to each candidate node, which can approximately represent the importance of each node. It has been shown that the length of the path is the most important factor affecting the blocking probability of a path when there is no wavelength conversion [2]. Wavelength converters can improve the blocking performance mainly because the converters divide a path into several segments, and thus, alleviate the effect of wavelength continuity constraint [10]. Therefore, the blocking probability of a path is mostly related to the maximum segment length of that path. This observation leads to our heuristic algorithm, which is trying to minimize the sum of the maximum segment length over the whole network. Considering that the offered traffic to each node pair may be different, we also take into account the traffic offered to each path.

Combining all the above factors, we propose the WMSL algorithm as follows.

1) Find the paths $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$ for each node pair a according to the LLR algorithm.
2) We approximately assume that the traffic offered to node pair a is distributed to all the provided routes evenly. Suppose $R_a^{(t)}$ is any path in the set of $R_a^{(1)}, R_a^{(2)}, \ldots, R_a^{(M_a)}$, $\alpha_{R_a^{(t)}}$ is the offered traffic to path $R_a^{(t)}$ of node pair a, then we can approximately have
$$\alpha_{R_a^{(t)}} = \frac{1}{M_a} A^a.$$
3) Calculate the weight value $W(v)$ for each candidate node v. $s_{R_a^{(t)}}$ is the original maximum segment length of $R_a^{(t)}$, and $s_{R_a^{(t)}}(v)$ is the maximum segment length of $R_a^{(t)}$ after a converter is placed on node v. The weight function $W(v)$ is then defined as follows:
$$W(v) = \sum_{\substack{\text{All } R_a^{(t)} \text{ that transit} \\ \text{through node } v}} \alpha_{R_a^{(t)}} \left(s_{R_a^{(t)}} - s_{R_a^{(t)}}(v) \right).$$
After the calculation over all the candidate nodes, we place a wavelength converter at the node with the maximum weight value.
4) If there are still wavelength converters left, go to Step 3).

The computational time complexity of the WMSL algorithm can be analyzed as follows. There are M steps, and in each step, we have to calculate the weight values for every candidate node. Each weight value can be calculated in $\mathrm{O}(N^2)$ time units if we assume that M_a is far less than N. So the total time complexity of the WMSL algorithm is $\mathrm{O}(MN^3)$.

IV. Numerical Results and Analysis

The benefit of wavelength conversion is first evaluated by simulations over an 8-node ring network and a 25-node mesh-torus network (Fig. 3(a) and (b), respectively). After that, extensive simulations are carried out to investigate the blocking performance of the proposed MBPF (for FAR-FF RWA algorithm) and WMSL (for LLR-FF RWA algorithm) algorithms over the 14-node NSFNET, 19-node EON, and 38-node CTNET network topologies (Fig. 3(c), (d), and (e), respectively). In our simulations, the call requests arrive to the network following a Poisson process, and the call-holding time is exponentially distributed. We assume that all the source–destination node pairs have the same traffic load in Erlang. Each fiber link is assumed to carry 40 wavelength channels. We provide two edge-disjoint shortest paths for each source–destination pair. The two paths are edge disjoint so that the blocking events on the two paths can be considered to be independent. Another consideration of edge disjoint is fault tolerance. If one path fails, the connection can be rerouted to another path. The granularity of a call connection is lightpath, which has a huge bandwidth in the order of Gb/s. The 10-Gb/s transmission system on one wavelength is already commercially available, and the system of 40 Gb/s per wavelength has also been demonstrated in the lab.

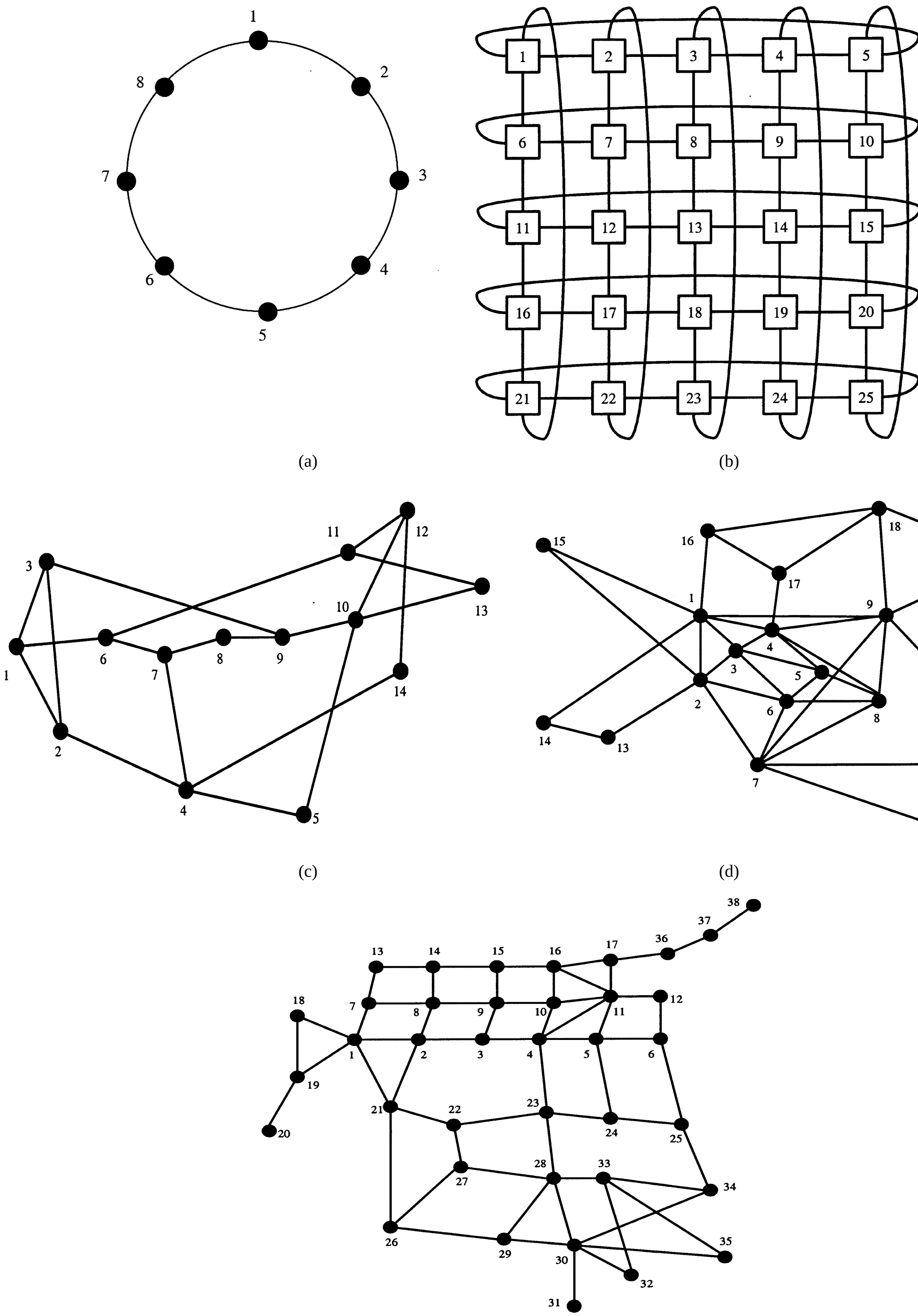

Fig. 3. (a) 8-node ring network. (b) 25-node mesh-torus network. (c) 14-node NSFNET network. (d) 19-node EON network. (e) 38-node CTNET network.

A. Evaluation of the Benefit of Wavelength Conversion

We first conduct simulations over an 8-node ring network and a 25-node mesh-torus network in order to evaluate the benefit of wavelength conversion. Ring network is a representation of a sparse network, and mesh-torus network is a representation of a dense network. For simplicity, we use the FAR-FF RWA algorithm for the ring network, and the MBPF algorithm is used to

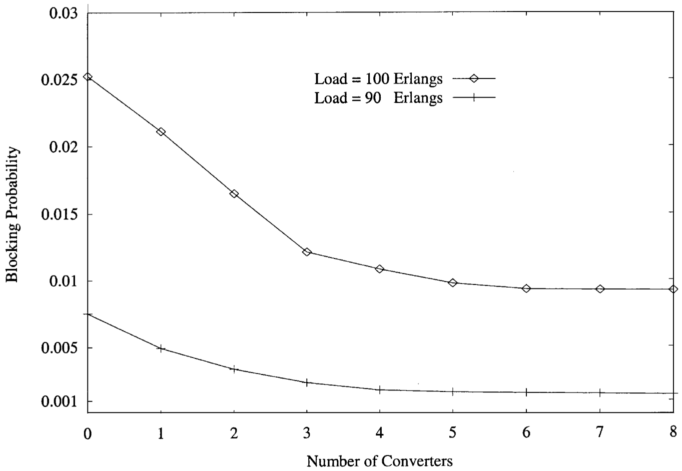

Fig. 4(a). Blocking probability versus number of converters in ring network using FAR-FF algorithm.

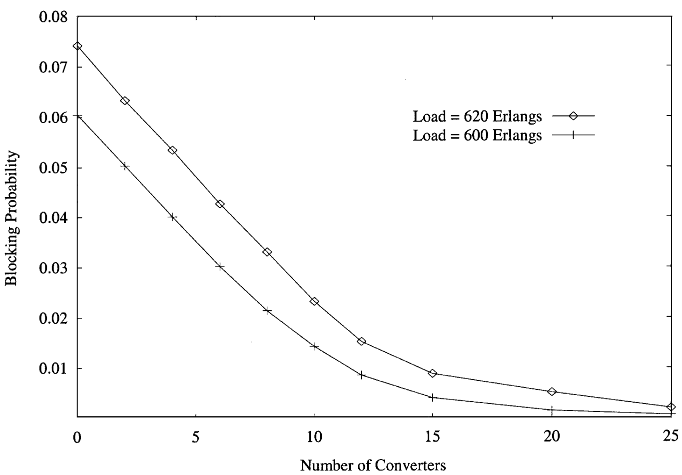

Fig. 4(b). Blocking probability versus number of converters in mesh-torus network using LLR-FF algorithm.

solve the converter placement problem. For the mesh-torus network, we employ the LLR-FF RWA algorithm and the WMSL converter placement algorithm. We do simulations for all the possible number of wavelength converters, i.e., from zero to the total number of nodes.

Fig. 4(a) illustrates the blocking probability versus the number of converters in the eight-node ring network, which employs the FAR-FF RWA algorithm. We can observe that with the increase of the number of wavelength converters, the average blocking probability decreases. It is also very obvious that with only a few converters, the blocking probability can be decreased by a large margin. Once the number of converters is beyond some threshold, the blocking probability will decrease very slowly. Therefore, we can conclude that sparse wavelength conversion is quite important and meaningful in the sense that a 25%–50% investment can achieve almost 80%–90% of the best performance.

For the mesh-torus network, the benefit of wavelength conversion is even more remarkable, as illustrated in Fig. 4(b). This is coincident with the conclusion in [2] that wavelength conversion is more beneficial in a dense network than in a sparse network. Barry and Humblet [2] quantified this effect using the interference length, which is defined as the expected number of links shared by two lightpaths. They have shown that the benefit of wavelength conversion decreases as the interference length increases. In a ring network, two lightpaths are very likely to share some links, which results a long interference length, whereas, in a mesh-torus network, the interference length is relatively short. From Fig. 4(b), we can also observe that with only a fraction of nodes equipped with wavelength converters, the blocking probability can be decreased significantly.

B. *Performance Evaluation of the FAR-FF and MBPF Algorithms*

In this section, we evaluate the performance of the FAR-FF algorithm and the proposed MBPF algorithm. First of all, the blocking performance of sparse wavelength conversion is compared to the performance of no wavelength conversion and full wavelength conversion. This can again illustrate the benefit of sparse wavelength conversion. Secondly, we compare the blocking performance of the MBPF converter placement algorithm with the random converter placement algorithm[4] the total outgoing traffic (TOT) converter placement algorithm proposed in [1], and also the WMSL algorithm. This is to validate that a well-designed converter placement algorithm is very important in order to achieve good performance. Simulations are conducted under two different cases: two wavelength converters and five wavelength converters. For the random converter placement, we do simulations for a large number of different random placement schemes and then calculate the average values of blocking probabilities. When there are two wavelength converters, we do simulations for all the possible placement schemes, and for the case of five wavelength converters, we randomly choose 100 different placement schemes and calculate the average results. Thus, we can get a reasonable average blocking performance over all the placement schemes. The TOT algorithm places converters at nodes that have the highest outgoing traffic. It has been shown to perform almost as well as optimal placement in networks that employ the static routing and random wavelength assignment RWA algorithm. The WMSL converter placement algorithm is designed for the LLR routing algorithm. However, it is also interesting to evaluate the performance of WMSL under the FAR routing algorithm.

Fig. 5 shows the blocking probability versus the total traffic load for the 14-node NSFNET network. The resultant converter placement schemes of different algorithms are shown in Table I, where M is the number of converters. The cases of no conversion and full conversion are also investigated. We find that wavelength conversion can improve the blocking performance significantly with low traffic load. With the increase of traffic load, the benefit of wavelength conversion decreases. This can be explained by the fact that when the traffic is low, connection requests are blocked, mainly because of the wavelength continuity constraint, thus, wavelength conversion can improve the performance significantly because it can break the wavelength continuity constraint [10]. However, when the traffic load is heavy,

[4]In our random converter placement algorithm, each node in the network has the same probability of being equipped with a wavelength converter.

TABLE I
CONVERTER PLACEMENT IN 14-NODE NSFNET FOR TWO AND FIVE CONVERTERS

M	Random Placement	TOT Placement	MBPF Placement	WMSL Placement
2	All combinations	(6,10)	(4,6)	(4,6)
5	100 random combinations	(3,4,6,7,10)	(3,4,6,9,10)	(3,4,6,10,12)

TABLE II
CONVERTER PLACEMENT IN 19-NODE EON FOR TWO AND FIVE CONVERTERS

M	Random Placement	TOT Placement	MBPF Placement	WMSL Placement
2	All combinations	(1,9)	(1,7)	(1,7)
5	100 random combinations	(1,2,4,6,9)	(1,2,4,7,9)	(1,2,4,7,9)

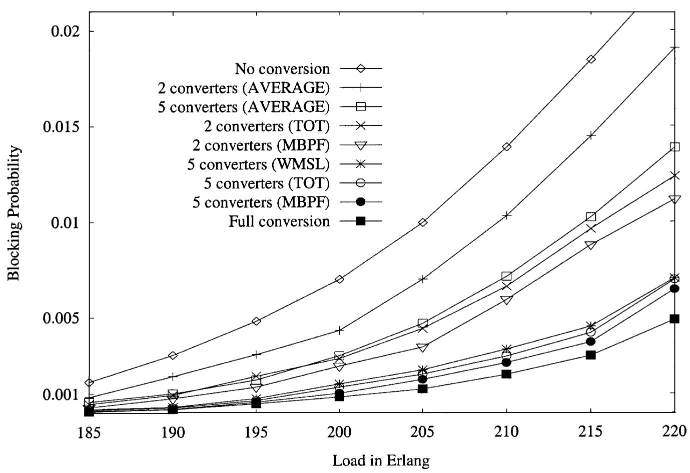

Fig. 5. Blocking probability versus traffic load in NSFNET using FAR-FF algorithm.

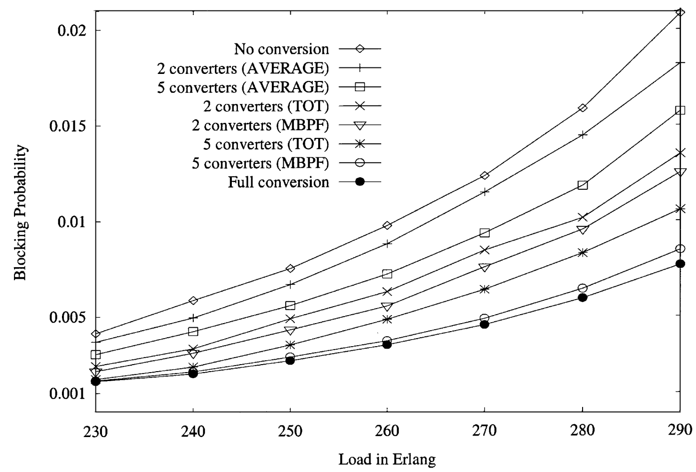

Fig. 6. Blocking probability versus traffic load in EON using FAR-FF algorithm.

connection requests are blocked mainly because wavelength resources are exhausted.

From Fig. 5, we observe that the average performance of random wavelength converter placement is very limited. However, the TOT, WMSL, and MBPF algorithms can achieve much better performance. This validates that wavelength converter placement is an important issue. An appropriate placement of two converters could achieve better performance than a bad placement of five converters. In the case of two converters, MBPF and WMSL result in the same converter placement scheme. Besides, we observe that the MBPF algorithm outperforms both the TOT algorithm and WMSL algorithm. The simulation results show that the MBPF algorithm can decrease the blocking probability by 10%–20% compared to the TOT algorithm. The performance of the WMSL algorithm is even worse than the TOT algorithm when there are five converters. Another observation is that only five converters (about 35% of all the nodes) can achieve almost the same performance as full wavelength conversion.

In the 19-node EON network, simulations are also carried out using two converters or five converters. The resultant converter placements of different algorithms are shown in Table II. For the random placement, we conduct simulations using all the possible combinations of placement for two converters and get the average performance. We choose 100 different placement schemes randomly when there are five converters and then calculate the average blocking probabilities, simply because it is not practical to do simulations for all the possible placement schemes. The blocking performances of different converter placement approaches are shown in Fig. 6. We find that the EON network can carry much more traffic than the NSFNET under the same blocking probability. This is because the EON network is denser than the NSFNET network: the average node degree of EON is 4, while it is only 2.86 for NSFNET. The benefit of wavelength conversion is very significant. Only two converters can decrease the blocking probability by half if we place them appropriately. If we use five converters (about 25% of all the nodes), the performance of the MBPF algorithm will be very close to the performance of full wavelength conversion. Again, the average performance of random converter placement is very poor, for both cases of two and five converters. In this topology, the MBPF and WMSL algorithm have the same converter placement schemes for both two and five converters. The simulation results also show that MBPF algorithm can decrease the blocking probability by 10%–20%, compared with the TOT algorithm.

TABLE III
CONVERTER PLACEMENT IN 38-NODE CTNET FOR TWO AND SIX CONVERTERS

M	Random Placement	TOT Placement	MBPF Placement	WMSL Placement
2	100 random combinations	(4,21)	(2,4)	(4,11)
6	100 random combinations	(2,4,11,21,23,30)	(2,4,11,21,23,30)	(2,4,11,21,28,30)

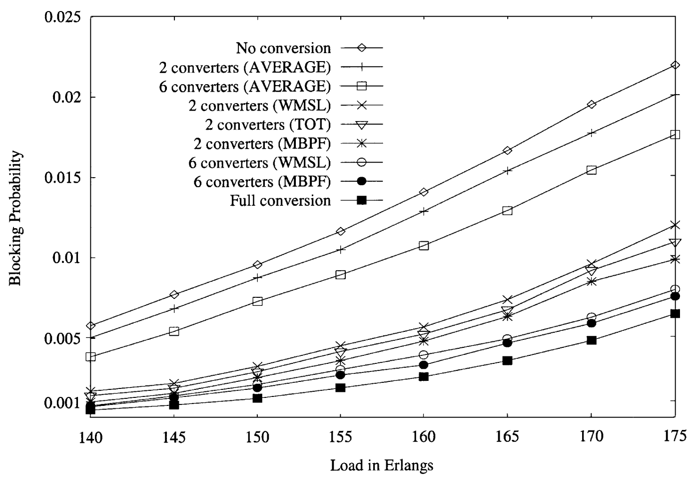

Fig. 7. Blocking probability versus traffic load in CTNET using FAR-FF algorithm.

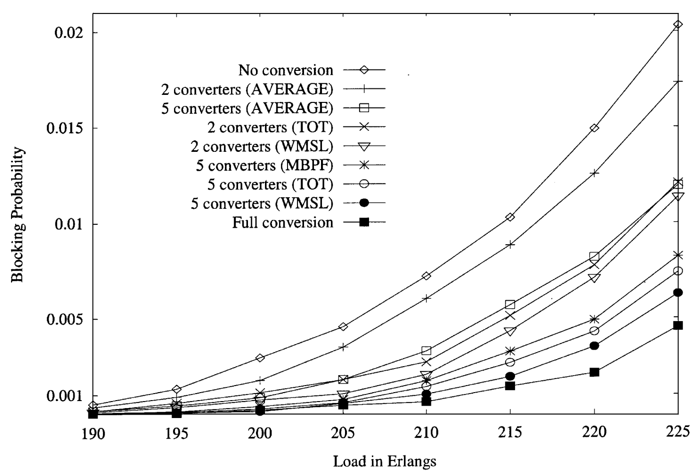

Fig. 8. Blocking probability versus traffic load in NSFNET using LLR-FF algorithm.

In the 38-node CTNET network, simulations are carried out using two converters or six converters. The results of converter placements using different algorithms are shown in Table III. The blocking performances of different converter placement approaches are depicted in Fig. 7. It can be observed that the average performance of random placement of six converters is much worse than the performance of MBPF placement of two converters. In the case of two wavelength converters, the simulation results show that the MBPF algorithm can decrease the blocking probability by 10% compared to the TOT algorithm, and the performance of the WMSL algorithm is not even as good as the TOT algorithm. However, in the case of six wavelength converters, the MBPF and TOT result in the same converter placement scheme, which can achieve almost the same performance compared with the case of full wavelength conversion. The WMSL algorithm does not perform well in the case of six converters.

C. Performance Evaluation of the LLR-FF and WMSL Algorithms

The WMSL algorithm is designed for the LLR algorithm. Therefore, in the following simulations, the LLR-FF RWA algorithm is employed. The performance of the proposed WMSL algorithm is compared to the cases of no wavelength conversion and full wavelength conversion. We also compare it with the average performance of the random converter placement algorithm, and TOT and MBPF converter placement algorithms.

In the 14-node NSFNET network, simulations are carried out using two converters or five converters. The resultant converter placements of different algorithms are shown in Table I. The case of no conversion and full conversion are also investigated. Fig. 8 shows the blocking probability versus the total traffic load for the NSFNET network. We find that wavelength conversion can improve the blocking performance significantly with low traffic load when the LLR-FF RWA algorithm is employed. With the increasing of traffic load, the benefit of wavelength conversion decreases.

From Fig. 8, we observe that the average performance of the random wavelength converter placement scheme is negligible. However, the TOT and WMSL algorithms can achieve much better performance. We also observe that the WMSL algorithm outperforms the TOT algorithm in both cases of two and five converters. The simulation results show that WMSL algorithm can decrease the blocking probability by 10%–20%, compared with the TOT algorithm. Another observation is that only five converters can achieve almost the same performance as full wavelength conversion.

In the 19-node EON network, simulations are also carried out using two or five converters. The resultant converter placements of different algorithms are shown in Table II. The blocking performances of different converter placement approaches are shown in Fig. 9. Only two converters can decrease the blocking probability when the WMSL algorithm is used. If we use five converters, the performance of the WMSL algorithm will be very close to the performance of full wavelength conversion. The simulation results show that the WMSL algorithm can decrease the blocking probability by 20%–30%, compared with the TOT algorithm.

In the 38-node CTNET network, simulations are carried out using two or six converters. The results of converter placements of different algorithms are shown in Table III. The blocking performances of different converter placement approaches are de-

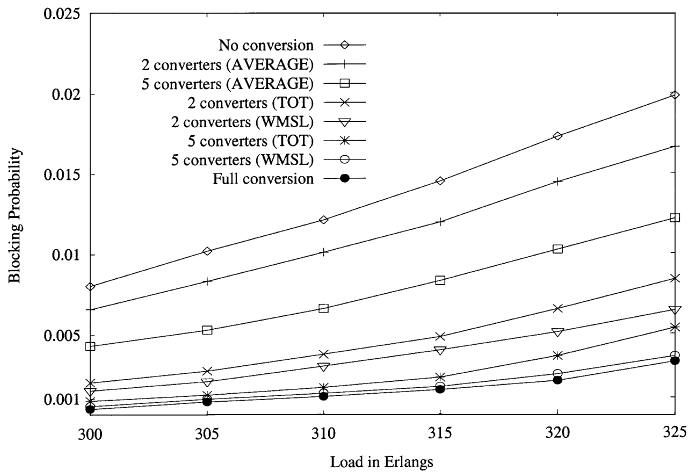

Fig. 9. Blocking probability versus traffic load in EON using LLR-FF algorithm.

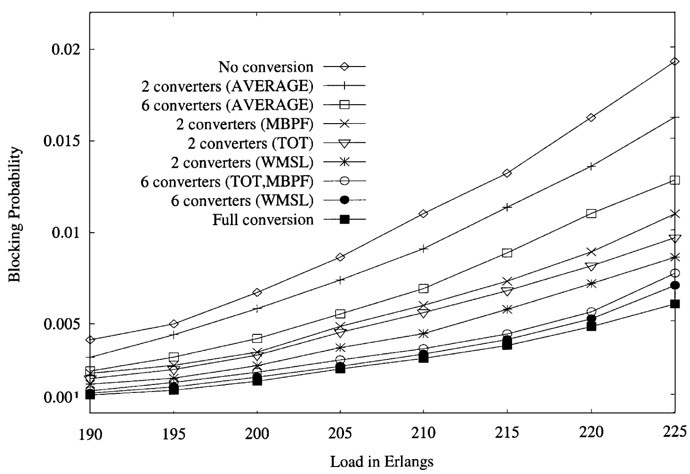

Fig. 10. Blocking probability versus traffic load in CTNET using LLR-FF algorithm.

picted in Fig. 10. The benefit of wavelength conversion is remarkable. If we compare Fig. 10 with Fig. 7, we can find that the LLR-LL algorithm can achieve better performance than the FAR-FF algorithm in terms of carried traffic under the same blocking probability. It can be observed that the average performance of random placement of six converters is worse than the performance of TOT and WMSL placement of two converters. Once we place six converters according to the WMSL algorithm, the blocking performance is almost the same as that of full wavelength conversion. The simulation results also show that WMSL algorithm can decrease the blocking probability by 10%–15%, compared with the TOT algorithm.

From the above simulation analysis, we can conclude that sparse wavelength conversion can improve the blocking performance significantly in mesh networks if we place the converters appropriately. The average performance of random converter placements is not acceptable. However, the proposed MBPF and WMSL algorithms can achieve very good performance with the appropriate RWA algorithms.

V. Conclusion and Future Work

In this paper, we investigated the problem of wavelength converter placement under different RWA algorithms in wavelength-routed all-optical networks. The purposes of this study are two-fold: 1) we demonstrated that the performance of a wavelength converter placement scheme is dependent on the underlying RWA algorithm; and 2) given that most of the existing wavelength converter placement algorithms assume fixed routing and random wavelength assignment, we showed that the two proposed wavelength converter placement algorithms, the MBPF algorithm under the FAR-FF RWA scheme and the WMSL algorithm under the LLR-FF RWA scheme can easily outperform the existing wavelength converter placement algorithm in term of blocking probability. Furthermore, both the MBPF and WMSL algorithms need only 15%–35% of all the network nodes equipped with wavelength converters to achieve almost the same performance comparable with the full wavelength conversion.

One of the key assumptions in this paper, as in all existing work, is that the wavelength converter placement algorithm relies on a given RWA scheme in order to quantitatively compare the blocking performance. One possible future research avenue is to carry out more extensive studies on the design of a single generic wavelength converter placement algorithm that can achieve good performance under different RWA algorithms. On the other hand, the wavelength converter placement could be done at some earlier stage, during capacity planning, while RWA is done at a later stage, during routing. The key point is that these two issues should be somehow considered jointly, which is beyond the scope of this paper to fully address. Interestingly, how to do RWA in the presence of wavelength converter is also a difficult issue, which we have studied in a companion paper [7]. The reality could be that some iterative approaches be taken in order to achieve better overall blocking performance. This is currently under investigation.

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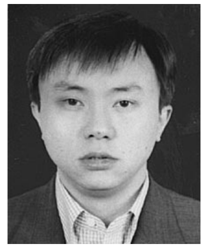

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