PAPER

Blocking Models of All-Optical WDM Networks under Distributed Wavelength Assignment Policies

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SUMMARY In this paper, we investigate the blocking characteristics of all-optical WDM (Wavelength-Division Multiplexing) networks under distributed wavelength assignment policies. For assigning wavelengths in a distributed manner, we consider two algorithms: random and locally-most-used algorithm. For a random wavelength assignment policy, we develop new blocking models of unidirectional/bidirectional ring networks based on the $M/M/c/c$ queueing models under uniform/nonuniform traffic conditions. These models are shown to be more accurate than the previous blocking models since our approach considers the large traffic correlation among links in ring networks. We also analyze the blocking performance of the locally-most-used algorithm by comparing with that of the globally-most-used algorithm in fixed routing networks. We show that our analysis models match well with the simulation results in ring and mesh networks. Through the comparison with the previous centralized/distributed algorithms, it is demonstrated that the distributed locally-most-used algorithm is computationally efficient with good blocking performance.

key words: Wavelength-division multiplexing (WDM) network, wavelength assignment, distributed algorithm, blocking performance.

1. Introduction

All-optical WDM (Wavelength-Division Multiplexing) networking has emerged as a promising technology for future broadband networks. All-optical transmission enables data to be transferred from a source to a destination without opto-electric/electro-optic conversion, which overcomes network bottlenecks while simplifies network management. An optical fiber in WDM networks can accommodate multiple channels, each of which operates at a different wavelength and at a high speed of the order of gigabit per second.

In WDM networks, a call request is accommodated by a direct optical path (called a lightpath) established between two communicating nodes. A lightpath may span along several nodes which have optical switches [3][4] with a capability of wavelength routing. If each node does not have a wavelength conversion capability, establishing a lightpath may require a wavelength which is commonly idle at all links on its routing path. This requirement is known as a *wavelength continuity constraint*. There have been considerable researches on the blocking performance of all-optical WDM networks with/without a wavelength conversion capability [5][6][7]. Usually, a network with a wavelength conversion capability shows a lower call blocking rate than that without it.

To decrease the call blocking probability, it is very important to determine how to route a lightpath on a physical network and how to assign a wavelength. This is typically known as *routing and wavelength assignment (RWA)*. As the number of wavelengths available at a link increases, the utilization of a wavelength may be improved by efficient RWA. The RWA problem in WDM networks has also been extensively studied [1][8]-[14] by relying on linear programming or heuristic algorithms.

The RWA algorithms are operated in either a centralized or a distributed manner depending on whether or not there exists a supervisory node responsible for maintaining and controlling the global network. For example, the most-used (MU) algorithm [1] assumes a centralized control because a supervisory node finds out a wavelength being used the most in the network for setting up a lightpath. In general, a centralized algorithm needs a larger control traffic overhead because a supervisory node must always maintain the state information of whole networks. It also accompanies large computational complexity to obtain an optimal solution in controlling a global network. On the other hand, a distributed algorithm exploits less amount of network information, but is sub-optimal compared to a centralized algorithm. Most of the previous works have focused on a centralized RWA algorithm and its blocking performance without considering the inherent computational overhead.

In this paper, we investigate the performance characteristics of the distributed wavelength assignment (DWA) algorithms. We assume a circuit-switched network where any source-destination pair can be connected by a single-hop lightpath on a fixed routing path. As DWA algorithms, we consider a random assignment algorithm and a locally-most-used (LMU) algorithm in WDM networks without a wavelength conversion capability. In the LMU algorithm, a wavelength is as-

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signed that is being used the most on the links which are connected to the routing node where a call request is routed.

As a major contribution, we investigate the blocking performance of the DWA algorithms by deriving blocking models under fixed routing in ring and mesh networks. In particular, under the random wavelength assignment policy, we present new blocking models of ring networks based on uniform/nonuniform $M/M/c/c$ traffic models [2] which take into account the large traffic correlation among links. We also analyze the blocking performance of the LMU algorithm by comparing with that of the globally-most-used algorithm [1] in fixed routing networks. By simulation, we compare the two DWA algorithms with the previous centralized/distributed wavelength assignment algorithms in terms of blocking performance. The comparison shows that the analytical results closely match the simulation results.

This paper is organized as follows. We present the definitions for the DWA algorithms in section 2 and analyze the blocking performance in section 3. In section 4, we provide the numerical results on the blocking performance of various centralized/distributed wavelength assignment algorithms obtained through simulation using a uniform $M/M/c/c$ traffic model. Finally, we conclude this paper in section 5 .

2. Distributed Wavelength Assignment Algorithms

In this section, we describe the distributed wavelength assignment (DWA) policies for WDM networks. For DWA, we consider two kinds of algorithms: the random algorithm and the locally-most-used (LMU) algorithm. In the random algorithm, each node can select a wavelength randomly among available wavelengths and assigns it to a lightpath originating from the node. This algorithm has an effect of distributing the traffic load uniformly to all wavelengths, so that each wavelength exhibits nearly the same utilization.

The LMU algorithm assigns a wavelength to a lightpath which is being used the most at a local area. Given a routing path from a source node to a destination node, the local area refers to a subnet which consists of the nodes on the routing path and the fiber links connected to the nodes. The LMU algorithm has an effect of packing available wavelengths to increase the efficiency. Since each node on a routing path maintains the information of whether the wavelength is busy at the fiber links connected to it, the most-used wavelength at a local area can be determined in a distributed manner unlike the centralized MU algorithm[1], where a supervisory node communicates frequently with the other nodes to maintain and control the global network.

To characterize the LMU algorithm, we define some terminology.

Notations:

- N : Number of nodes in a network.
- $\{w_i | 1 \leqq i \leqq W\}$: Set of all wavelengths in a network.
- I : Set of wavelengths which are commonly idle on a routing path before wavelength assignment. That is, wavelength w_i is idle on the routing path for all $i \in I$.
- Ψ_g : Number of fiber links in a network.
- Ψ_l : Number of fiber links at a local area.
- $\rho_{l,i}$: Utilization of a wavelength w_i at a local area.
- $h_{s,d}$: Physical hop distance of the routing path from a source node s to a destination node d.

Assume that w_m is a locally-most-used wavelength at a local area consisting of Ψ_l fiber links for $m \in I$. Then, it is obvious that

$$\rho_{l,m} = \max\{\rho_{l,i} \mid i \in I\}. \quad (1)$$

Considering the fact that a wavelength w_i is commonly idle on a routing path for all $i \in I$, w_m is also the most-used wavelength on $(\Psi_l - h_{s,d})$ fiber links.

Before we develop the blocking models in section 3, we discuss the complexity of the amount of information needed by the LMU algorithm, which is usually far less than the centralized algorithm. In order to see that, we compare the average value of Ψ_l, i.e., $\bar{\Psi}_l$, with a value of Ψ_g, where $\bar{\Psi}_l$ is computed as follows:

$$\begin{aligned}\bar{\Psi}_l &= [(\bar{h}_{s,d} + 1) \cdot 2\Delta] - 2 \cdot \bar{h}_{s,d} \\ &= 2(\Delta - 1) \cdot \bar{h}_{s,d} + 2\Delta\end{aligned} \quad (2)$$

where $\bar{h}_{s,d}$ denotes the average physical hop distance and Δ denotes an in-degree and an out-degree of a node. In general, $\bar{h}_{s,d}$ depends on a virtual topology as well as a physical topology in a network. Particularly in a bidirectional $\sqrt{N} \times \sqrt{N}$ two-dimensional mesh-torus network, $\bar{h}_{s,d}$ is given as follows [15]:

$$\bar{h}_{s,d} = \frac{2 \cdot \sqrt{N} \cdot \lfloor \frac{N}{4} \rfloor}{N-1}. \quad (3)$$

In this case, by Eqs. (2)-(3),

$$\bar{\Psi}_l = O(\sqrt{N}). \quad (4)$$

On the other hand, it is straightforward that

$$\Psi_g = \frac{N \cdot 2\Delta}{2} = N\Delta. \quad (5)$$

Since our algorithm operates by referring to $O(\sqrt{N})$ fiber links, it requires a lot smaller control traffic overhead and computational complexity than those of the centralized wavelength assignment algorithms.

As an example, Fig. 1 is a bidirectional 5×5 two-dimensional mesh-torus network. In this example, a lightpath is to be set up by assigning a wavelength along the marked nodes from source node 7 to destination node 14. The thick fiber lines in Fig. 1 denote the fiber

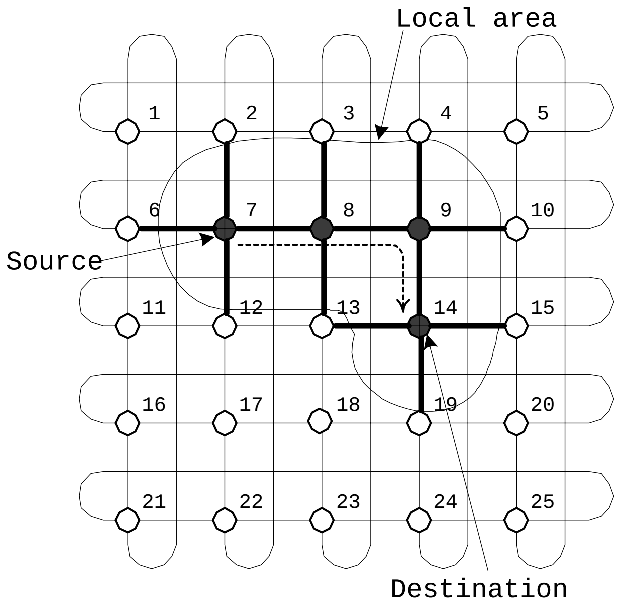

Fig. 1 Example of a local area around a routing path in a 5 × 5 bidirectional mesh-torus network.

links belonging to the local area. Since $N = 25$, $\Delta = 4$, and $\bar{h} = 2.5$, it is obvious that $\Psi_g = 100$ and $\bar{\Psi}_l = 23$. The algorithm looks for a wavelength w_m which is used the most on thick fiber links among $\{w_i \mid i \in I\}$ in Fig. 1 and assigns it to the lightpath.

3. Analysis of Blocking Performance

In this section, we present the analytical blocking performance of the random and the LMU algorithm. We first apply the random algorithm to unidirectional and bidirectional ring networks under the uniform/nonuniform $M/M/c/c$ queueing models. By investigating the large traffic correlation among links in detail in ring networks, we obtain accurate analytical results. Then we analyze the blocking performance of the LMU algorithm by comparing with that of the MU algorithm [1] under a fixed routing policy. In this analysis, we consider a mesh as well as a ring network.

A. Random Wavelength Assignment Algorithm

We present the call blocking performance of unidirectional/bidirectional ring networks under a random wavelength assignment policy by using the $M/M/c/c$ queueing model. The $M/M/c/c$ model represents a loss system with a limited number of c service channels. For this model, we denote the arrival rate and the service rate at a node k ($1 \leqq k \leqq N$) as λ_k and μ_k, respectively. We call the arrival rate uniform if λ_k is the same at all nodes; otherwise we call it non-uniform. In ring networks, the state of one link is heavily correlated to that of another because of very weak connectivity. We investigate this correlation existing among links in detail, obtaining an accurate blocking model.

We first consider a unidirectional ring network with a total number of available wavelengths, W. Nodes are numbered from 1 to N. Let $P_{b,i}^{s,d}$ denote a probability that a wavelength w_i is already used on at least one link in its routing path from a node s to a node d. Given a call request from the node s to node d, the call blocking probability $P_b^{s,d}$ is given as follows:

$$P_b^{s,d} = \prod_{i=1}^{W} P_{b,i}^{s,d}. \tag{6}$$

For mathematical convenience, we assume $d > s$. Defining $A_{k,i}$, $s \leqq k \leqq d-1$, as an event that a wavelength w_i is idle on a link from a node k to $k+1$, then by the conditional probability theory,

$$\begin{aligned} 1 - P_{b,i}^{s,d} &= \Pr(A_{s,i}) \cdot \Pr(A_{s+1,i} \mid A_{s,i}) \\ &\quad \cdots \Pr(A_{d-1,i} \mid A_{s,i}, A_{s+1,i}, \cdots, A_{d-2,i}). \end{aligned} \tag{7}$$

In this equation, $\Pr(A_{s,i}) = 1-\bar{\rho}$ where $\bar{\rho}$ is the average utilization of a wavelength in the network. We also define $B_{k,i}$ as an event that there exists a lightpath with a wavelength w_i originating from a node k. Then, it is straightforward that

$$\begin{aligned} &\Pr(A_{k,i} \mid A_{s,i}, A_{s+1,i}, \cdots, A_{k-1,i}) = \\ &\quad 1 - \Pr(B_{k,i} \mid A_{s,i}, A_{s+1,i}, \cdots, A_{k-1,i}). \end{aligned} \tag{8}$$

The average number of lightpaths originating from a node k is approximated to λ_k/μ_k under the assumption that the blocking probability is much less than 1 as in circuit-switching networks. Similarly, the average number of lightpaths on a link not originating from a node k is $W\bar{\rho}_{(-k)}$ where $\bar{\rho}_{(-k)}$ is equal to $\bar{\rho}$ times the ratio of $\sum_{j \neq k}(\lambda_j/\mu_j)$ to $\sum_{j=1}^{N}(\lambda_j/\mu_j)$. Since a node k selects a wavelength among $W(1-\bar{\rho}_{(-k)})$ wavelengths to set up a lightpath accommodating the call request,

$$\Pr(B_{k,i} | A_{s,i}, A_{s+1,i}, \cdots, A_{k-1,i}) = \frac{\lambda_k}{\mu_k} \frac{1}{W(1-\bar{\rho}_{(-k)})}. \tag{9}$$

By Eqs. (7)-(9),

$$P_{b,i}^{s,d} = 1 - (1-\bar{\rho}) \prod_{k=s+1}^{d-1} \left[1 - \frac{\lambda_k}{\mu_k} \frac{1}{W(1-\bar{\rho}_{(-k)})} \right]. \tag{10}$$

To describe the call blocking probability for any s and d, we use the following definition.

Definition: $R(s,d)$ is the index set of intermediate nodes on the routing path from a node s to d. For example, $R(1,5)$ denotes $\{2,3,4\}$ and $R(5,3)$ denotes $\{6, 7, \cdots, N, 1, 2\}$.

Then, by Eqs. (6) and (10),

$$P_b^{s,d} = \left(1 - [1-\bar{\rho}] \prod_{k \in R(s,d)} \left[1 - \frac{\lambda_k}{\mu_k} \frac{1}{W(1-\bar{\rho}_{(-k)})} \right] \right)^W. \tag{11}$$

Averaging $P_b^{s,d}$ for all s and d ($\neq s$), we can get the average blocking probability,

$$P_b = \frac{\sum_{s=1}^{N}\sum_{d\neq s} P_b^{s,d}}{N(N-1)}. \tag{12}$$

As a special case, under the uniform traffic condition, $\lambda_k = \lambda$ and $\mu_k = \mu$ for $1 \leqq k \leqq N$. Then by definition, the cardinality of $R(s,d)$, ($|R(s,d)|$), is equal to $h_{s,d} - 1$. Thus, Eqs. (11) and (12) are reduced as follows, respectively:

$$P_b(h_{s,d}) = \frac{\sum_{h_{s,d}=1}^{N-1}\left(1-[1-\bar{\rho}]\left[1-\frac{\lambda}{\mu}\frac{1}{W(1-\frac{N-1}{N}\bar{\rho})}\right]^{h_{s,d}-1}\right)^{W}}{N-1} \tag{13}$$

$$P_b = \frac{\sum_{h_{s,d}=1}^{N-1} P_b(h_{s,d})}{N-1}. \tag{14}$$

Next, for a bidirectional ring network, we assume that a lightpath is routed along the shorter path between a clockwise and a counterclockwise path. To formulate the routing path, we use the following definitions.

Definitions: $R_1(s,d)$ is the index set of intermediate nodes on the counterclockwise path from a node s to d. Similarly, $R_2(s,d)$ is that on the clockwise path. For example, $R_1(3,7)$ denotes $\{4,5,6\}$ and $R_2(3,7)$ denotes $\{8,9,\cdots,N,1,2\}$.

The cardinality of $R(s,d)$ is then given as follows:

$$|R(s,d)| = \min\{|R_1(s,d)|,\ |R_2(s,d)|\}, \tag{15}$$

from which it is obvious that $0 \leqq |R(s,d)| \leqq \lfloor (N-2)/2 \rfloor$. Assuming that a call request at a node k is uniformly serviced along either a clockwise or a counterclockwise path, the average number of lightpaths originating from a node k along each directional path is approximated to $\lambda_k/2\mu_k$. The call blocking probability thus is given as follows:

$$P_b^{s,d} = \left(1-[1-\bar{\rho}]\sum_{k\in R(s,d)}\left[1-\frac{\lambda_k}{2\mu_k}\frac{1}{W(1-\bar{\rho}_{(-k)})}\right]\right)^{W}, \tag{16}$$

and the average blocking probability can be computed in a similar manner as in Eq. (12) under the non-uniform $M/M/c/c$ queueing model. Under the uniform traffic condition, Eqs. (13) and (14) are reduced as follows, respectively:

$$P_b(h_{s,d}) = \left(1-[1-\bar{\rho}]\left[1-\frac{\lambda}{2\mu}\frac{1}{W(1-\frac{N-1}{N}\bar{\rho})}\right]^{h_{s,d}-1}\right)^{W} \tag{17}$$

$$P_b = \begin{cases} \dfrac{\sum_{h_{s,d}=1}^{[N-2]/2} 2\cdot P_b(h_{s,d}) + P_b(N/2)}{N-1}, & N \text{ even number} \\ \dfrac{\sum_{h_{s,d}=1}^{[N-1]/2} 2\cdot P_b(h_{s,d})}{N-1}, & N \text{ odd number.} \end{cases} \tag{18}$$

B. Distributed LMU Algorithm

In this part, we analyze the blocking performance of the LMU algorithm by comparing with that of the MU algorithm under a fixed routing policy. We first assume that wavelength usage on one optical fiber is statistically independent of that on another and that a routing path is predetermined regardless of wavelength utilization. We define $\mathrm{X}_{g,i}$ to be the number of fiber links with a busy wavelength w_i in a global network. Similarly, we define $\mathrm{X}_{l,i}$ to be the number of fiber links with a busy wavelength w_i at a local area. Assuming that v is the number of wavelengths commonly idle on a routing path, the probability distribution function of $\mathrm{X}_{l,m}$ is given as follows for a locally-most-used wavelength w_m:

$$\begin{aligned} P_{\mathrm{X}_{l,m}}(n) &= \Pr(\mathrm{X}_{l,m} \leqq n) - \Pr(\mathrm{X}_{l,m} \leqq n-1) \\ &= \prod_{i=1}^{v}\Pr(\mathrm{X}_{l,i} \leqq n) - \prod_{i=1}^{v}\Pr(\mathrm{X}_{l,i} \leqq n-1) \\ &= [f(n)]^v - [f(n-1)]^v \end{aligned} \tag{19}$$

where

$$f(n) = \begin{cases} \sum_{j=0}^{n}\begin{pmatrix}\Psi_l \\ j\end{pmatrix}\bar{\rho}^j(1-\bar{\rho})^{\Psi_l - j}, & n \geqq 0 \\ 0, & n < 0. \end{cases} \tag{20}$$

Then, the average of $\mathrm{X}_{l,m}$, $\bar{\mathrm{X}}_{l,m}$, is given as

$$\bar{\mathrm{X}}_{l,m} = \sum_{n=0}^{\Psi_l} n\cdot P_{\mathrm{X}_{l,m}}(n) = \Psi_l\cdot[f(\Psi_l)]^v - \sum_{n=0}^{\Psi_l-1}[f(n)]^v. \tag{21}$$

The average utilization $\bar{\rho}_{l,m}$ of a wavelength w_m at a local area with Ψ_l fiber links is thus given as follows:

$$\bar{\rho}_{l,m} = \frac{\bar{\mathrm{X}}_{l,m}}{\Psi_l} = [f(\Psi_l)]^v - \frac{\sum_{n=0}^{\Psi_l-1}[f(n)]^v}{\Psi_l}. \tag{22}$$

Since, by assumption, a local area is determined regardless of wavelength utilization, $\bar{\rho}_{l,m}$ can be approximated to the average utilization of a wavelength w_m in the network. The average of $\mathrm{X}_{l,m}$ is thus obtained from Ψ_g and $\bar{\rho}_{l,m}$:

$$\bar{\mathrm{X}}_{g,m} \approx \Psi_g\left([f(\Psi_l)]^v - \frac{\sum_{n=0}^{\Psi_l-1}[f(n)]^v}{\Psi_l}\right). \tag{23}$$

However, a locally-most-used wavelength at the local area is not always equal to a globally-most-used wavelength when there exists $\mathrm{X}_{g,i}$ which is larger than $\bar{\mathrm{X}}_{g,m}$ for some i ($\neq m$). The conditional probability that a locally-most-used wavelength is not equal to a globally-most-used wavelength for some v is then given as follows:

$$\begin{aligned}&\Pr(\exists\, i \text{ such that } i \neq m \text{ and } X_{g,i} > \bar{X}_{g,m} \mid \mathrm{V} = v) \quad (24)\\ &= 1 - \Pr(X_{g,i} \leqq \bar{X}_{g,m} \text{ for all } i (\neq m) \mid \mathrm{V} = v)\\ &= 1 - \left[\sum_{j=0}^{\bar{X}_{g,m}} \begin{pmatrix} \Psi_g \\ j \end{pmatrix} \bar{\rho}^j (1-\bar{\rho})^{\Psi_g - j} \right]^{v-1}\end{aligned}$$

where V is a random variable denoting the number of wavelengths commonly idle on a routing path. Since the probability that a wavelength is commonly idle on consecutive $\bar{h}_{s,d}$ fiber links is $(1-\bar{\rho})^{\bar{h}_{s,d}}$,

$$\Pr(\mathrm{V} = v) = P_{\mathrm{V}}(v) = \begin{pmatrix} W \\ k \end{pmatrix} p^v (1-p)^{W-v} \tag{25}$$

where

$$p = (1-\bar{\rho})^{\bar{h}_{s,d}}. \tag{26}$$

Consequently, the probability that a locally-most-used wavelength is not equal to a globally-most-used wavelength is given as P_d where

$$\begin{aligned}P_d &= \Pr(\exists\, i\,,\, i \neq m \text{ and } X_{g,i} > \bar{X}_{g,m}) \qquad (27)\\ &= \sum_{\mathrm{v}=2}^{W} \Pr(\exists\, i\,,\, i \neq m \text{ and } X_{g,i} > \bar{X}_{g,m} \mid \mathrm{V} = v) \cdot P_{\mathrm{V}}(v).\end{aligned}$$

To obtain the analytical blocking performance of the LMU algorithm, we relate P_b^{LMU} with P_b^{MU} as a function of P_d where P_b^{LMU} and P_b^{MU} are the blocking probabilities of the LMU and the MU algorithm, respectively. That is,

$$P_b^{LMU} = P_b^{MU} \cdot f(P_d) \tag{28}$$

where $f(P_d)$ is defined as a weighting function.

In case $P_d = 0$, which means that the wavelength selected by the LMU algorithm is always equal to the wavelength selected by the MU algorithm, it is obvious that P_b^{LMU} is the same as P_b^{MU}, i.e.,

$$P_b^{LMU} = P_b^{MU} \cdot f(P_d = 0) = P_b^{MU}. \tag{29}$$

Thus,

$$f(P_d = 0) = 1. \tag{30}$$

In case $P_d = 1$, the wavelength selected by the LMU algorithm is no longer the same as the globally-most-used wavelength selected by the MU algorithm. Though the locally-most-used wavelength has been selected to have a packing effect of wavelength usage at a local area, it may not have a global packing effect. Hence, from the aspect of a global network, a locally-most-used wavelength can be assumed to be close to a randomly-selected-wavelength when $P_d = 1$. In that case, P_b^{LMU} can be approximated to P_b^R, i.e.,

$$P_b^{LMU} = P_b^{MU} \cdot f(P_d = 1) = P_b^R \tag{31}$$

and

$$f(P_d = 1) = \frac{P_b^R}{P_b^{MU}}. \tag{32}$$

Unfortunately, however, it is difficult to conjecture how $f(P_d)$ appears except for the values of $P_d = 0$ and 1. In this paper, we assume that $f(P_d)$ could be approximated to a monotonously increasing or decreasing function of P_d. We show in the next section that this approximation is quite valid by comparing with the simulation results. So, instead of getting the exact form of $f(P_d)$, we simplify $f(P_d)$ to a linear function of P_d using the end-point values obtained from (30) and (32) as follows:

$$f(P_d) = (1 - P_d) + P_b^R / P_b^{MU} \cdot P_d. \tag{33}$$

As a result, the blocking probability of the LMU algorithm is obtained as in the following equation:

$$P_b^{LMU} = (1 - P_d) \cdot P_b^{MU} + P_d \cdot P_b^R. \tag{34}$$

4. Simulation and Performance Comparison

In this section, we compare the blocking performance of various centralized/distributed wavelength assignment algorithms. We also verify the accuracy of the analytic models developed in the previous section by comparing with simulation results. Throughout the simulation, we use a uniform $M/M/c/c$ queueing model, where calls are generated at each node according to the Poisson process with the same rate λ. Each call arrival at a node is independent of another call, and the call duration is exponentially distributed with mean $\frac{1}{\mu}$. When a call request arrives at a node, it is destined to the other nodes with an equal probability. More than 10^6 calls are generated and statistics are gathered after the network has reached the steady state. The traffic load per wavelength per fiber link is given in Erlang as follows:

$$\frac{\lambda}{\mu} \frac{N\,\bar{h}_{s,d}}{\Psi_g\, W}. \tag{35}$$

In Fig. 2 and 3, we consider the blocking model of the random wavelength assignment in unidirectional/bidirectional networks. We compare our blocking model with the blocking model presented in [5] and the Lee's blocking model [17], [18]. The results show that our model is the most accurate among them. Since the Lee's model ignores the large link correlation in ring networks, it results in a higher blocking probability compared to the simulation results. The blocking model in [5] considers the link correlation, but is less accurate than our models because it assumes that a link has the same wavelength utilization as another regardless of link connectivity. It is noted that the difference between the simulation results and the analytical results becomes larger as the number of wavelengths increases. This is because the models are represented

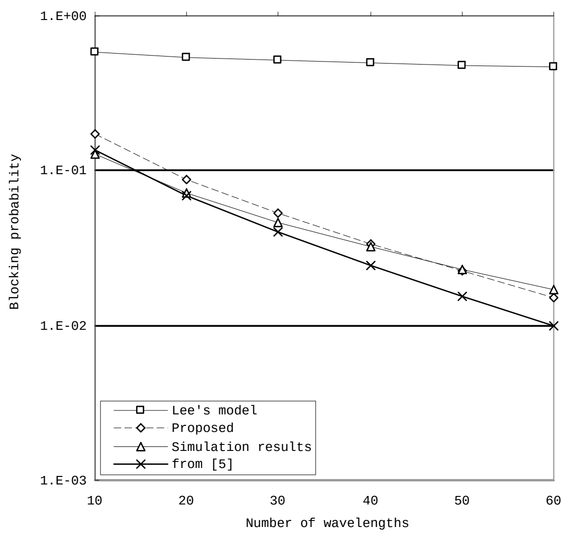

Fig. 2 Comparison of blocking performances versus the number of wavelengths in a 10-node unidirectional ring network under the random wavelength assignment algorithm.

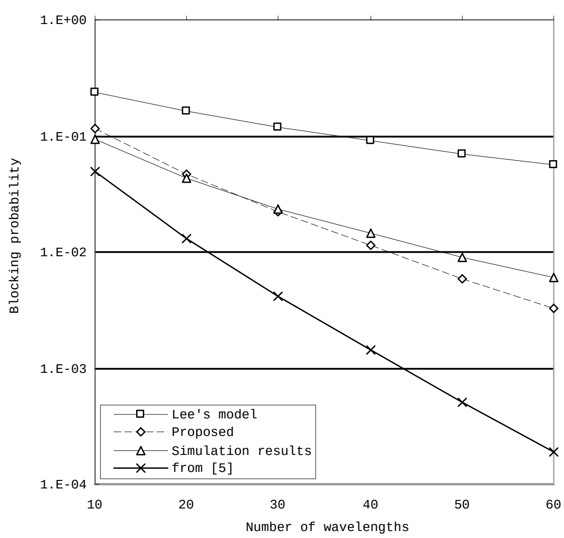

Fig. 3 Comparison of blocking performances versus the number of wavelengths in a 10-node bidirectional ring network under the random wavelength assignment algorithm.

by the average utilization of a wavelength raised to the power of the number of wavelengths. With such blocking models, it is actually very difficult to estimate the blocking performance correctly when the number of wavelengths is large because the blocking probability becomes very sensitive to the variation of average utilization of a wavelength.

Next, we compare the LMU algorithm with other

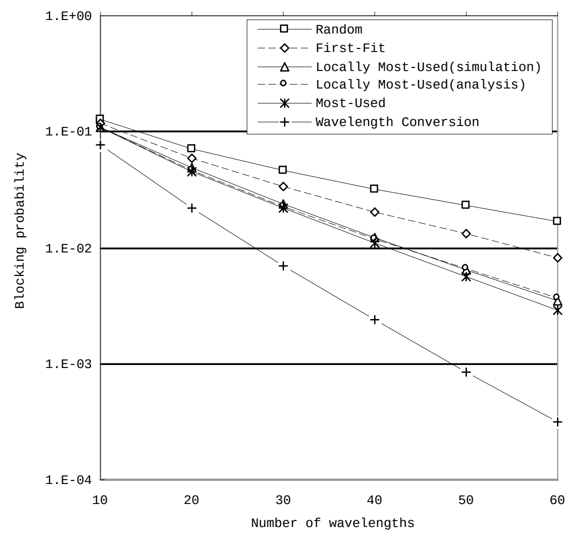

Fig. 4 Blocking probabilities of various wavelength assignment algorithms versus the number of wavelengths in a 10-node unidirectional ring network; traffic load/wavelength/optical fiber = 0.6 [Erlang].

heuristic wavelength assignment algorithms. For the comparison, we consider the first-fit (FF) and the MU algorithm. In the FF algorithm, wavelengths are indexed in an ascending order and a wavelength with the lowest index among available wavelengths is chosen and assigned [1], [9]. The least-loaded and minimum-sum algorithms described in [16] can be reduced to the MU algorithm in case of a single-fiber network. We evaluate the blocking performance with three types of networks: a 10-node unidirectional ring network, a 10-node bidirectional ring network, and a 5×5 bidirectional mesh-torus network. A bidirectional link consists of two single optical fibers, each of which directs to opposite directions. A unidirectional ring network represents a topology with very weak connectivity, while a mesh-torus network represents a topology with relatively strong connectivity. For a fixed routing policy [8], we use the X-Y routing algorithm presented in [9] for a bidirectional mesh-torus network, and use the general shortest-path routing algorithm for a bidirectional ring network.

Fig. 4, 5, and 6 show the analytical results and the simulation results on the blocking probability versus the number of wavelengths in three types of networks. We also plot the blocking probabilities of networks with wavelength conversion, which show the best blocking performance. It is observed that the LMU algorithm has better blocking performance than the random and the first-fit wavelength assignment algorithm. It is also observed that the algorithm has nearly the same blocking performance as the MU algorithm. The blocking

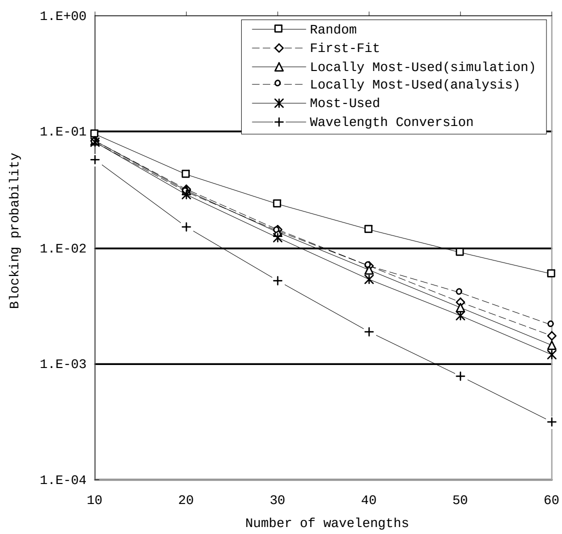

Fig. 5 Blocking probabilities of various wavelength assignment algorithms versus the number of wavelengths in a 10-node bidirectional ring network; traffic load/wavelength/optical fiber = 0.56 [Erlang].

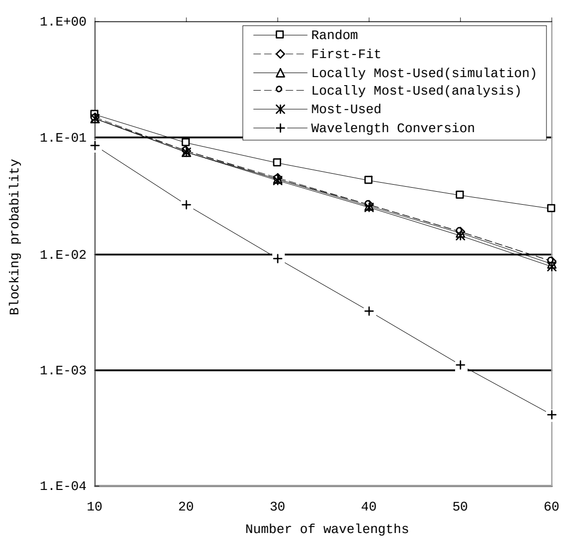

Fig. 6 Blocking probabilities of various wavelength assignment algorithms versus the number of wavelengths in a 5×5 node bidirectional mesh-torus network; traffic load/wavelength/optical fiber = 0.625 [Erlang].

performance of the LMU algorithm is conspicuously better than the FF algorithm in a unidirectional ring network, but is marginal in a bidirectional mesh-torus network. Considering the fact that the LMU algorithm simply exploits the status of wavelength usage in only two links in a unidirectional ring network, its blocking

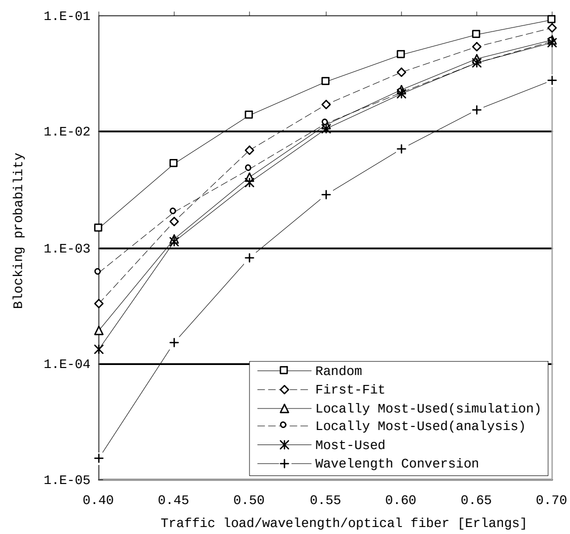

Fig. 7 Blocking probabilities of various wavelength assignment algorithms versus traffic load in a 10-node unidirectional ring network; number of wavelengths = 30.

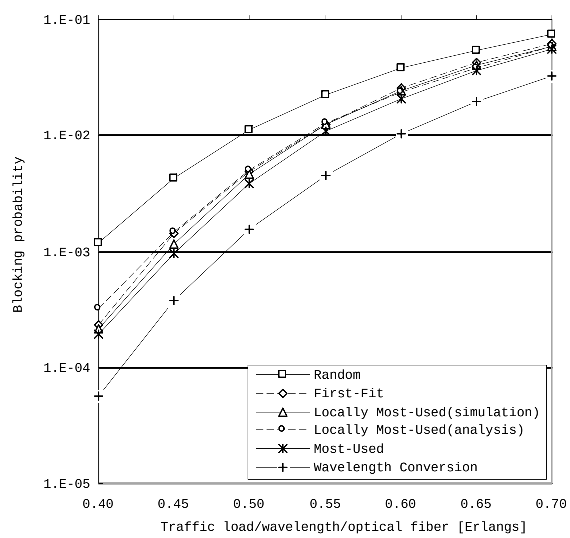

Fig. 8 Blocking probabilities of various wavelength assignment algorithms versus traffic load in a 10-node bidirectional ring network; number of wavelengths = 30.

performance is quite comparable and can be regarded as satisfactory.

We also plot the blocking probabilities versus traffic load in Fig. 7, 8, and 9. As shown in the figures, the MU and LMU algorithms outperform the distributed FF algorithm in a unidirectional ring network, but show almost the same blocking performance in a bidirectional ring and a bidirectional mesh-torus network. In Fig. 7,

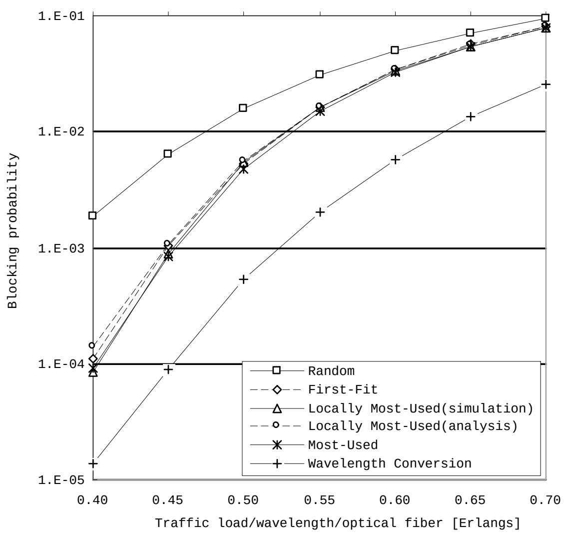

Fig. 9 Blocking probabilities of various wavelength assignment algorithms versus traffic load in a 5×5 bidirectional mesh-torus network; number of wavelengths = 30.

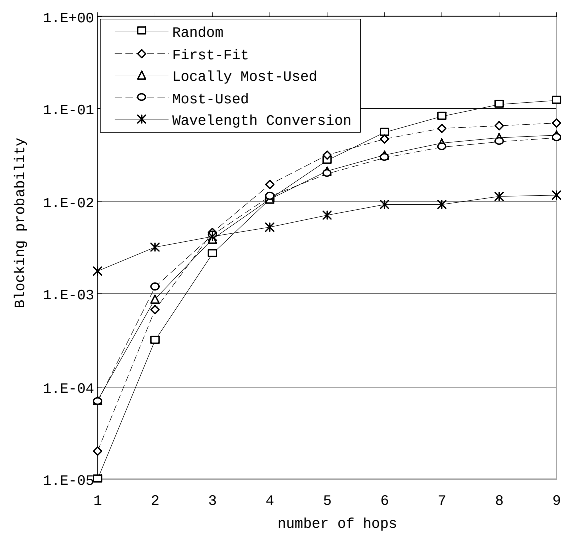

Fig. 10 Blocking probabilities of various wavelength assignment algorithms versus the number of hops in a unidirectional ring network; traffic load/wavelength/optical fiber = 0.6 [Erlang], number of wavelength = 30.

the blocking probabilities of the LMU algorithm are higher than those of the MU algorithm by 5 to 12%, while the blocking probabilities of the FF algorithm shows about 32 to 89% increases compared to those of the MU algorithm. In Fig. 8 and Fig. 9, the average increase in blocking probabilities becomes smaller compared to those of Fig. 7. In those figures, the average increase of the blocking probability in the FF algorithm is 25% and 6% each, and that of the LMU algorithm is 18% and 3%, which is greatly reduced value compared to Fig. 7. From these numerical results, it can be seen that the blocking performance of the distributed LMU algorithm is better than those of the distributed random and the FF wavelength assignment algorithm, but is slightly worse than that of the centralized MU algorithm. However, considering that the centralized MU algorithm requires a large amount of information on a global network to assign a wavelength, the LMU algorithm is more efficient in large-size distributed WDM networks.

We finally perform simulations to see how the blocking probability of the LMU algorithm changes depending on the length of lightpaths. We get the results of the blocking probability versus the number of hops for all of the mentioned algorithms in Fig. 10. The Figure shows that the blocking probability of the LMU algorithm is nearly the same as that of the MU algorithm in all the number of hops. It is consistently observed in all topologies with the various numbers of wavelengths and various loads.

5. Conclusions

In this paper, we investigate the performance of distributed wavelength assignment algorithms in all-optical WDM networks. We present new blocking models of the random wavelength assignment algorithm in unidirectional/bidirectional ring networks. Our blocking models consider the large traffic correlation in detail among links, and show more accurate results than the previous blocking models [5], [17]. The analytical results on the blocking performance of the LMU algorithm also match well with the simulation results in ring and mesh networks.

In addition, we show that the blocking performance of the LMU algorithm is better than those of the random and the FF algorithm, while it is almost the same as that of the centralized MU algorithm. The results indicate that the LMU algorithm can be an efficient solution for large-size WDM networks in terms of blocking performance, control traffic overhead, and computational complexity.

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