An Efficient Algorithm for Converter Placement in Dynamic WDM Networks

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***Abstract*— Wavelength conversion is effective in reducing the connection blocking probability and increasing the link utilization in wavelength-routed WDM networks. However, wavelength converters are expensive in the foreseeable future, which means only a limited number of converters can be deployed in a network. In such case, placement algorithms are used to determine the locations of a given number of converters such that the connection blocking probability is minimized. This paper developed a low-complexity analytical model to reflect the impact of the converter locations on the network blocking probability. Based on this model, an algorithm is developed for converter placement. Since an analytical approach is taken, the algorithm has the advantage of high efficiency, allocation of 500 converters in two exiting networks with 14 and 19 nodes takes no more than 1 second using a personal computer. Simulations show that the proposed approach outperforms the best existing algorithm in terms of blocking probability.**

I. Introduction

Wavelength routing together with wavelength division multiplexing (WDM) technology have been considered as a strong candidate for future high performance networks. In such networks, lightpaths spanning multiple physical links can be established dynamically to provide a direct connection between two nodes. Without wavelength conversion, a lightpath must occupy the same wavelength in each link, which is called wavelength continuity constraint. By using wavelength converters (WCs), a lightpath may be switched from on wavelength to another, hence the connection blocking probability is reduced. While the cost of WCs remains to be high in the foreseeable future, converter placement becomes a significant issue, in which the locations of a given number of WCs are carefully designed such that the connection blocking probability is minimized.

The conversion ability of a WDM network is classified into several types (Table I) according to the number of converters and their locations, where we have two assumptions:

- Each converter contains only a single pair of input/output ports;
- The conversion can be made between any wavelength channels (full range conversion).

Full complete conversion offers the lowest blocking probability, however, it requires huge amount of converters and is impractical. Sparse nodal conversion reduces the cost by deploying converters in a small number of *critical* nodes. Within this context, the issue of placement is to find the best subset of nodes and give them unlimited conversion ability, which has been intensively investigated in literature. References [1]–[3] propose to allocate the given convertible nodes one by one; the optimal solution is derived in [4] by formulating the problem as a $0-1$ programming; a heuristic based on [4] is given in [5]; reference [6] proposes to sort the nodes with certain ranks, and choose the convertible nodes sequentially; the optimal placement under uniform and non-uniform load is studied in [7] and the results for ring and bus topologies are presented; an efficient exhaustive search is presented in [8].

Suppose each fiber contains W wavelengths, a node with D fiber connections requires $W \times D$ converters for unlimited conversion ability. This shows sparse nodal conversion still brings considerable cost. Note that in each node

- A large percentage of traversing connections can be established using wavelength-continuous channels;
- Connections starting from or ending at the node do not require conversion.

Thus providing unlimited conversion ability to a node is neither cost-effective nor technologically necessary.

On the other hand, partial conversion is a good compromise between the performance and the cost, where the converters in a node are less than the output channels. Sparse partial conversion is a special case by limiting converters within a small number of nodes. Figure 1 shows two architectures for partial conversion [9][10]. Like existing algorithms, our proposal can be used for both architectures.

Research on the converter placement in networks with partial conversion ability is limited. Given M converters to

TABLE I

Classification of Network Conversion Abilities.

Type	Nodes with Converters	Node Conversion Ability
Full Complete	All	Unlimited [1]
Sparse Nodal	A small number	Unlimited
Sparse Partial	A small number	Limited
Partial	No constraint	Limited

[1] The conversion ability of a node can be *regarded* as unlimited provided each of its output channel contains a converter.

an N-node network, there are totally $\binom{N+M-1}{M}$ different converter distributions, which makes exhaustive search impractical, especially as the scale of the network increases. An intuitive approach is to give more allocations to the high-degree nodes [9], however, it cannot always guarantee a near-optimal result. Reference [11] proposes to first get the the converter utilization distribution using simulation, and then place the converters according to the statistics, which has been shown to be the best available approach [11]. A heuristic algorithm is proposed in [12], which first distributes the converters in a roughly uniform way, and then adjusts the allocation iteratively. However, it does not discuss how to quantitatively evaluate the performance of each adjustment, which dominates the computation complexity. The case of sparse partial conversion is investigated in [13], where the maximum converter utilization of each node is obtained from simulation, and then the converters are deployed among a subset of heavy-load nodes proportionally to the utilization. However, the analysis in [14] shows that sparse partial conversion can hardly perform as good as full complete conversion, especially in the case of light load.

This paper develops an analytical model to reveal the impact of converter distribution on the blocking probability. Based on this model, a low-complexity converter placement algorithm is proposed to provide optimized partial conversion ability to WDM networks. Our algorithm differs from existing ones in that it is analysis-based rather than simulation-based, which reduces both the computation and implementation complexity. Experiments show that our algorithm is highly efficient: placing 500 converters in either NSFNet or EON takes no more than 1 second using a personal computer with Athlon 1 GHz processor. It is also shown that the proposed algorithm outperforms the best existing one in terms of blocking probability.

The rest of this paper is organized as follows: Section II proposes the framework of the converter placement algorithm; Section III describes the analytical model; Section gives some discussions; and Section V presents the simulated performance. Finally, Section VI briefly concludes the paper and addresses the future work.

II. Overview of the Placement Algorithm

Given M converters to a network with N nodes, we propose a multi-cycle heuristic placement algorithm, in which each cycle deploys a single converter based on the network from the previous one, as illustrated in Fig. 2. Within a cycle, the converter is tested for each node in turn, and then the location providing the best performance is selected for the deployment.

Although the framework is brief, the main problem lies in how to evaluate the blocking probability efficiently. Denote the complexity of the evaluation under a given converter distribution with ξ, the total complexity of the algorithm is

$$\xi^* = NM\xi. \tag{1}$$

It is straightforward to estimate the blocking probability using simulation, yet the implementation complexity and execution time result in high ξ. An analytical method is

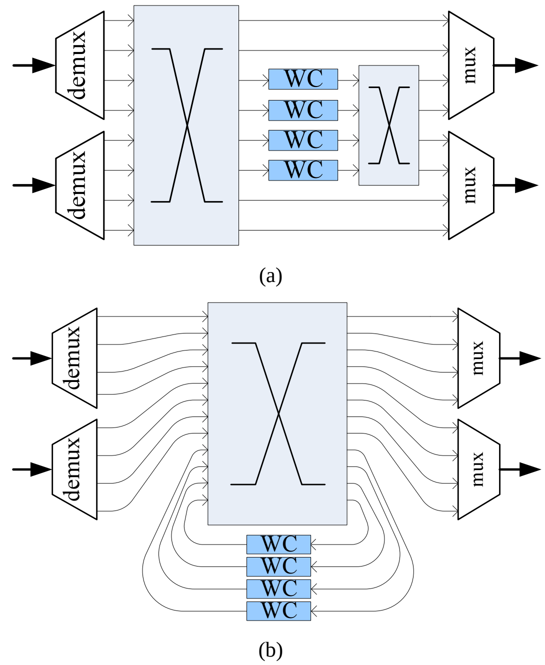


Fig. 1. Node architectures for partial conversion.

proposed in [13], however, it also brings considerable ξ due to iteration. In case of large scale networks with a lot of converters, the above approaches lead to a high complexity ξ^*. Note that network designers usually need to examine multiple cases (e.g., various traffic matrices, different converter numbers, several routing policies, etc.) before deciding the final converter deployment, it is significant to reduce both the implementation and the computation complexity.

Our algorithm takes an analytical approach that yields a closed-form performance metric, thus the implementation is greatly facilitated. Since our objective is to compare between different converter distributions, a performance metric that is able to distinguish a good allocation from a bad one is enough. In another word, the performance metric only needs to reflect the *quality* difference between various converter distribution patterns rather than to *quantitatively* represent the *precise value* of the blocking probability. Following this principle, it is possible to introduce a number of assumptions and simplifications to get a low complexity analytical model for blocking probability evaluation, which is elaborated in the next section.

III. Analytical Model

A. Performance metric

Given an N-node WDM network, all the nodes forms a set $\mathbf{V}$, and all the directed links are contained in a set $\mathbf{E}$. Suppose fixed path routing policy is adopted the lightpath establishment, the predetermined directed routes are indicated with a set $\mathbf{R}$. For each route $r \in \mathbf{R}$, the blocking probability for the connections along r can be divided into two mutual exclusive parts:

1) P^r_{BW}: caused by insufficient wavelength;

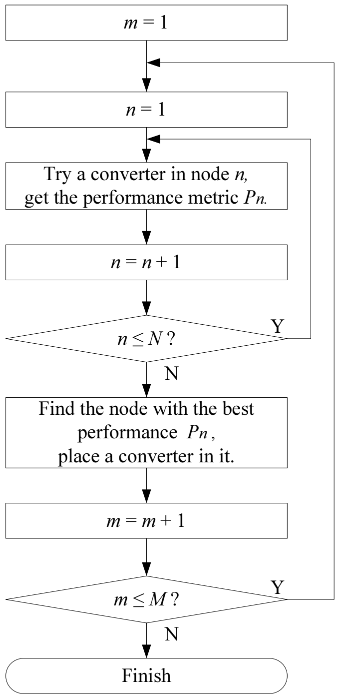


Fig. 2. Heuristic algorithm for converter placement.

2) P_{BC}^r: due to lack of converter,
and the total blocking probability is

$$P_B^r = P_{BW}^r + P_{BC}^r, \quad \forall r \in \mathbf{R}. \tag{2}$$

The overall blocking probability of the network is expressed as

$$\begin{aligned} P_B &= \frac{\sum_{r\in\mathbf{R}} \lambda^r P_B^r}{\sum_{r\in\mathbf{R}} \lambda^r} \\ &= \frac{\sum_{r\in\mathbf{R}} \lambda^r P_{BW}^r}{\sum_{r\in\mathbf{R}} \lambda^r} + \frac{\sum_{r\in\mathbf{R}} \lambda^r P_{BC}^r}{\sum_{r\in\mathbf{R}} \lambda^r}, \end{aligned} \tag{3}$$

where λ^r is the load of route r and the converter-induced blocking probability is denoted with

$$P_B^* = \sum_{r\in\mathbf{R}} \lambda^r P_{BC}^r. \tag{4}$$

Although the blocking probability caused by insufficient wavelength (P_{BW}^r) is not absolutely independent to the converter distribution, our simulations show that the correlation between them is quite small. For simplicity, we assume that they are independent to each other. With this assumption, performance comparison between two converter distribution patterns C_1 and C_2 can be carried out using P_B^* since

$$P_B(C_1) - P_B(C_2) = P_B^*(C_1) - P_B^*(C_2). \tag{5}$$

Although the above assumption is not absolutely accurate, applying it to the performance evaluation in Fig. 2 achieves good performance, which is verified by the experiment results in Section V. At the same time, using P_B^* rather than P_B brings considerable reduction on the complexity since the computation of P_{BW}^r is avoided.

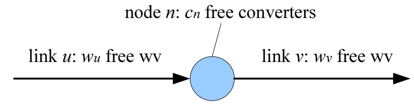


Fig. 3. One node section of a route.

B. Blocking probability of a single route

To calculate (4), the blocking probability of each route P_{BC}^r needs to be obtained. Suppose there are N^r intermediate nodes for route r ($r \in \mathbf{R}$), the route can be expressed as $s^r \to n_1^r \to n_2^r \to \ldots \to n_{N^r}^r \to d^r$, and the directed links are denoted with $l_1^r, l_2^r. \ldots, l_{N^r+1}^r$. Denote the probability of blocking due to lack of converter in node n_i^r with $B_{n_i^r}^r$, we get

$$P_{BC}^r = 1 - \prod_{i=1}^{N^r} (1 - B_{n_i^r}^r) \quad \forall r \in \mathbf{R}. \tag{6}$$

Substitute (6) into (4), we have

$$P_B^* = \sum_{r\in\mathbf{R}} \lambda^r - \sum_{r\in\mathbf{R}} \lambda^r \prod_{i=1}^{N^r} (1 - B_{n_i^r}^r). \tag{7}$$

Next we discuss the calculation of $B_{n_i^r}^r$.

C. Blocking in a single node

Consider a section of a route consisting of input link u, node n and output link v (Fig. 3), the probability that a connection request from u to v gets blocked due to lack of converter in node n is denoted with $B(u \to v : n)$. We have $B_{n_i^r}^r = B(l_i^r \to l_{i+1}^r : n_i^r)$.

With the assumption that the resource occupation in the links and the node is independent, and the request arrivals follow a Poisson process, both the wavelength utilization in each link and the converter usage in each node can be modeled with $M/G/K$ systems with no waiting queue, For the general case, the probability for the system to have j busy servers is expressed as [15]

$$\begin{aligned} p_j &= \frac{\rho^j}{j!} p_0, \qquad j = 1, \ldots, K, \end{aligned} \tag{8}$$

$$\begin{aligned} p_0 &= \left(\sum_{i=0}^{K} \frac{\rho^i}{i!} \right)^{-1}, \end{aligned} \tag{9}$$

where ρ is the load of the system. Then the probability for the system to have k free servers is

$$q(\rho, K, k) = \frac{\rho^{K-k}}{(K-k)! \sum_{i=0}^{K} \frac{\rho^i}{i!}}, \qquad k = 0, \ldots, K. \tag{10}$$

Suppose each fiber contains W wavelengths and there are w_u and w_v free wavelength channels in link u and v, respectively, we denote the number of common free wavelengths between the two links with w_{uv} and the number of free converters in node n with c_n. With the independence assumption, we have

$$\begin{aligned} & B(u \to v : n) \\ = \; & P(w_u > 0, w_v > 0, w_{uv} = 0, c_n = 0) \\ = \; & P(c_n = 0) \sum_{i,j=1}^{W} P(w_{uv} = 0 | w_u = i, w_v = j) \\ & \cdot P(w_u = i) P(w_v = j). \end{aligned} \tag{11}$$

Assume that the free wavelengths are randomly distributed, then

$$P(w_{uv} = 0 | w_u = i, w_v = j) = \begin{cases} \frac{\binom{W-i}{j}}{\binom{W}{j}} & \text{if } i + j \leq W \\ 0 & \text{if } i + j > W \end{cases}. \tag{12}$$

Substitute (12) into (11), we get

$$\begin{aligned} & B(u \to v : n) \\ = & q(\beta_n, C_n, 0) \sum_{i=1}^{W-1} \sum_{j=1}^{W-i} \frac{\binom{W-i}{j}}{\binom{W}{j}} q(\alpha_u, W, i) q(\alpha_v, W, j) \end{aligned} \tag{13}$$

where the calculation of link load α_e ($e \in \mathbf{E}$) and node load β_n ($n \in \mathbf{V}$) is discussed in the next two subsections.

Back to (7), the overall performance metric can be obtained as a closed-form expression

$$P_B^* = \sum_{r \in \mathbf{R}} \lambda^r - \sum_{r \in \mathbf{R}} \lambda^r \prod_{i=1}^{N^r} (1 - B(l_i^r \to l_{i+1}^r : n_i^r)). \tag{14}$$

D. Load of each link

The load of each link can be obtained by summing up all the traversed traffic:

$$\alpha_e = \sum_{r : e \in \text{route } r} \lambda^r, \qquad e \in \mathbf{E}. \tag{15}$$

E. Converter load of each node

The concept of *converter load* indicates the requirement for converters in a given node, which, unlike link load, does not equal to the accumulation of the traversed traffic. Consider the case in Fig. 4(a), the interaction between route a, b and c does not generate wavelength fragment, hence no converter is needed. On the other hand, the coexistence of a and b in Fig. 4(b) may leave only interleaved wavelength channels for route c, thus converters must be employed to connect different wavelengths for the lightpath establishment. The example shows that it is necessary to examine the relationship among different routes to study the requirement for converters in each node.

Denote the ingress and egress links of route r at node n with u_n^r and v_n^r, respectively ($u_n^r = 0$ indicates r has no ingress at n and $v_n^r = 0$ corresponds to no egress), the relationship between two routes traversing the same node is defined as follows.

Definition 1: Given a node n, two routes x and y are said to be *orthogonal* at n if and only if the following two conditions are satisfied:

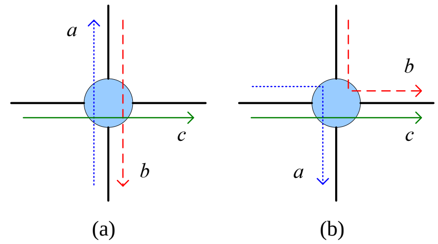


Fig. 4. Orthogonal and correlated routes.

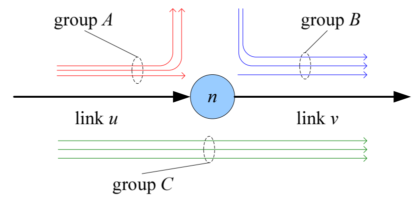


Fig. 5. Classification of correlated routes.

1) $u_n^x \neq u_n^y$ or $u_n^x = u_n^y = 0$;
2) $v_n^x \neq v_n^y$ or $v_n^x = v_n^y = 0$.

Otherwise, they are said to be *correlated*.

Since orthogonal routes do not compete for wavelength channels, the interaction between them does not bring any requirement for converters (like Fig. 4(a)). In contrast, correlated traffic is the main source of converter load. To investigate the demand for converters in a certain node, we only need to consider the correlated routes. Consider ingress link u and egress link v of node n, the correlated routes can be classified into three groups as illustrated in Fig. 5:

1) Group A: all the routes $r_A \in \mathbf{R}$ with $u_n^{r_A} = u$ and $v_n^{r_A} \neq v$, the group load is $\lambda_n^u = \sum_{r_A} \lambda^{r_A}$;
2) Group B: all the routes $r_B \in \mathbf{R}$ with $u_n^{r_B} \neq u$ and $v_n^{r_B} = v$, the group load is $\lambda_n^v = \sum_{r_B} \lambda^{r_B}$;
3) Group C: all the routes $r_C \in \mathbf{R}$ with $u_n^{r_C} = u$ and $v_n^{r_C} = v$, the group load is $\lambda_n^{uv} = \sum_{r_C} \lambda^{r_C}$.

For simplicity, our analysis is based on the assumption that a request belonging to group C does not require any converter provided there is a wavelength-continuous channel from link u to v. Although this is not always consistent with the real case, it is reasonable and the effectiveness is verified by the experiments in section V. With this assumption, the connections in group C requires wavelength conversion if:

1) The occupied channels of group A and B are interleaved in terms of wavelength index; and
2) The available channels in u and v do not fall into the same wavelength.

Since the conversion requirement is tightly related to the load of the three groups, we set the converter load from u to v to be

$$\beta_n^{uv} = \gamma \min(\lambda_n^u, \lambda_n^v, \lambda_n^{uv}), \tag{16}$$

where the factor γ is introduced to adjust the load. In particular, the above definition shows that converters are no longer effective for the reduction of blocking probability once one of the groups has zero load. Suppose $\lambda_n^u = 0$, as long as there is a free wavelength in link v, it must be available in link u. Thus each request from group C will not be blocked unless all the wavelengths in link v are occupied, in this case, every blocking is caused by lack of wavelengths and converters do not make any difference.

From (16), the converter load of each node can be obtained as

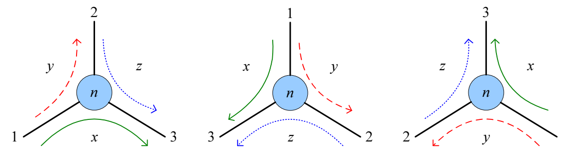
$$\begin{aligned}\beta_n &= \gamma \sum_{u\in\mathbf{E}}\sum_{v\in\mathbf{E}} \beta_n^{uv} \\ &= \gamma \sum_{u\in\mathbf{E}}\sum_{v\in\mathbf{E}} \min(\lambda_n^u, \lambda_n^v, \lambda_n^{uv}), \qquad n \in \mathbf{V}. \quad (17)\end{aligned}$$

Note that a large number of connections from group C can be established using wavelength-continuous channels, the percentage of connections employing converters is relatively small, which is reflected by γ. It has been shown that more than 90% of connections do not use converter [13], our experiments show that an empirical value of $\gamma = \frac{1}{2W}$ results in good performance.

IV. Discussions

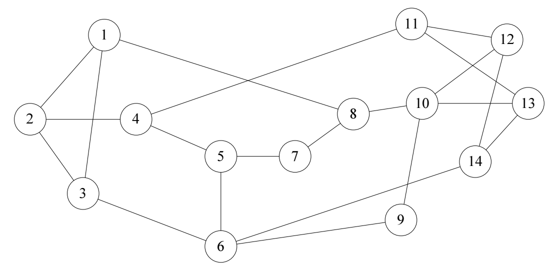
With the formulation of link and node load, the value of (14) can be easily obtained and applied to the algorithm in Section II for a low-complexity implementation. In summary, the algorithm has the following properties:

- Although the analytical model is based on the assumptions of independent Poisson arrival and random wavelength assignment, the algorithm still yields good performance with real traffic and wavelength assignment algorithms (such as first-fit). This is because various policies have similar resource utilization patterns and our model reflects the elemental impacts of converter locations on the network performance. At the same time, the assumptions bring significant reduction of implementation as well as computation complexity.
- The algorithm can be implemented in an *incremental* way. Each time to test a converter on a certain node n, only the affected parts need to be updated—$q(\beta_n, C_n, 0)$, which greatly facilitates the computation of overall performance metric.
- The definition of converter load in (17) has good fairness to nodes with different number of outgoing links. Consider the example in Fig. 6, where node n has three undirected links 1, 2, 3 and bears only three routes x, y and z. In Fig. 6(a), routes x, y and z belong to group A, B and C, respectively (denoted as $(x, y, z) \Rightarrow (A, B, C)$), which leads to a non-zero converter load. When the figure is rotated clockwise for $2\pi/3$ and $4\pi/3$, as in Fig. 6(b) and 6(c), it is easy to see that $(z, x, y) \nRightarrow (A, B, C)$ and $(y, z, x) \nRightarrow (A, B, C)$, which means the two rotated cases do not contribute to the converter load. This shows the group classification is *not rotatable*, and the interaction among a certain group of traffic will be counted only once. Thus the calculation in (17) is fair to nodes with either large or small number of outgoing links.

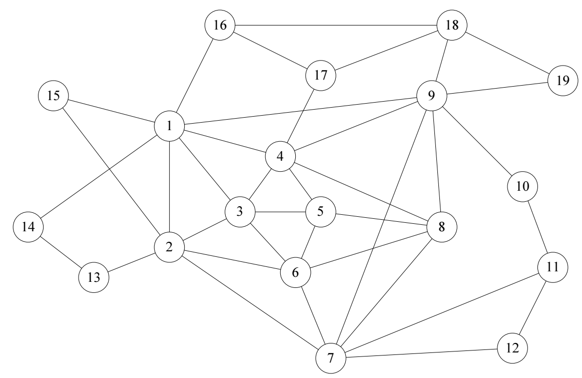


(a) No rotation (b) $2\pi/3$ (c) $4\pi/3$

Fig. 6. Fairness of converter load computation.



(a) NSFNet



(b) EON

Fig. 7. Network topologies.

V. Performance Evaluation

A. Computation Efficiency

Since the proposed algorithm has a closed-form expression and does not require simulated statistics, it has low implementation complexity and the computation is quite efficient. With large number of converters, the efficiency of the proposed algorithm is examined in NSFNet and EON (Fig. 7), respectively. Experiments show that allocation of 500 converters in either topology can be completed within 1 second using a personal computer with an Athlon 1 GHz processor and 512 MB RAM.

B. Results with small number of converters

With a small number of converters, we examine the placement results of the proposed algorithm to get an intuitive evaluation. When the number of the converters is increased from 1 to 8, the computed allocations are listed in Table II.

Intuitively, node 6, 10 in NSFNet and 1, 9 in EON are critical ones with the highest degree and should be the first few nodes to get converters, which is consistent with the computation results. With more converters, some other nodes also get allocation, however, the critical ones are still favored with multiple converters.

TABLE II

CONVERTER DISTRIBUTION.

Converter #	NSFNet	EON
1	6	9
2	6, 10	1, 9
3	6, 8, 10	1, 9, 9
4	5, 6, 8, 10	1, 1, 9, 9
5	5, 6, 8, 10, 14	1, 1, 7, 9, 9
6	5, 6, 6, 8, 10, 14	1, 1, 2, 7, 9, 9
7	4, 5, 6, 6, 8, 10, 14	1, 1, 2, 7, 9, 9, 9
8	4, 5, 6, 6, 8, 10, 13, 14	1, 1, 1, 2, 7, 9, 9, 9

It is worth noting that the results of the two networks have great difference: the converter distribution in NSFNet tends to be *balanced*, while the results in EON is quite *unbalanced*. This is due to the characteristics of the two topologies: NSFNet is similar to a random network where all the nodes have roughly the same significance; while EON is more like a power law network containing a few *critical* nodes with much higher degrees than the others [16].

C. Results with large number of converters

Our heuristic is compared with Xiao's algorithm [11], which, to our knowledge, is the best existing algorithm for converter placement in WDM networks with partial conversion ability. The results with full complete conversion is also presented for comparison.

Given a number of converters, each algorithm is employed to get a converter distribution, and then the blocking probability of the network with each converter distribution is obtained using simulation. For simplicity, we choose fixed shortest path routing and a first-fit based wavelength assignment algorithm. Upon the arrival of a connection request, the first wavelength-continuous channel is adopted; if it is not available, the first channel using the least number of converters is selected; otherwise the request is blocked.

With 8 wavelengths in each fiber, experiments are carried out for NSFNet and EON, respectively, and the results are shown in Fig. 8–11, from which we draw the following conclusions:

1) The proposed algorithm makes effective utilization of converters. In each figure, the blocking probability of partial conversion drops quickly with the converter number increasing from 0 and approaches that of full complete conversion after the number exceeds a certain value.
2) Compared to the simulation-based algorithm, our approach brings more performance improvement. This is because the analytical model of our algorithm reflects the impact of the converter distribution more accurately than simulation-based ones.
3) Our algorithm brings more improvement than its counterpart in case of light load. The reason is the percentage of converter-induced blocking increases with the decrease of network load, which makes the effect of optimized converter placement more significant.

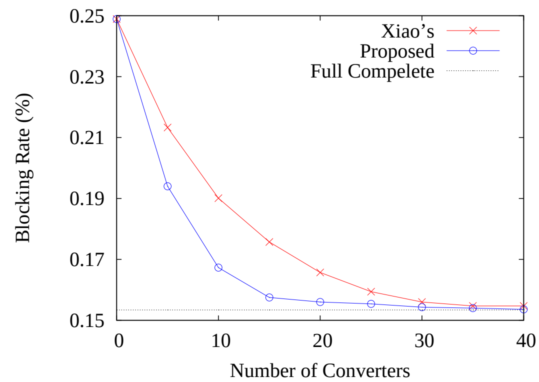


Fig. 8. NSFNet: 40 erlang.

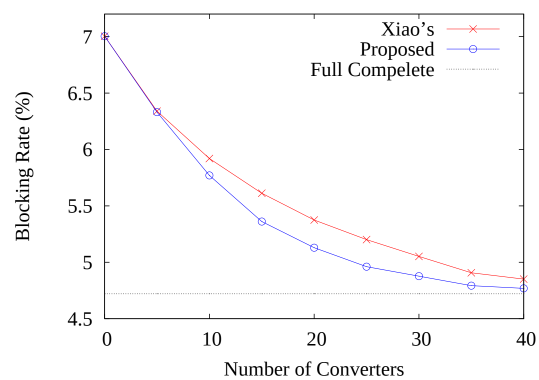


Fig. 9. NSFNet: 80 erlang.

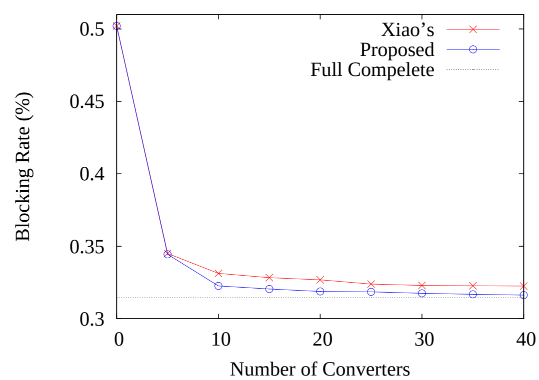


Fig. 10. EON: 50 erlang.

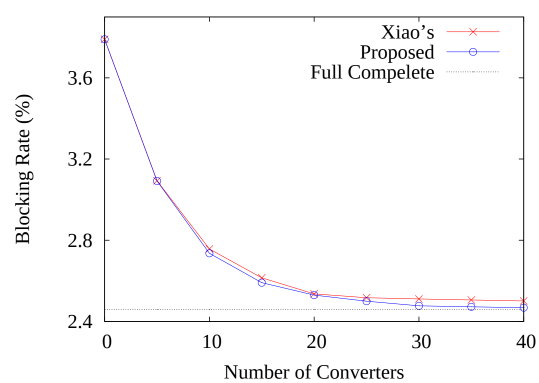


Fig. 11. EON: 80 erlang.

4) Compared to NSFNet, the two algorithms have similar performance in EON, especially with a small number of converters. This is because the difference between node degree in EON is much larger than that in NSFNet—a few nodes have very high degree, which makes it particularly superior to concentrate the given converters at the critical nodes. Thus it is highly possible for the two algorithms to have similar allocations and blocking probabilities, especially with a few converters.

Bearing in mind that the maximum possible improvement from wavelength conversion is a limited value, it is worth pointing out that we do not mean to develop an algorithm to significantly outperform the best existing solution. Rather, the contribution of this paper mainly lies in the analytical model that can be used to construct a placement algorithm with both good performance and high efficiency.

VI. CONCLUSION

This paper proposes a low-complexity algorithm for efficient converter placement in dynamic WDM networks with partial conversion ability. The main contribution of this paper lies in the analytical model developed for performance evaluation of different converter distribution patterns, which gives a closed-form performance metric with low implementation and computation complexity. The proposed algorithm is highly efficient and can be applied to large scale networks with many converters. It can also be used to examine various traffic patterns to find out the necessary number of converters during the stage of network planning. Simulations in NSFNet and EON show that our approach outperforms existing algorithm in terms of blocking probability. Starting from this algorithm, our future work will be focused on networks with other routing policies, such as alternate routing and adaptive routing.

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