Sparse-Partial Wavelength Conversion in Wavelength-Routed All-Optical Networks*

Xiaowen Chu,[1] Bo Li,[2] and Zhensheng Zhang[3]

[1]Department of Computer Science, Hong Kong Baptist University
[2]Department of Computer Science, Hong Kong University of Science and Technology
[3]Microsoft Research Asia, Beijing, China

ABSTRACT

Wavelength conversion has been shown as one of the key techniques that can improve the blocking performance in a wavelength-routed all-optical network. Given that wavelength converters nowadays are still very expensive, how to make effective use of the limited number of wavelength converters becomes an important issue. In this paper, we propose a novel sparse-partial wavelength conversion (SPWC) architecture with the inherent flexibility that can facilitate network carriers to migrate the optical backbone to support wavelength conversion. We demonstrate that this architecture can significantly save the number of wavelength converters while still achieving excellent blocking performance. We further investigate the wavelength converter placement problem. Simulation results indicate that, with appropriate wavelength assignment and wavelength converter placement scheme, the performance of the wavelength-routed all-optical network with only 1-5% of wavelength conversion capability is very close to that of the networks with full-complete wavelength conversion capability.

I. INTRODUCTION

Wavelength-routed all-optical WDM networks are considered to be candidates for the next generation wide-area backbone networks [3]. The physical wavelength-routed network consists of a set of wavelength routers connected by fiber links. Each fiber link can support a number of wavelength channels using dense WDM technology; wavelength routers can switch the optical signal according to its wavelength. Two wavelength routers can communicate with each other by setting up a "lightpath" in between, which is a direct optical connection without any intermediate electronics. In a word, the wavelength-routed WDM network can provide the circuit-switched lightpath service. A sequence of lightpath requests arrives over time and each lightpath has a random holding time. Due to the capacity limitation of the network, some lightpath requests may not be satisfied, resulting in *blocking*. One of the primary design objectives in wavelength-routed optical networks is to minimize this blocking probability.

To establish a lightpath, it is normally required that the same wavelength be allocated on all the fiber links along the path. This limitation is known as the *wavelength continuity constraint*, which makes the wavelength-routed networks different from the traditional circuit-switched telephone networks. Wavelength conversion can eliminate the wavelength continuity constraint and thus improve the blocking performance significantly [7]. Wavelength converter is a device which can convert the optical signal from one wavelength to another. A wavelength router with conversion capability is called a wavelength-convertible router, or WCR. Since the wavelength converters are still very expensive nowadays, different types of WCR architectures have been proposed to save the cost:

Complete wavelength conversion: An example of a WCR with complete wavelength conversion capability is shown in Fig. 1. Each output port of the optical switch is associated with a dedicated wavelength converter. This kind of WCR can convert all the input wavelengths to any other wavelengths simultaneously without any limitation. The number of converters is equal to the number of the output fiber links multiplied by the number of wavelengths per fiber. Since the number of wavelengths could be hundreds or even more, the number of converters inside a WCR will be very large and the cost of such architectures can be prohibitively high.

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Partial wavelength conversion: It has been shown that a WCR with a limited number of converters can achieve very close performance to complete wavelength conversion [1] [8]. The architecture of a WCR with share-per-node partial wavelength conversion is shown in Fig. 2. There is a pool of wavelength converters which are shared by all the output ports. This architecture requires much less number of wavelength converters. But the system is more complicated than the common wavelength router without wavelength conversion because it needs an addition small optical switch (OSW), thus increases the switch complexity. This makes it difficult to add this partial wavelength conversion capability to a wavelength router by simply adding some wavelength converters; also it is non-trivial to determine the number of converters equipped in a WCR.

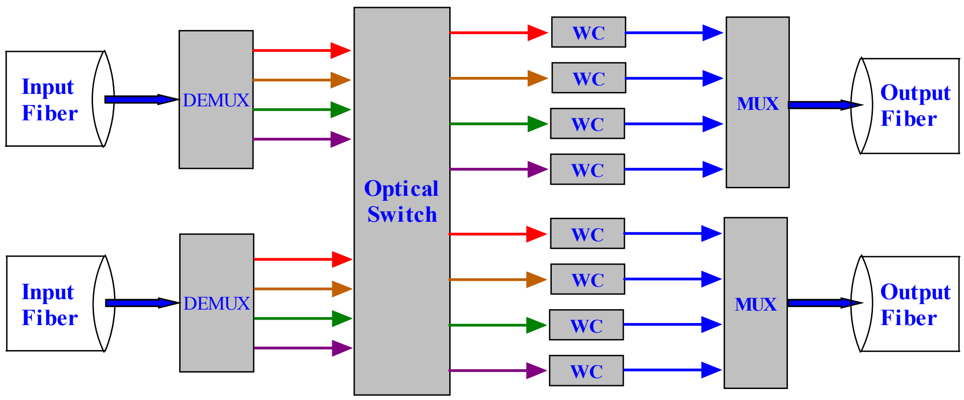


Fig.1. A wavelength router with complete wavelength conversion

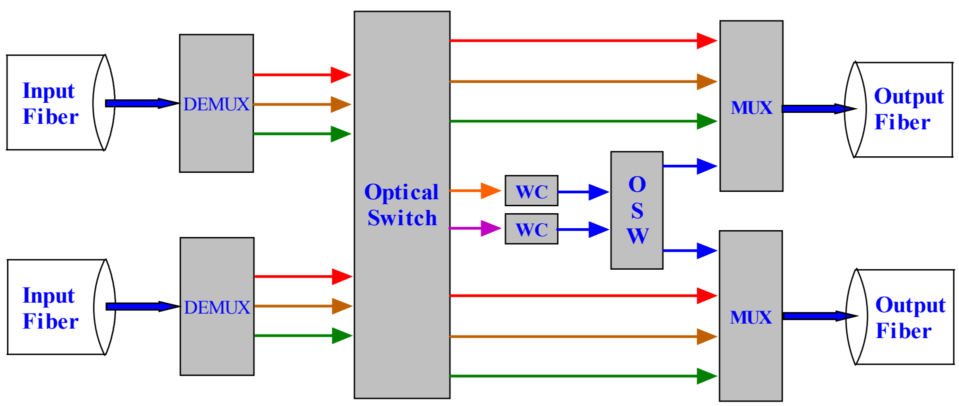


Fig. 2. A wavelength router with partial wavelength conversion

If all the wavelength routers in the network support wavelength conversion (either complete conversion or partial conversion), we call it *full wavelength conversion*. Another effective network architecture, called s*parse wavelength conversion*, has recently attracted lots of attention. In such networks, only selected the wavelength routers is capable of wavelength conversion, while other routers have no conversion capability [10]. Sparse wavelength conversion can save the number of WCRs, while at the same time offers a flexible solution for the network carriers to upgrade their network gradually to support wavelength conversion. Most of the previous studies simply assume that, the WCRs in a sparse wavelength conversion networks all have the capability of complete wavelength conversion, which is very costly and ineffective in practice.

In this paper, we first investigate the partial wavelength conversion that leads to the following observations: First, in order to achieve small blocking probability, over-provisioning is usually done in the backbone network. This implies that only a relatively small portion of the overall capacity is used to carry actual traffic; second, only bypassing lightpaths potentially require wavelength conversion. As long as the number of bypass lightpaths is not large, a limited number of converters will be adequate; third, a careful designed wavelength assignment algorithm can save the number of converters significantly. Most of the lightpaths can be setup successfully without wavelength conversion if we assign the wavelengths appropriately.

We next propose the *sparse-partial wavelength conversion* architecture, which aims to combine the advantages of partial wavelength conversion and sparse wavelength conversion. In such networks, a part of wavelength routers are WCRs with partial wavelength conversion, while other wavelength routers have no wavelength conversion capability. The main advantages of this architecture are: 1) it can significantly reduce the number of wavelength converters needed; 2) it is very flexible for the network carrier to migrate their network to support wavelength conversion, either by adding more converters into the WCRs, or by replacing the old wavelength routers with new WCRs. For comparison, if all the wavelength routers in the network are WCRs with partial wavelength conversion, we call it *full-partial wavelength conversion*.

Wavelength converter placement problem has been widely investigated for sparse wavelength conversion [4] [5] [11] [12]. We redefine the problem for sparse-partial wavelength conversion architecture and propose an effective scheme to solve it. Extensive numerical results demonstrate that only 1-5% number of wavelength converters can achieve comparable performance to that of full-complete wavelength conversion by placing them appropriately.

The rest of the paper is organized as follows. In Section II, we present quantitative analysis on why partial wavelength conversion can usually achieve almost the same performance as complete wavelength conversion. In Section III, we describe the proposed sparse-partial wavelength conversion architecture and investigate the wavelength converter placement problem. Numerical results are presented in section IV. Finally, Section V concludes the paper.

II. PARTIAL WAVELENGTH CONVERSION

In this section, we first show that under a small blocking probability, the total network traffic carried in the network has to remain relatively low. And the number of lightpaths concurrently bypassing a wavelength router is relatively small compared to its theoretical capacity. These are the essential reasons that a small number of wavelength converters is usually enough to achieve the needed blocking performance. A well-designed wavelength assignment algorithm can further reduce the number of wavelength converters required.

A. Network Assumptions

1. The arbitrary mesh WDM network consists of N nodes and J fiber links. The nodes are labelled from 1 to N, and the links are labelled from 1 to J.
2. The nodal degree of node n is denoted by $D(n), 1 \le n \le N$.
3. For simplicity, we consider bi-directional links. Each link can support W wavelengths in both directions.
4. We assume that lightpath connection requests arrive at end-to-end node pair a following a Poisson process with rate A_a. We also assume that the connection holding times are exponentially distributed with a unit time. The total traffic offered to the network is T.
5. For simplicity, we assume the fixed shortest path routing algorithm is used. The route between node pair a is denoted by R_a, and the length of the route in hop-count is $h(R_a)$. We further define that the ith link of route R_a is $R_a(i), 1 \le i \le h(R_a)$.
6. The blocking probability of route R_a is denoted by B_{R_a}.

B. Calculation of Overall Blocking Probability

For network carriers, it is very crucial to predict how much traffic the network can bear under a given blocking probability. Usually the network with full-complete wavelength conversion can achieve the best performance in terms of blocking probability. The main objective of this section is to provide a scheme to find out how much traffic can be allowed to carry in order to guarantee a low blocking probability (let us say no more than 2%). The following analysis provides a simple model to calculate the blocking probability of a wavelength-routed WDM network with full-complete wavelength conversion. In such networks, each node is a WCR with complete wavelength conversion. The number of converters inside node n is denoted by $F(n)$ which is given by $F(n) = D(n)W$.

The overall blocking probability B is defined as the ratio of blocked traffic to the offered traffic. That is,

$$B = \frac{\sum_a A_a B_{R_a}}{\sum_a A_a}. \tag{1}$$

To obtain the steady-state probability of the number of available wavelengths on each link, we use the reduced load approximation method presented in [2]. Let X_j denote the random variable representing for the number of free wavelengths on link j. We assume that the random variables $X_j, j \in \{1, \ldots, J\}$ 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 $M/M/m/m$ (m-server loss) system and the corresponding Markov chain is illustrated in Fig. 3. By solving the Markov chain, we can derive

$$q_j(m_j) = P(X_j = m_j) = \frac{\prod_{i=1}^{m_j}(W - i + 1)}{\alpha_j^{m_j}} P(X_j = 0), \tag{2}$$

and

$$q_j(0) = P(X_j = 0) = \left[1 + \sum_{m_j=1}^{W} \frac{\prod_{i=1}^{m_j}(W - i + 1)}{\alpha_j^{m_j}}\right]^{-1}. \tag{3}$$

Following the approximation made in [6] for the carried traffic on link j, we can determine α_j by the following equation,

$$\alpha_j(1 - q_j(0)) = \sum_{\substack{a,\text{ where link } j \\ \text{belongs to } R_a}} A_a(1 - B_{R_a}). \tag{4}$$

A route can be setup if and only every link on the route has free wavelengths. So we can calculate the blocking probability of a route by the following equation:

$$B_{R_a} = 1 - \prod_{i=1}^{h(R_a)} (1 - q_{R_a(i)}(0)). \tag{5}$$

The above equations lead to a set of fixed-point non-linear equations and they can be solved by the following iterative substitutions:

(1) Initialize B_{R_a} as 0 for all paths. $q_j(0)$ is initialized as 0 for all links.

(2) Determine α_j using Eq. (4) for all links.

(3) Determine $q_j(m_j)$ using Eq. (2) and Eq. (3) for all links.

(4) Determine B_{R_a} for all paths using Eq. (5). If new values of B_{R_a} are converged[†] 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 B using Eq. (1).

We use the above method to calculate the blocking probability for the NSFNET (Fig. 4) topology. We assume that the traffic load is uniformly distributed to all the node pairs. Suppose the average route length is denoted by *L*, we can simply estimate the average wavelength utilization *U* using $U = \frac{T * (1 - B) * L}{W * J}$. According to the shortest path

[†] The convergence here means that the difference between the new value and old value is less than some pre-defined small value.

routing scheme, the average route length L is 2.18. We then get the results of Table 1, given that the overall blocking probability B equals to 2%[‡]. We can observe that the average wavelength utilization is only around 60%.

Table 1 Total traffic that can be carried on NSFNET when B = 2%

Number of Wavelengths: W	40	50	60	70	80	90	100
Total Traffic in Erlangs: T	208	270	333	397	460	525	590
Wavelength Utilization: U	56%	58%	59%	61%	61%	62%	63%

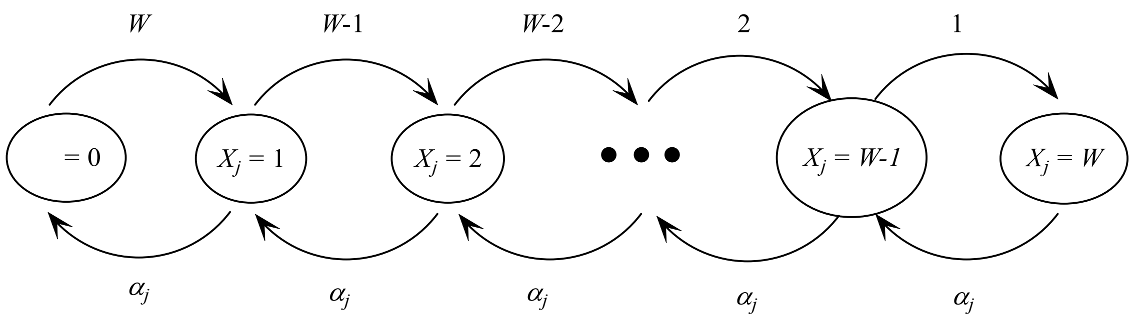


Fig. 3. Markov chain for free wavelength distribution on link j

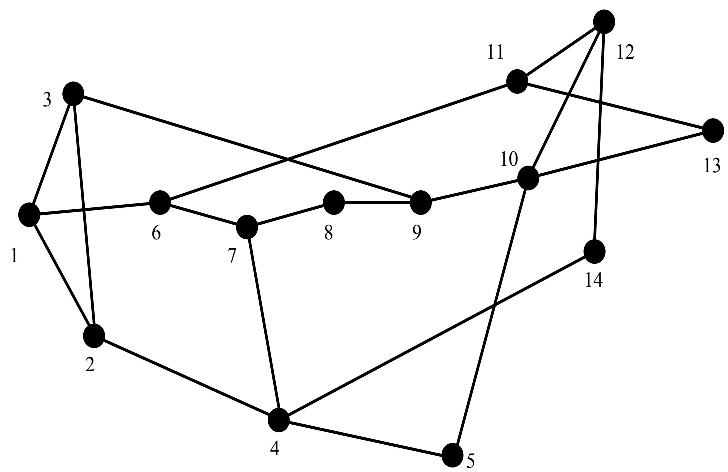


Fig. 4. 14-node NSFNET network

C. *Analysis of Node Bypassing Traffic*

After knowing how much traffic the network can handle, we can further analyze the traffic bypassing each node. A lightpath does not need wavelength conversion at its two end nodes, thus for each node, only the bypassing lightpaths potentially need wavelength conversion. So what we are interested is the number of concurrent lightpaths passing through each node, which excludes the lightpaths that are generated by or terminated at that node. We assume that the bypassing lightpaths arrive at node n following a Poisson process with rate β_n. It is straightforward that

$$\beta_n = \sum_{\substack{a\text{, where route } R_a \\ \text{bypasses node } n}} A_a \quad . \tag{6}$$

Let $p_n(f_n)$ denote the probability that f_n lightpaths are concurrently bypassing node n. So f_n varies from 0 to $F(n)$ because node n can support at most $F(n)$ lightpaths at the same time. According to our assumption, the arrival

[‡] This can be done very quickly by a binary search on the traffic load.

and departure behavior of the bypassing lightpaths on each node also forms an $M/M/m/m$ (m-serve loss) system. By solving the Markov chain, we have

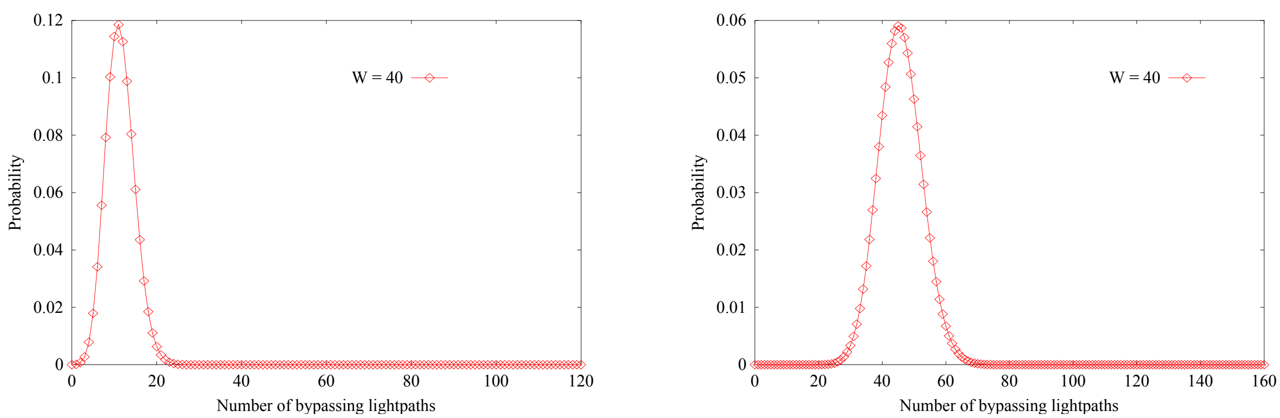
$$p_n(f_n) = \frac{(\beta_n)^{f_n} \frac{1}{f_n!}}{\sum_{i=0}^{F(n)} (\beta_n)^i \frac{1}{i!}}, \quad 0 \le f_n \le F(n) \tag{7}$$

Given that the blocking probability of the $M/M/m/m$ system is very low, the $M/M/m/m$ system can be approximated by an $M/M/\infty$ system. So the average number of bypassing lightpaths is simply β_n because the service time is exponentially distributed with unit time. We still use NSFNET as an example. Assume 40 wavelengths are available, the blocking probability is 2%. From the results of Section (B), the total traffic is 208 Erlangs and each node pair has a traffic of 2.286 Erlangs. So we can get the traffic bypassing each node by Eq. (6):

Table 2 β_n and $F(n)$ of NSFNET when total traffic = 208 Erlangs

Node *n*	*1*	*2*	*3*	*4*		*6*	*7*
β_n	11.4	18.3	11.4	45.7	11.4	27.4	25.1
$F(n)$	120	120	120	160	80	120	120
	8	*9*	*10*	*11*		*13*	*14*
β_n	2.3	18.3	36.6	16.0	18.3	0	4.6
$F(n)$	80	120	160	120	120	80	80

The above results show that, the ratio of $\frac{\beta_n}{F(n)}$ ranges from 0 to 28.6%, and in most cases it is only about 10-15%. We also show the curves of $p_n(f_n)$ in Fig. 5 (a) and Fig. 5(b) for node 1 and node 4 respectively, which give the probability distribution of the number of bypassing lightpaths. We can see that the probability of more than 20 lightpaths are concurrently bypassing node 1 is almost zero. So 20 wavelength converters are absolutely enough to achieve the same performance as complete wavelength conversion, which needs 120 converters. Node 4 has the highest bypassing traffic, and the probability of more than 70 lightpaths are concurrently bypassing node 4 is almost zero, which means that only 70 converters are necessary.



(a) Node 1 (b) Node 4

Fig. 5. Probability distribution of the number of bypassing lightpaths

However, one reason of the small volume of bypassing traffic in NSFNET is that, its average route hop length is only 2.18. For a network with an average route length of *L*, the percentage of bypassing traffic should be approximately

$\frac{L-1}{L+1}$ because in a route with length *L*, the lightpath will pass through *L*+1 nodes and only the intermediate *L*-1 nodes consider the lightpath as a "bypassing" one. That is to say, for each node, about $\frac{2}{L+1}$ of the lightpaths are not bypassing lightpaths. We argue that, for most networks with modest network size and network diameter, the average route length are not expected to be very large; otherwise the efficiency of the network will be very low [2].

To conclude, from the node's perspective, there is considerable percentage of lightpaths that are not "bypassing lightpaths". Since only the bypassing lightpaths require wavelength conversion, the number of wavelength converters equipped in each node can be small.

D. Wavelength Assignment Problem

In the previous section, we conclude that only a limited number of lightpaths can bypass a node concurrently. In this section, we show that for these bypassing lightpaths, most of them do not need wavelength conversion by appropriate wavelength assignment schemes.

We conduct simulations for the NSFNET topology without wavelength conversion. So each lightpath has to use the same wavelength on its entire path. The total network traffic is 208 Erlangs and 1,000,000 lightpath requests are generated. We use the simple First-fit wavelength assignment scheme in our simulation. For each node, we obtain the percentage of the bypassing lightpaths that are established successfully, shown in Table 3. We can see that more than 90% of the bypassing lightpaths can be setup without wavelength conversion by using the simple First-fit wavelength assignment scheme[§]. In another word, no more than 10% of the bypassing lightpaths actually need wavelength conversion. Recall the results of Section II (C) that the number of concurrently bypassing lightpaths on node *n* are much less than the value of $F(n)$, we can therefore conclude that, a very small number of wavelength converters can achieve almost the same performance as complete wavelength conversion. However, the detail number of wavelength converters required to equip in a WCR depends on lots of factors, such as network traffic, nodal degree, the number of wavelengths, and the wavelength assignment scheme.

Table 3 The percentage of the bypassing lightpaths that are setup successfully

Node *n*	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Percentage	96.9%	95.3%	97.8%	93.9%	96.0%	92.9%	92.3%
Node *n*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Percentage	100%	95.0%	95.5%	94.8%	96.0%	100%	97.5%

III. SPARSE-PARTIAL WAVELENGTH CONVERSION

In this section, we propose the sparse-partial wavelength conversion architecture, which aims to combine the advantages of partial wavelength conversion and sparse wavelength conversion.

E. Sparse-Partial Wavelength Conversion

Given that wavelength conversion technology is still not mature, it is not practical for the network carrier to replace all the wavelength routers with WCRs. It has been shown that sparse wavelength conversion can achieve very close performance to full wavelength conversion[**]. Therefore we combine the advantages of partial wavelength conversion and sparse wavelength conversion and propose the sparse-partial wavelength conversion architecture. There are two kinds of nodes in the network: common wavelength routers without wavelength conversion capability, and WCRs with partial wavelength conversion capability. By using sparse conversion and partial conversion together, only a small number of wavelength converters are needed to achieve comparable performance as full-complete wavelength conversion. And it only requires that a small fraction of wavelength routers be replaced with WCRs, which is very flexible for the network carriers to migrate the existing network to support wavelength conversion.

[§] Among the blocked lightpaths, part of them is due to wavelength continuity constraint, another part of them is due to the unavailability of free wavelengths.

[**] The number of required WCRs depends on the network topology, traffic load, etc.

Upon arrival of a lightpath request, if there is any link in the selected route has no free wavelength, we have to block this request. Otherwise, we first try to find a common free wavelength on all the links along the selected path. We have shown in Section II (D) that, most of the lightpath requests can be set up in this way without using any wavelength converters. If there is no common free wavelength, we will check whether wavelength converters can help. A lightpath is divided into several segments by the intermediate WCRs *which currently have free converters*, as shown in Fig. 5. Notice that, a WCR can not provide conversion if its wavelength converters have all been allocated. Each segment still suffers the wavelength continuity constraint because there are no WCRs in a segment (except the two end nodes of the segment). The lightpath can be set up successfully if and only if every segment has common free wavelength(s). So we have to check whether there exist common free wavelengths for each segment individually. Wavelength converters will be allocated if necessary. Once the lightpath is terminated, the allocated converters will also be released.

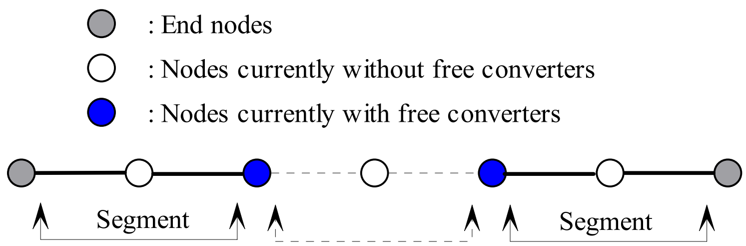


Fig. 5. A lightpath and its segments

F. Wavelength Converter Placement Problem

Traditionally, the wavelength converter placement problem is defined under the assumption of sparse wavelength conversion, which is to determine a set of routing nodes with complete wavelength conversion capability such that the overall network blocking probability can be minimized. In our sparse-partial wavelength conversion architecture, we redefine the wavelength converter placement problem as two sub-problems: (1) how to find a set of nodes which will be placed with a WCR? (2) Given the total number of *M* converters, how to place them in each WCR? In the following, we will propose a simulation-based converter placement scheme. And its performance is evaluated in Section IV.

We first conduct simulations assuming full-complete wavelength conversion. From the simulations, we can observe how many wavelength conversions are conducted in each node. Thus we obtain statistics on the following two parameters for each node n :

1) $A(n)$: the average number of busy converters

2) $P(n)$: the maximum number of busy converters

We still use the 14-node NSFNET topology as an example. We assume each fiber link can support 40 wavelengths. 1,000,000 consecutive lightpath requests are generated. The total network traffic is 200 Erlangs and they are uniformly distributed to all the node pairs. The routing and wavelength assignment algorithm is described as follows:

Upon arrival of a lightpath request:

1) Find the shortest path between the two end nodes of the lightpath request.
2) In the shortest path, if there exists any link that has no free wavelength currently, the lightpath request will be blocked.
3) If there exist common free wavelengths among all the links in the path, choose the one with the smallest label and set up the lightpath;
4) Otherwise, for each link we use the first-fit wavelength assignment scheme, and wavelength converters are utilized in the intermediate nodes if necessary.

The simulation results are shown in Table 4.

Table 4 Conversion Statistics of NSFNET

Node *n*	*1*	*2*	*3*	*4*	*5*	*6*	*7*
A(n)	0.4	0.7	0.3	2.3	0.4	1.8	1.6
P(n)	9	12	9	22	11	19	16

Node n	8	9	10	11	12	13	14
$A(n)$	0	0.7	1.4	0.7	0.6	0	0.1
$P(n)$	0	13	16	12	11	0	6

From the values of $A(n)$ and $P(n)$ in Table 4, we can observe that the utilization of wavelength converters is amazingly low. Generally, a node with higher nodal degree is likely to have more bypassing traffic and more wavelength converters are needed. Although the peak value of concurrently busy wavelength converters is very large, most of the time only a small fraction of converters are busy. To illustrate this, we obtain the probability distribution of the number of busy converters for node 4 and show it in Figure 6. Notice that, we do not plot the probability of no busy converter, which is about 93.5%. Similar behavior can be observed in all the other nodes.

One advantage of the sparse-partial wavelength conversion is its flexibility for the network carriers to install WCRs gradually. From Table 4, we can see that nodes 4, 6, 7, 10 have much more wavelength conversion activities than other nodes. The nodes 2, 9, 11, 12, 1, 5, 3 are less important. Nodes 8, 13, 14 almost do not need wavelength conversion at all. These can provide some good reference for the network carriers to choose where to place the WCRs. As an example, we choose the set $K = \{4,6,7,10\}$ to place the WCRs. In Step 2, we simply assign converters to the nodes in set K proportionally to the value of $A(n)$. For example, if there are 50 converters, the converter placement scheme is shown in Table 5.

Table 5 Proportional Placement Scheme for NSFNET, *M*=50

Node n	4	6	7	10
Number of converters	16	13	11	10

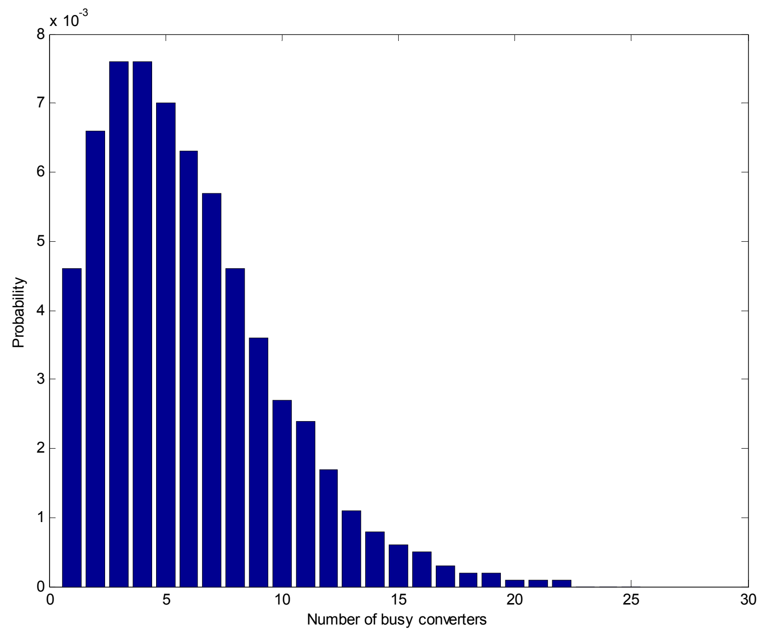


Fig. 6. Distribution of the number of busy wavelength converters at Node 4

IV. PERFORMANCE EVALUATION

In this section, we compare the performance of the following different conversion schemes for NSFNET topology (Fig. 4) and 100-node mesh-torus network topology (Fig. 9): no wavelength conversion, full-partial wavelength conversion, sparse-partial wavelength conversion, and full-complete wavelength conversion. In our simulations, we assume that 40 wavelengths are available on each link. Traffic is uniformly distributed to all node pairs. The lightpath requests arrive according to a Poisson process and the holding time is exponentially distributed with a unit time.

A. Performance evaluation for NSFNET

Fig. 7 shows the blocking probabilities for full-partial wavelength conversion and spars-partial wavelength conversion under different traffic loads. The first observation is that, wavelength conversion can decrease the blocking probability by a large margin. The second result is that, compared to the 1,600 converters used in the full-complete wavelength conversion, only 50 converters can achieve satisfactory performance if full-partial wavelength conversion or sparse-partial wavelength conversion schemes are used.

The performances of full-partial wavelength conversion and sparse-partial wavelength conversion schemes are very close for the case of M = 50. However, it is obvious that the performance of sparse-partial wavelength conversion is bounded by sparse-complete wavelength conversion. If we want to further improve the performance, we have to install more WCRs. To illustrate this, we also conduct simulations for M = 100, and the results are shown in Fig. 8. We find that the performance of sparse-partial wavelength conversion of M = 100 is almost the same as that of M = 50. However, the performance of full-partial wavelength conversion is improved and it is very close to the performance of full-complete wavelength conversion. In fact, if we add more wavelength converters into the WCRs, the performance of full-partial wavelength conversion can be the same as full-complete wavelength conversion.

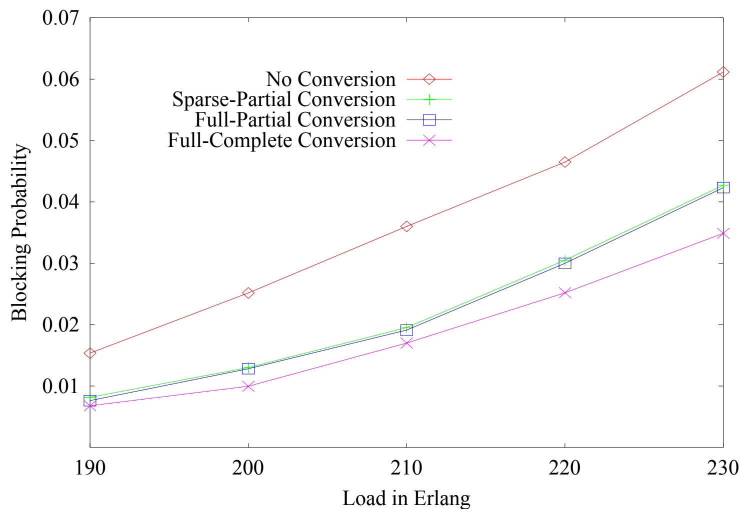


Fig. 7. Blocking Prob. versus Traffic Load in NSFNET, M = 50

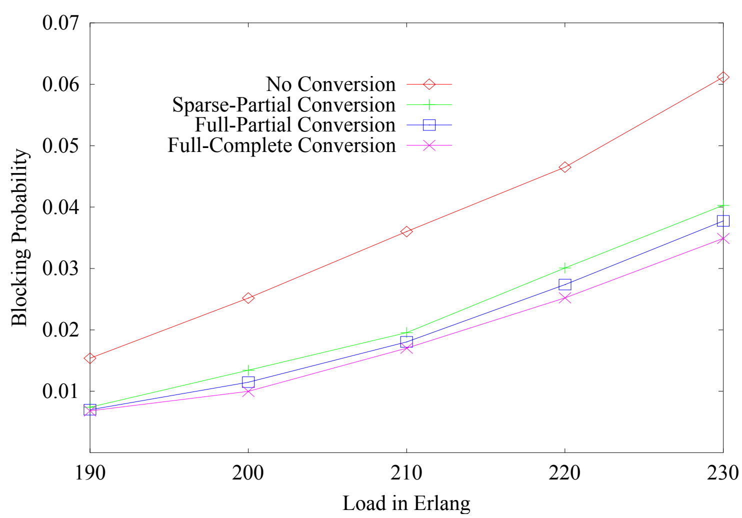


Fig. 8. Blocking Prob. versus Traffic Load in NSFNET, M = 100

B. Performance evaluation for mesh-torus network

In the mesh-torus network topology, full-complete wavelength conversion requires 100 WCRs and 16,000 wavelength converters. We follow the approach in Section III (B) to place wavelength converters in the 100-node mesh-torus network. We first conduct simulations assuming full-complete wavelength conversion and get the conversion statistics. It turns out that each of the nodes 1, 2, …, and 10 has much more wavelength conversion activities than the other 90 nodes. So we decide to use 10 WCRs and place them on nodes 1, 2, …, 10. Assume there are 200 wavelength converters, a straightforward placement scheme is to equip 20 converters for each WCR because of the symmetry of the mesh-torus topology. We then conduct extensive simulations for the four different conversion cases: no conversion, sparse-partial wavelength conversion with 10 WCRs where each WCR has 20 wavelength converters, sparse-complete wavelength conversion with 10 WCRs with complete wavelength conversion, and the full-complete wavelength conversion. Due to the large number of node-pairs, we generate 10,000,000 lightpath requests to make the results more credible.

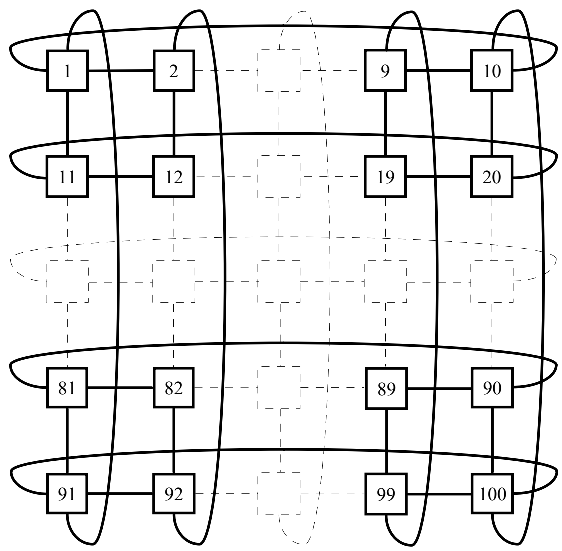


Fig. 9. 100-node Mesh-torus network

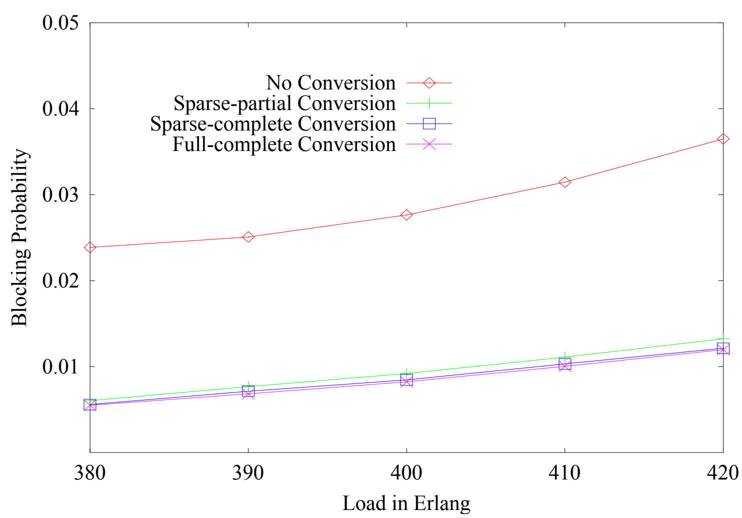


Fig. 10. Blocking Prob. versus Traffic Load in 100-node mesh-torus network, $M = 200$

The simulation results are shown in Fig. 10. We can see that sparse-partial wavelength conversion works very well in mesh-torus topology. First, because of the effect of sparse conversion, 10 WCRs can achieve almost the same performance as 100 WCRs; secondly, because of the effect of partial conversion, only 20 wavelength converters for each

WCR can achieve almost the same performance of 160 wavelength converters. Actually our simulation also shows that, if each of the 10 WCRs are equipped with 40 wavelength converters, the performance of sparse-partial wavelength conversion will be the same as that of sparse-complete wavelength conversion. To conclude, only 200 wavelength converters are required for the 100-node mesh-torus network to achieve very close performance to that of 16,000 wavelength converters.

V. CONCLUSIONS

In this paper, we first present a quantitative analysis why partial wavelength conversion can achieve very close performance to complete wavelength conversion. We then propose the sparse-partial wavelength conversion architecture, which has the flexibility to install the partial WCRs gradually into the network. The number of wavelength converters can be decreased significantly. By using our scheme, 3% of wavelength conversion capability is enough for NSFNET, and 1% of wavelength conversion capability is enough for 100-node mesh-torus network.

In our study, static shortest path routing is assumed. However, other routing algorithms have been shown to perform much better. Different routing algorithms will cause different traffic distribution among the network. Wavelength converter placement and wavelength assignment algorithms for more complicated routing algorithms are waiting for future investigation.

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