On-Line Integrated Routing in Dynamic Multifiber IP/WDM Networks

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***Abstract*—This paper focuses on dynamic integrated routing in multifiber Internet protocol/wavelength-division multiplexing (IP/WDM) networks, which can be implemented through either one-step routing (OSR) or two-step routing (TSR) approach. Based on an extended layered-graph, two resource assignment strategies, termed *channel-level balance* (CLB) and *link-level balance* (LLB), are proposed to balance the traffic in the network at different levels. To further improve the performance, a parameter $\mathcal{K}$ is introduced to make a dynamic tradeoff between the logical-layer links and the optical-layer links. Simulation studies are carried out for various topologies. The results show that LLB is better than CLB in most cases, and LLB combined with OSR has the optimal performance. Also, we find that the routing approach and the resource assignment strategy individually play different roles with different values of r_l that is introduced to indicate the *resource richness* of the network.**

As a multifiber network is functionally equivalent to a single-fiber network with limited wavelength conversion, we investigate the effects of wavelength conversion by studying the multifiber IP/WDM networks. The analysis shows that, when the granularity of each connection request is much smaller than the wavelength granularity, wavelength conversion may increase the request blocking probability in the network.

***Index Terms*—Integrated routing, Internet protocol (IP) layer, Internet protocol/wavelength-division multiplexing (IP/WDM), lightpath, multifiber network, optical layer, wavelength conversion.**

I. Introduction

OVER THE PAST years, the Internet protocol (IP) has become the dominant protocol for new networks, and the amount of IP traffic has been growing exponentially. Meanwhile, dynamically reconfigurable optical networks using wavelength-division multiplexing (WDM) technology have emerged to meet the ever-growing bandwidth demands. IP-based optical WDM networks have, thus, become a major component of the next-generation Internet [1].

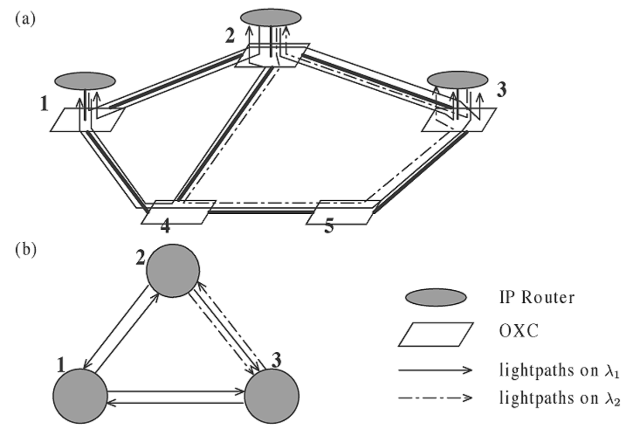

Fig. 1. Sample IP/WDM network. There are two fibers in each link and two wavelengths in each fiber. (a) Physical topology. (b) Logical topology defined by the lightpaths in the optical layer.

In IP/WDM networks, optical cross-connects (OXCs) are interconnected by optical fiber links to construct a wavelength-routed *optical layer*, and IP routers are attached to the OXCs through wavelength ports comprising of optical transceivers. The optical layer provides point-to-point connectivity between the IP routers in the form of coarse-grained *lightpaths*. A lightpath usually spans multiple optical fiber links, on which the data is switched optically by the OXCs. It must use the same wavelength on all the optical fiber links along its path if the OXCs have no *wavelength conversion* capability [2], which is known as *wavelength continuity constraint*. The number of optical fiber links spanned by a lightpath is termed as its *optical hops*. Unlike the OXCs, the IP routers process data streams electronically, and are assumed to support multiprotocol label switching (MPLS [3]). Through transceivers, an IP router switches fine-grained label switched paths (LSP) over the established lightpaths. Once a lightpath is no longer used by any LSPs, it will be torn down and the wavelengths on all the optical fiber links along its path will be released. A sample IP/WDM network is shown in Fig. 1. In this network, three IP routers are attached to the OXCs. As shown in Fig. 1(b), seven lightpaths are established in the optical layer defining a logical IP network.

In this architecture, the IP and optical layers can be combined in either *overlay model* or *peer model*, depending on the relationship of the control planes in the two layers [1], [4], [5]. In the overlay model, management and control of the two layers remain separate. The optical layer concerns with routing lightpaths in the optical layer. The resources used by the optical

Manuscript received January 27, 2003; revised July 8, 2004. This work was supported in part by the Natural Science Foundation of China under Contact 69990540, Contract 90304002, and Contract 60407008

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Digital Object Identifier 10.1109/JSAC.2004.835752

layer include fibers and wavelengths, which are not exposed to the IP layer. The set of lightpaths built up in the optical layer defines a *logical topology*, and the IP layer routes LSPs over the established logical topology. In the peer model, the IP routers in the IP layer act as the peer of the OXCs in the optical layer. The topology perceived by the nodes (the OXCs and the IP routers) is the integrated IP/WDM topology consisting of wavelength utilization of the optical fiber links and bandwidth usage of the lightpaths. The IP routers can compute the complete paths to other IP destinations across the IP/WDM network. In this case, generalized MPLS (GMPLS [6]) can be used to provide a uniform control plane, while label distribution protocols (LDP/CR-LDP) [7], [8] and extensions of the resource reservation protocols (RSVP/RSVP-TE) [9], [10] can be used to set up and tear down the lightpaths, as well as the LSPs. When the LSPs are routed over the integrated topology, RSVP-TE or CR-LDP is automatically triggered to set up the lightpaths if necessary; otherwise, the LSPs are switched over the established lightpaths. The advantage of the peer model is that it allows seamless interconnection of IP and optical networks.

Integrated routing is a routing approach that supports the peer interconnection model [4]. In this case, the network is assumed to run the same instance of an IP routing protocol (e.g., open shortest-path first (OSPF) [11]) with suitable "optical" extensions. This makes the integrated routing more efficient and more robust to changing traffic patterns in the IP layer than a scheme, which uses dynamic routing in the IP layer based only on a static logical topology determined by preassumed traffic distribution [12].

Several resource assignment strategies [12], [13] have been proposed for the integrated routing in IP/WDM networks. Kodialam *et al.* [12] proposed two schemes (MOCA and IMH). MOCA picks a route for the current LSP request so that the residual capacities between the source-destination (s-d) IP router pairs are maximized. In IMH, all the entities (the lightpaths or the optical fiber links) that can accommodate the current LSP request have the same cost. IMH tries to minimize the number of the entities used by each request. Although MOCA performs much better than IMH, it suffers from much higher complexity, because the maximum flow values for all the router pairs have to be computed in order to implement MOCA. In [13], Assi *et al.* compared two route selection strategies: the least loaded routing (LLR) and the most loaded routing (MLR). LLR attempts to evenly distribute the load among the alternative routes between a given s-d router pair, whereas MLR tries to pack the traffic into the most loaded route. However, to find an LSP for each request, multiple alternative routes should be computed before LLR or MLR is implemented, which incurs high computational overhead. In this paper, the layered-graph model in [14] is extended to precisely describe the multifiber IP/WDM networks without any increase in the number of nodes and the associated computation complexity. Based on the extended layered-graph model, two strategies are proposed to balance the traffic in the network. It is shown that the two strategies, having the same complexity as IMH, clearly outperform the latter.

Integrated routing can be carried out by either one-step routing (OSR) approach [12] or two-step routing (TSR) approach [5], [13], [15]. OSR considers the IP layer and the optical layer jointly in the path selection, while TSR considers these two layers separately. A parameter $\mathcal{K}$ is introduced in this paper to optimize the performance of the OSR-based algorithms. Our basic idea is to find a tradeoff between the IP layer and the optical layer via regulating the value of $\mathcal{K}$. OSR or TSR combined with different resource assignment strategies generates different algorithms. The performance studies are carried out for these algorithms for various topologies. We find that the routing approach and the resource assignment strategy have different weighting factors in different network topologies.

All of the previous works address the integrated routing schemes in single-fiber IP/WDM networks. However, multifiber networks are of great interest due to the fact that fiber bundles are typically being widely installed in cables for the purpose of future network growth and fault tolerance [14]. Moreover, the multifiber networks have partial wavelength conversion capacity, thus, providing an attractive alternative to the networks with limited wavelength conversion capability [16], [17]. A network, with n fibers in each link and m wavelengths on each fiber, is functionally equivalent to an nm-wavelength single-fiber network with limited wavelength conversion of degree n [14], [16], [17]. Therefore, we investigate the effects of wavelength conversion by studying multifiber IP/WDM networks.

Previous results [2] show that wavelength conversion can, in general, improve the performance of wavelength-routed optical networks. However, unlike a lightpath request, the bandwidth requirement of an LSP request is usually much smaller than the wavelength granularity in IP/WDM networks. Therefore, the following question arises: can IP/WDM networks benefit from wavelength conversion? We try to answer the question in this paper. Our simulation and analysis show that the effects of wavelength conversion are sensitive to the granularities of the LSP requests. When the granularity of each LSP request is much smaller than the wavelength granularity, wavelength conversion may degrade the blocking performance even though the network traffic is not very heavy.

The rest of this paper is organized as follows. In Section II, we describe the structure of the extended layered-graph. In Section III, we propose two resource assignment strategies, and describe the implementation of our strategies based on the layered-graph. Simulation results and analysis for the multifiber networks are presented in Section IV. Section V concludes this paper.

II. Model for Multifiber IP/WDM Networks

Two types of nodes are included in the IP/WDM networks. The first type contains an OXC. In this paper, it is assumed that the OXC is dynamically reconfigurable but without wavelength conversion capability, and it can only switch optical signals at the wavelength level. The second type is an IP/WDM node. For simplicity, an IP/WDM node [5], [13], [15] is called an IP-OXC in this paper. It consists of two components: an OXC and an electronic IP router. The IP router is attached to the OXC, and the OXC is controlled by the IP router. The functions of the IP router include addressing, routing, topology discovery, provisioning LSPs, multiplexing/demultiplexing LSPs at different granularities to/from lightpaths, management of optical resources (i.e., lightpath establishment and release), and restoration. Moreover, since the IP routers process traffic flows in the electronic layer, it can route traffic flows from any incoming interface to any outgoing interface regardless of the incoming and outgoing wavelengths. According to Fig. 1, for example, there are two OXCs and three IP-OXCs in the network. In this paper, we assume that the number of transceivers is large enough and the IP processing ability is sufficient.

A. Layered-Graph for IP/WDM Network

An IP/WDM network can be s defined by a graph $G(N, E)$, where N denotes the set of nodes and E is the set of bidirectional optical fiber links. For any link $e_{ij} \in E$, there are F optical fibers, each of which contains W wavelengths. The wavelength set in each fiber is the same, i.e., $\{\lambda_1, \lambda_2, \cdots, \lambda_W\}$. Let R be the set of IP-OXCs in G, $R \subseteq N$.

Based on the description of the nodes, we expand a node (IP-OXC and OXC), and then divide it into several function subnodes. An IP-OXC is made up of an *input subnode* (ISN), an *output subnode* (OSN), and W *optical subnodes* (OPSN). An OXC is composed of W OPSNs. An OSN demultiplexes and terminates low-speed flows coming from the lightpaths. An ISN receives low-speed flows from upper layer clients or the OSN, and then multiplex them and send them to the lightpaths. The wth $(1 \leq w \leq W)$ OPSN of the node can only perform the cross-connection for the lightpaths assigned with wavelength λ_w. We use directed arcs from the OPSNs to the OSN to denote the function of demultiplexing, and those from the ISN to the OPSNs to represent the function of multiplexing. The directed arc from the OSN to the ISN stands for the function of IP electronic processing. All these arcs are called *function link*s. The layered-graph for a given network can be, therefore, obtained as follows.

- Expand all the nodes in G according to the equivalence relation. If a node $i \in N$ is an IP-OXC, node i is expanded to an ISN denoted by n_i^I, an OSN denoted by n_i^O, and W OPSNs that are represented by n_i^w $(1 \leq w \leq W)$, respectively. If a node $i \in N$ is an OXC, node i is expanded to W OPSNs. These subnodes can then be connected by function links.
- For all $i, j \in R$ and $i \neq j$, connect n_i^I to n_j^O using a directed arc, which is called *logical-layer link* and denoted by l_{ij}^0. If there are lightpaths from i to j, then l_{ij}^0 carries several channels termed as *logical-layer channels*. The zeroth layer constructed by n_i^Is, n_i^Os, and l_{ij}^0s forms the *logical layer*.
- If there is $e_{ij} \in E$ in G, for all $1 \leq w \leq W$, connect n_i^w to n_j^w using a directed arc called *wavelength-layer link* denoted by l_{ij}^w. Link l_{ij}^w carries F equivalent channels, each of which is termed *wavelength-layer channel*. The wth layer formed by n_i^ws and l_{ij}^ws defines the wth *wavelength layer*.

In the layered-graph, the total number of the nodes is $W|N| + 2|R|$, and the total number of the links is $W|E| + |R|(|R| - 1)$. Clearly, the layered-graph in [14] is *extended* to precisely describe the characteristics of both the IP layer and the optical layer *without* any increase in the number of the nodes.

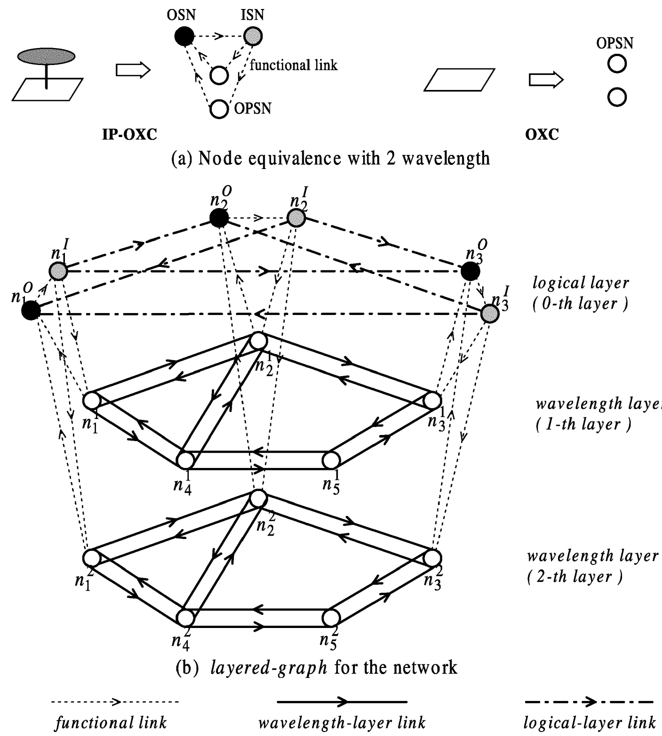

Fig. 2. Layered-graph for the sample network shown in Fig. 1. (a) Equivalence relations of IP-OXC and OXC. (b) Layered-graph for the network. In the layered-graph, the zeroth layer represents the logical layer and the wth layer indicates the wth wavelength layer $(1 \leq w \leq 2)$.

Herein, we illustrate how to construct a layered-graph for the sample network in Fig. 1. In this network, the wavelength set is $\{\lambda_1, \lambda_2\}$ and $F = 2$. The equivalence relations of the nodes are shown in Fig. 2(a), where an OXC is expanded to two OPSNs and an IP-OXC is expanded to an OSN, an ISN and two OPSNs. We then use function links to connect the subnodes. The layered-graph for the network is depicted in Fig. 2(b). Each wavelength-layer link carries two wavelength-layer channels. Different logical-layer links contain different amount of logical-layer channels. For example, l_{23}^0 carries two logical-layer channels, because there are two lightpaths from IP-OXC 2 to IP-OXC 3 in Fig. 1.

B. Notations

We assume that the capacity of a full wavelength is one unit. To facilitate presentation in the following sections, some notations are provided as follows.

For current LSP request.

$\vec{\mathcal{A}}$	Current LSP request.
s_a	Source IP-OXC of $\vec{\mathcal{A}}$.
d_a	Destination IP-OXC of $\vec{\mathcal{A}}$.
b_a	Bandwidth requirement of $\vec{\mathcal{A}}$ and $0 < b_a \leq 1$. In this paper, we assume that $\vec{\mathcal{A}}$ should be routed without traffic splitting.

For the layered-graph.

K_{ij}^0	Number of logical-layer channels in l_{ij}^0.
$l_{ij}^0(k)$	kth $(k \leq K_{ij}^0)$ logical-layer channel in l_{ij}^0.
$b_{ij}^0(k)$	Residual capacity of $l_{ij}^0(k)$, which is less than 1. Note that, $l_{ij}^0(k)$ is *unavailable* for $\vec{\mathcal{A}}$ if $b_{ij}^0(k) < b_a$, since $\vec{\mathcal{A}}$ should be routed without traffic splitting.

f_{ij}^w Number of free wavelength-layer channels in l_{ij}^w. A free wavelength-layer channel must be *available* for $\vec{\mathcal{A}}$. Note that $0 \leq f_{ij}^w \leq F$.

III. Dynamic Integrated Routing Algorithms

In dynamic IP/WDM networks, LSP requests arrive randomly with arbitrary holding time. It is important for a network to accept as many requests as possible without the knowledge of future requests. In this section, we address this issue in the framework of multifiber networks. In Section III-A, two resource assignment strategies are designed for multifiber networks. The link-state information maintained for each strategy is described in Section III-B. Finally, Section III-C discusses how to implement the routing algorithms based on the layered-graph.

A. Resource Assignment Strategies

Most route selection algorithms in networks are based on Dijkstra's algorithm [18], which selects a route with minimal cost out of all possible routes. The assignment of link costs provides a strategy for routing selection. In the layered-graph, there are three kinds of arcs: the function link, the logical-layer link, and the wavelength-layer link. The cost of each function link in the layered-graph is ε ($\varepsilon \rightarrow 0^+$) based on the assumption that the number of the transceivers is large enough and the IP electronic processing ability is sufficient. Therefore, the LSP selection is mainly determined by the cost of the layer links.

As explained in Section II, in the layered-graph of a multifiber IP/WDM network, a link may contain multiple channels. A link usually has multiple possible states such as "all the channels are available," "partial channels are available," and "all the channels are unavailable." The link-state information describes a network traffic distribution. Based on such information, a good resource assignment strategy can optimize the network resource utilization. In this part, we propose two resource assignment strategies: channel-level balance (CLB) and link-level balance (LLB). Our objective is to *balance* the traffic in the network at different levels based on the link-state information.

1) CLB Strategy: In CLB, a channel (wavelength-layer channel or logical-layer channel) with high residual capacity, which is called *wide* channel, is more likely to be used. The cost of a link is determined by the residual capacity of its widest channel as follows.

- Wavelength-Layer Link: Since all the free wavelength-layer channels have the same capacity (i.e., one unit), the wavelength-layer links with free channels have the same cost. For l_{ij}^w, the cost function is defined as

$$C_{ij}^w = \begin{cases} \alpha, & \text{if } f_{ij}^w > 0 \\ \infty, & \text{if } f_{ij}^w = 0 \end{cases} \tag{1}$$

  where α is a constant used to control the weight of a wavelength-layer link.
- Logical-Layer Link: The logical-layer channels typically have different residual capacities. A logical-layer link will have low cost, if the residual capacity of its widest logical-layer channels is high. For l_{ij}^0, the cost function is given as

$$C_{ij}^0 = \begin{cases} \dfrac{\gamma}{\max\limits_{k \leq K_{ij}^0} b_{ij}^0(k)}, & \text{if } \max\limits_{k \leq K_{ij}^0} b_{ij}^0(k) \geq b_a \\ \infty, & \text{if } \max\limits_{k \leq K_{ij}^0} b_{ij}^0(k) < b_a \end{cases} \tag{2}$$

  where γ is a constant used to control the weight of a logical-layer link.

Clearly, when a link is selected to route the request, its widest channel will be chosen to provide the bandwidth, based on the CLB scheme.

2) LLB Strategy: As mentioned in Section II, a link may contain a group of channels connecting two adjacent nodes in the layered-graph. The basic idea of LLB is to balance the traffic at the channel-group level. If the sum of the residual capacities of the available channels in a link is defined as the *carrying capability* of this link, then LLB always prefers the link with the highest carrying capability among the ones that can satisfy the request. Therefore, for $\vec{\mathcal{A}}$, the cost of a link is determined by the sum of the residual capacities of the available channels in the link. The cost associated with the LLB strategy is given as follows.

- Wavelength-Layer Link: The residual capacity of a wavelength-layer channel is 1 or 0, depending on whether this channel is free or occupied. Therefore, for a link l_{ij}^w, the cost function is determined by f_{ij}^w

$$C_{ij}^w = \begin{cases} \dfrac{\alpha}{f_{ij}^w}, & \text{if } 0 < f_{ij}^w \leq F \\ \infty, & \text{if } f_{ij}^w = 0 \end{cases}. \tag{3}$$

- Logical-Layer Link: We define $y_{ij}^0(k)$ as an indicator function. If $l_{ij}^0(k)$ is an available channel, $y_{ij}^0(k) = 1$; otherwise, $y_{ij}^0(k) = 0$. The carrying capability of link l_{ij}^0 can be computed as $\mathcal{B}_{ij}^0 = \sum_k b_{ij}^0(k) \times y_{ij}^0(k)$. Thus, the cost of l_{ij}^0 is

$$C_{ij}^0 = \begin{cases} \dfrac{\gamma}{\mathcal{B}_{ij}^0}, & \text{if } \mathcal{B}_{ij}^0 \geq b_a \\ \infty, & \text{else} \end{cases}. \tag{4}$$

In LLB, if a logical-layer link is chosen to route the LSP request, the first available channel will be selected to provide the service for $\vec{\mathcal{A}}$.

3) Tradeoff Parameter: We introduce a parameter $\mathcal{K} = \gamma/\alpha$ to make a tradeoff between the logical-layer links and wavelength-layer links. The value of $\mathcal{K}$ ranges from 0 to ∞, which impacts the network performance accordingly. If $\mathcal{K} < 1$, the logical-layer links are more likely to be used, otherwise, i.e., $\mathcal{K} > 1$, the wavelength-layer links are more preferred. There are two extreme cases for $\mathcal{K}$: $\mathcal{K} = 0$ and $\mathcal{K} = \infty$. When $\mathcal{K} = 0$, the logical-layer links have the absolute selection priority. When $\mathcal{K} = \infty$, the usage of the logical-layer links is prohibited, and establishing new lightpaths is the only way to route the LSP requests. In this case, the problem of integrated routing in the IP/WDM networks *almost* reduces to the routing and wavelength assignment (RWA) problem [14].

B. Link-State Information and Layered-Graph Update

To realize distributed routing, each IP-OXC should maintain a layered-graph of the network according to its network link-state database (LSD), which is dynamically updated via link-state advertisement (LSA) with suitable extensions [19]. Maintenance (i.e., update) of the layered-graph is realized by cost assignment for each link in the layered-graph. Hence, different resource assignment strategies require different information exchanges.

1) Information Exchange for CLB: In CLB, the link-cost assignment is based on the residual capacity of the widest channel in the link, which should be known by the IP-OXC in order to implement CLB.

- LSA Trigger:
  — the maximal residual capacity of all the lightpaths from $i \in R$ to $j \in R$ is changed;
  — the number of free channels on λ_w from $i \in N$ to $j \in N$ is changed from 0 to 1 or from 1 to 0.
- Exchange Information:
  — the updated maximal residual capacity of all the lightpaths from $i \in R$ to $j \in R$;
  — whether the number of free channels on λ_w from $i \in N$ to $j \in N$ is larger than or equal to 0;
- LSD in each IP-OXC: there are $W|E| + |R|(|R| - 1)$ links in the layered-graph, thus an IP-OXC should keep $W|E| + |R|(|R| - 1)$ maximal values and its database dimension is $O(W|E| + |R|^2)$.

2) Information Exchange for LLB: In LLB, link-cost assignment is based on the sum of the residual capacities of its available channels (i.e., carrying capability). To compute the carrying capability of a link, an IP-OXC has to know exactly the residual capacity of each channel.

- LSA Trigger:
  — a lightpath from $i \in R$ to $j \in R$ is selected to provide the bandwidth or the bandwidth reserved for some LSPs in a lightpath is released;
  — the number of free channels on λ_w from $i \in N$ to $j \in N$ is increased or decreased, i.e., some lightpaths are established or released in the network.
- Exchange Information:
  — index and updated residual capacity of the selected lightpath from $i \in R$ to $j \in R$;
  — the number of free channels on λ_w from $i \in N$ to $j \in N$.
- LSD in each IP-OXC: if there are an average of $\overline{K}$ logical-layer channels in a logical-layer link, then the database dimension is $O(W|E| + \overline{K}|R|^2)$.

Based on the above discussion, it is clear that LLB needs larger link-state information database maintained in each IP-OXC and requires more frequent information exchange between the nodes than CLB.

C. Routing Algorithms

As discussed in Section I, there are two routing approaches in the networks: OSR approach and TSR approach. We explain how to implement them based on the extended layered-graph model.

1) OSR Approach: In this approach, all the links in the layered-graph are considered jointly, and the LSP selection is completed in one step. On arrival of $\vec{\mathcal{A}}$, OSR does the following.

Step 1) Assign costs for all the links.
Step 2) Find a minimal cost path from $n^I_{s_a}$ to $n^O_{d_a}$, using Dijkstra's algorithm.

If a finite cost route cannot be found, the request is blocked; otherwise, the request is accepted and the layered-graph is updated.

CLB- and LLB-based OSR approaches are called CLB-OSR and LLB-OSR algorithms, respectively. To finish Step 1), no more than $O(W|E|)$ time units are needed. Step 2) gives $O(W^2|N|^2)$. The complexity of CLB-OSR (or LLB-OSR) is $O(W^2|N|^2 + W|E|)$.

2) TSR Approach: TSR approach can be classified into logical-first routing (LFR) and optical-first routing (OFR). LFR attempts to establish a connection over the established lightpaths for each LSP request, and if the first step fails it then builds up a new direct lightpath on the optical fiber links. On the contrary, OFR first tries to set up a new direct lightpath over the optical fiber links for each traffic stream, and if the first step fails it then resorts to routing on the established lightpaths.

On arrival of $\vec{\mathcal{A}}$, OFR performs the following.

Step 1) Assign costs for all the links.
Step 2) Create a copy of the layered-graph in which all the logical-layer links and function links from OSNs to ISNs are disabled.
Step 3) Find a minimal cost path from $n^I_{s_a}$ to $n^O_{d_a}$, using Dijkstra's algorithm. If this step fails, go to step (4); otherwise, accept the request, update the original layered-graph, and then stop.
Step 4) Create another copy of the layered-graph in which all the wavelength-layer links are disabled.
Step 5) Run Dijkstra's algorithm again. If this step fails, block the request; otherwise, accept the request, update the original layered-graph, and then stop. In LFR, the sequence is similar except that Step 2) and Step 4) are exchanged.

By combining CLB and LLB with OFR and LFR, we get CLB-OFR, LLB-OFR, CLB-LFR, and LLB-LFR algorithms. To finish Step 1), no more than $O(W|E|)$ time units are needed, while Step 3) requires $O(W^2|N|^2)$ time units. In Step 5), only $2|R|$ subnodes are considered in Dijkstra's algorithm. Therefore, Step 5) yields $O(|R|^2)$ $(R \subseteq N)$. OFR takes two steps to compute the route in case Step 3) fails. The upper bound of OFR's complexity is also $O(W^2|N|^2 + W|E|)$.

OSR is more "*integrated*" than TSR. To route a request, TSR either creates a new lightpath using the wavelength-layer links or considers the logical-layer links. If TSR fails, the request will be dropped. However, OSR can find the route as long as there exists a path that consists of both the wavelength-layer links and the logical-layer links. Additionally, OSR can balance the traffic among all the links and make a tradeoff between the logical-layer links and the wavelength-layer links via the parameter $\mathcal{K}$, while TSR can only balance the traffic among either the wavelength-layer links or the logical-layer links, if both of them use CLB or LLB.

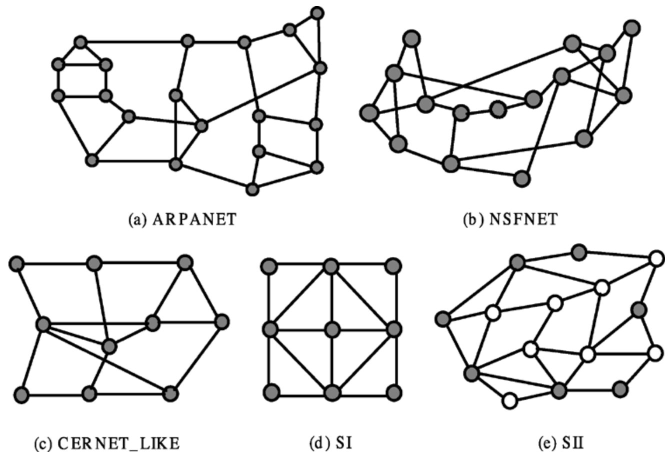

Fig. 3. Sample networks used in the simulations. (a) 20-node ARPANET. (b) 16-node NSFNET. (c) 10-node CERNET_Like. (d) 9-node Sample I. (e) 15-node Sample II. Each node with an open circle in the networks denotes an OXC, and each node with a gray circle denotes an IP-OXC.

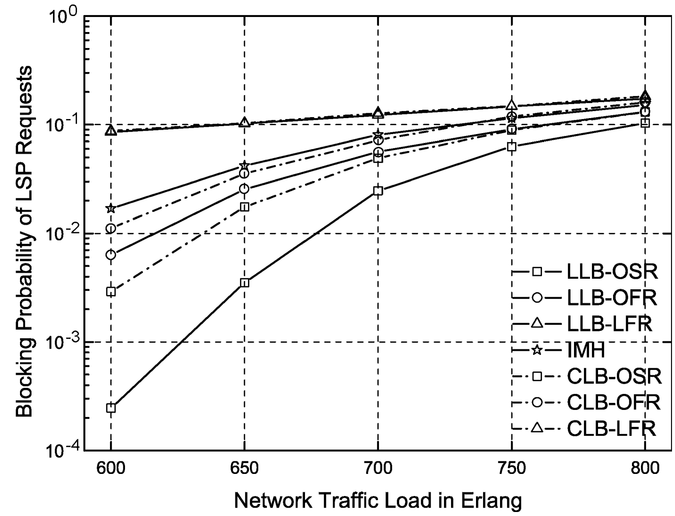

Fig. 4. Blocking probabilities of LSP requests versus network traffic load for the CERNET_Like with $F = W = 4$.

Note that, after a routing algorithm selects a path for $\vec{\mathcal{A}}$, the network takes additional time to provision an LSP. The LSP provisioning time may consist of the lightpath provisioning time and the bandwidth reservation time for the established lightpath. In the IP/WDM networks, the lightpath provisioning time dominates, because the configuration of an OXC could be time consuming due to possible mechanical adjustment. Therefore, the more wavelength-layer links a path spans, the longer LSP provisioning time it incurs.

IV. Simulation Results and Discussions

In this section, numerical simulations are conducted for various topologies. The simulation conditions and the performance metrics are given in Section IV-A. The performances of different algorithms are evaluated in Section IV-B. Since a multifiber network can be functionally equivalent to a single-fiber network with limited wavelength conversion, we investigate the effects of wavelength conversion by studying the multifiber networks in Section IV-C.

A. Simulation Conditions and Performance Metrics

Five network topologies are considered in our simulation. The networks shown in Fig. 3(a)–(c) are ARPANET, NSFNET, and CERNET_Like [20], respectively. We also introduce two sample networks, Sample I (SI) and Sample II (SII), as shown in Fig. 3(d) and (e) , respectively. All of these networks are bidirectional. All the nodes in Fig. 3(a)–(d) are IP-OXCs, while some of the nodes in network Fig. 3(e) (i.e., SII) are IP-OXCs, and the other ones are OXCs. There are seven IP-OXCs and eight OXCs in the SII.

Each IP-OXC can generate or terminate the traffic flows, whose bandwidth requirements are uniformly distributed between 0.2 and 0.4 U. The LSP requests are assumed to arrive at the network according to an independent Poisson process with an arrival rate of β_e. The s-d IP-OXC pairs are selected randomly according to a uniform distribution. The connection holding time is exponentially distributed with a mean value of $1/\mu_e$. The network traffic load is defined as $\rho_e = \beta_e/\mu_e$. In dynamic IP/WDM networks, the lightpaths are established and released randomly. In this paper, we define the traffic load in the optical layer as $\rho_o = \beta_o/\mu_o$, where β_o is the average arrival rate of the lightpath connection requests and μ_o is the average holding time of the lightpaths.

Two types of blocking performance metrics are studied here. The first one is the blocking probability of the LSP requests (BPLR) in the IP layer, which is defined as the number of the blocked LSP requests divided by that of the total LSP requests. The second one is the blocking probability of the lightpaths (BPL) in the optical layer defined as p/q, where q is the total number of the lightpath connection requests that are invoked by the algorithms, and p is the number of the lightpath connection requests rejected by the optical layer. Moreover, we introduce a new parameter herein. Baroni [21] used a parameter $r_p = 2|E|/[|N|(|N|-1)]$ to describe the physical connectivity of a bidirectional optical network. We modify this parameter by introducing

$$r_l = \frac{2|E|}{[|R|\,(|R|-1)]}$$

to characterize the ***resource richness*** of an IP/WDM network. The numerator is the number of the optical fiber links, and the denominator defines the size of the logical topology that is to be built up. Given F and W, large r_l means that the physical resource is relatively rich for constructing a logical topology, and small r_l means that the resource is relatively scarce.

B. Performance Evaluation

Figs. 4 and 5 show the BPLRs versus the network traffic load for the CERNET_Like and ARPANET, respectively. Based on the results, we have several observations as follows.

- The LLB strategy performs better than the CLB strategy for various networks.
- The difference between LLB-OSR and CLB-OSR is much larger than the difference between LLB-OFR and CLB-OFR.
- Employing the same strategy (CLB or LLB), OSR outperforms OFR and LFR.

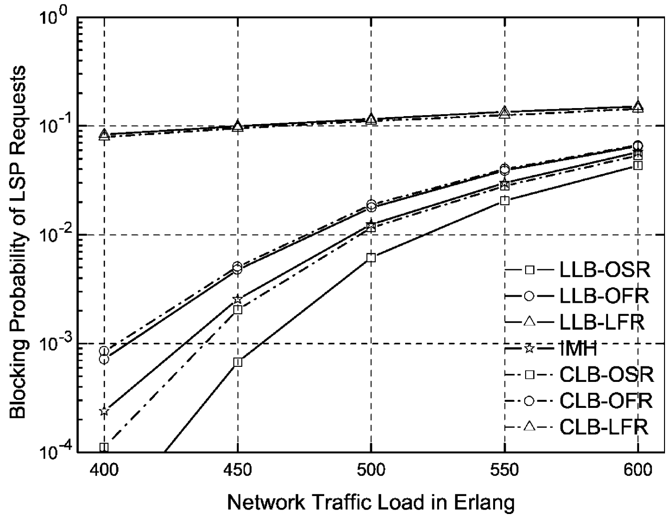

Fig. 5. Blocking probabilities of LSP requests versus network traffic load for the ARPANET with $F = W = 4$.

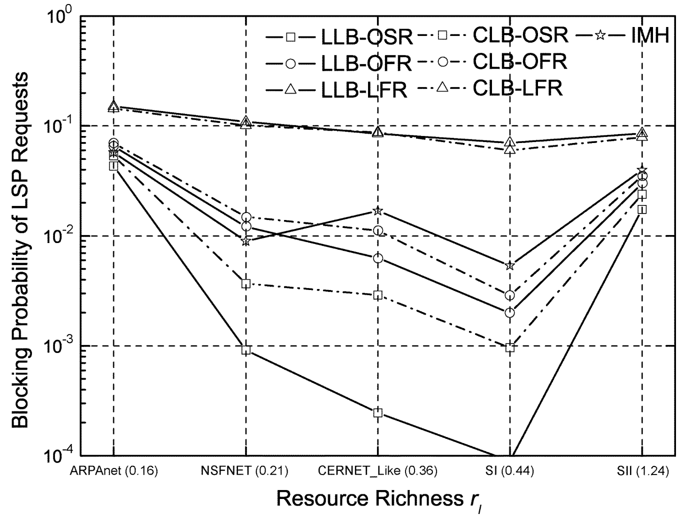

Fig. 6. Blocking probabilities of different algorithms versus network resource richness, fixed $F = W = 4$ and $\rho_e = 600$ Erlang.

The CLB strategy prefers the link with large maximal channel residual capacity, while the LLB strategy always selects the link with high carrying capability. Thus, the CLB strategy tends to result in exhaust of the bandwidth between two adjacent nodes more likely than the LLB strategy, which is the cause for the first observation. However, the LLB strategy requires more link-state information exchange in the network, as we have pointed out in Section III-B. The reason for other observations is that OSR is more "integrated" than OFR and LFR. OSR cannot only set up an LSP by traveling the existing lightpaths and establishing new lightpaths, but also balance the traffic among all the links using the CLB strategy or the LLB strategy, while OFR and LFR are not able to do so.

Also, the performance studies are carried out for different algorithms in various networks with different values of r_l. An interesting scenario is shown in Fig. 6. LLB-OFR and CLB-OFR outperform IMH when r_l is large (such as the CERNET_Like, SI and SII[1]), but IMH has better performance when r_l is small (such as the ARPANET and NSFNET). IMH is an OSR-based algorithm, while LLB-OFR and CLB-OFR are TSR-based algorithms. Thus, IMH is more "integrated" than LLB-OFR and CLB-OFR. On the other hand, LLB-OFR and CLB-OFR can balance the traffic based on their resource assignment strategies, while IMH cannot. We observed that, when r_l is large, the physical resource is rich enough to support a dynamic logical topology with high lightpath connectivity. In this case, the resource assignment strategy plays a key role in an algorithm. When r_l is small, only sparse logical connections can be constructed. In such cases, the routing approach is more important than the resource assignment strategy for an algorithm. Because both the routing approach and the resource assignment strategy of LLB-OSR are optimal, LLB-OSR performs well for all values of r_l.

As mentioned in Section III, the LLB-OSR and CLB-OSR algorithms can make a tradeoff between the logical-layer links and the wavelength-layer links using the parameter $\mathcal{K}$. With ρ_e being 600 Erlang and 650 Erlang, Figs. 7 and 8 show the effect of $\mathcal{K}$ on CLB-OSR and LLB-OSR, respectively, for the CERNET_Like. In Fig. 7, the BPLR decreases with increasing $\mathcal{K}$ and a minimal BPLR is achieved with $\mathcal{K} = 0.9$. When $\mathcal{K} > 0.9$, the BPLR increases slowly. Simulations have been conducted on the ARPANET and the NSFNET as well, and $\mathcal{K} = 0.9$ is also the optimal value for them. In Fig. 8, LLB-OSR has the best blocking performance at $\mathcal{K} = 3$. When $\mathcal{K} > 3$, the BPLR increases slowly. Our results also show that the ARPANET and the NSFNET have different optimal values of $\mathcal{K}$. This indicates that the optimal $\mathcal{K}$ changes with the topology when the LLB strategy is used. Another observation is that the optimal $\mathcal{K}$ can achieve larger performance improvement when the network load is smaller.

Through the simulations, we also note that all the algorithms tend to block the requests with high bandwidth requirements. This scenario is shown in Table I. The request with higher bandwidth requirement has a higher blocking probability. A special strategy is needed to solve this problem, which is beyond the scope of this paper. One should note that LLB-OSR can meet the highest bandwidth requirement (i.e., LLB-OSR has the highest bandwidth throughput). The result in Table I is consistent with the results shown in Figs. 4–6.

C. Effects of Wavelength Conversion

Previous results [2] show that wavelength conversion can in general lower the BPL in the wavelength-routed optical networks, though the benefits of wavelength conversion depend on many factors such as topology, traffic load, routing, wavelength selection strategies, etc. Here, we study the effects of wavelength conversion on BPLR in IP/WDM networks.

We consider two cases.

Case 1) The bandwidth requirement of each request is much smaller than one unit, and a lightpath can accommodate multiple LSPs. An example for this case is that the bandwidth requirements of the LSP requests are distributed between 0.2 and 0.4.

Case 2) Is an extreme case, in which the bandwidth requirement of each request is larger than 0.5, so a lightpath

[1]Note that, even though there are C_{15}^{7} different location distributions for 7 IP-OXCs in the SII, we have similar results for all the cases because the value of r_l is unchanged.

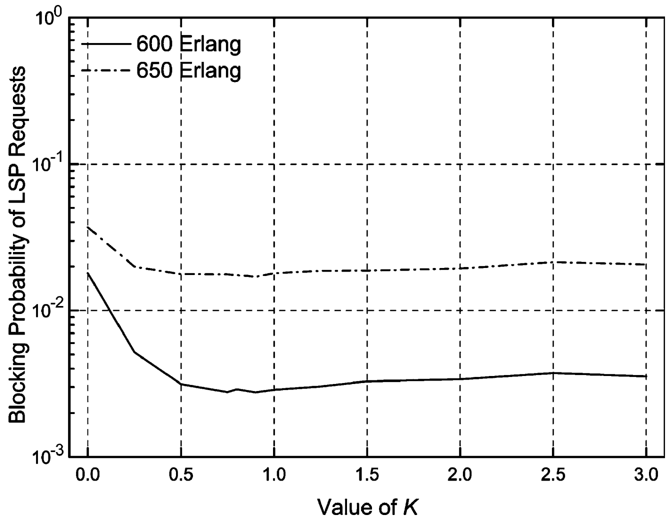

Fig. 7. Blocking probabilities of LSP requests of CLB-OSR versus parameter $\mathcal{K}$ for the CERNET_Like with $F = W = 4$.

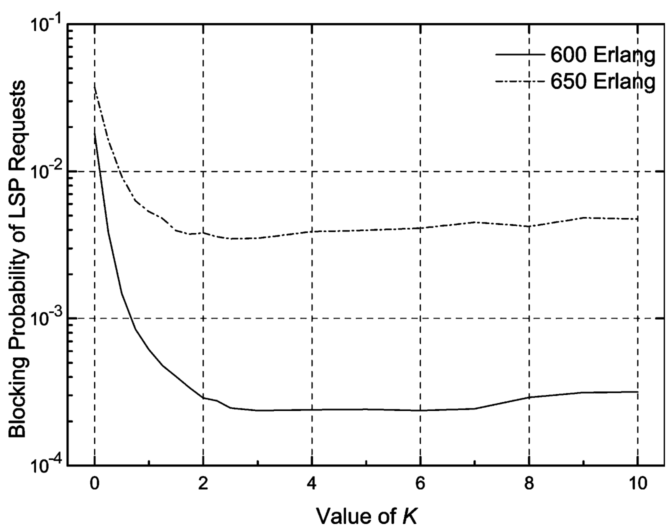

Fig. 8. Blocking probabilities of LSP requests of LLB-OSR versus parameter $\mathcal{K}$ for the CERNET_Like with $F = W = 4$.

can only provide service to one LSP. For example, the bandwidth requirements of LSP requests are distributed between 0.6 and 0.8.

Also, because a network with $F = n$ and $W = m$ is equivalent to an nm-wavelength single-fiber network with limited wavelength conversion of degree n, we investigate the effects of wavelength conversion on IP/WDM networks by studying multifiber networks.

1) Case 1): Figs. 9 and 10 plot the BPLRs of different algorithms for the CERNET_Like and NSFNET in Case 1) with $\rho_e = 650$ Erlang. $F \times W$ is fixed to be 16, and F is varied from 1 to 16. The network with $F = 16$ is equivalent to a 16-wavelength single-fiber network with full wavelength conversion. On the contrary, $F = 1$ means no wavelength conversion. When the value of F is increased from 1 to 16, the BPLRs of all the algorithms increase to different extends. This indicates that wavelength conversion *may* **degrade** the blocking performance even though BPLRs are small (i.e., ρ_e is low), when the bandwidth requirement of each request is low.

TABLE I
BPLRs OF REQUESTS WITH DIFFERENT BANDWIDTH REQUIREMENTS, IN THE NSFNET WITH $\rho_e = 600$ Erlang

	Bandwidth Requirement			Bandwidth
	0.2	0.3	0.4	Throughput
LLB-OSR	0	5.4×10^{-5}	2.9×10^{-3}	99.9%
CLB-OSR	0	1.7×10^{-4}	9.8×10^{-3}	99.6%
IMH	3.6×10^{-5}	2.7×10^{-4}	2.4×10^{-2}	98.9%
LLB-OFR	3×10^{-6}	1.2×10^{-3}	3.6×10^{-2}	98.4%
CLB-OFR	1.2×10^{-5}	2.1×10^{-3}	4.1×10^{-2}	98.1%
LLB-LFR	4.4×10^{-4}	3.8×10^{-2}	0.302	86.9%
CLB-LFR	1.9×10^{-4}	3.1×10^{-2}	0.271	85.3%

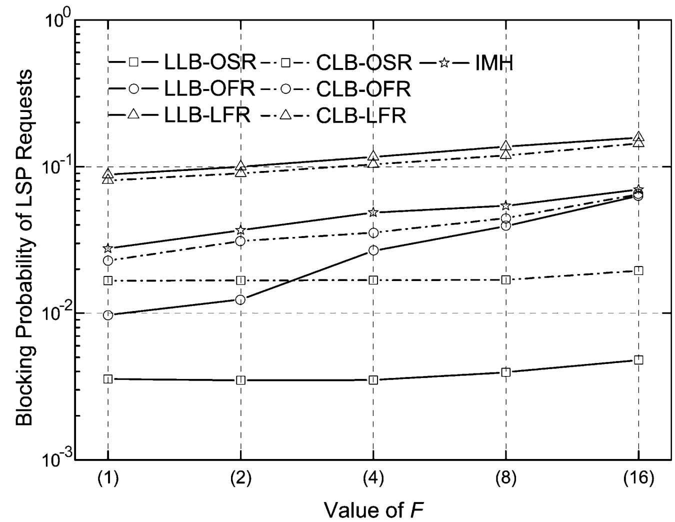

Fig. 9. Blocking probabilities of LSP requests versus the value of F for the CERNET_Like with $\rho_e = 650$ Erlang and $FW = 16$ under Case 1).

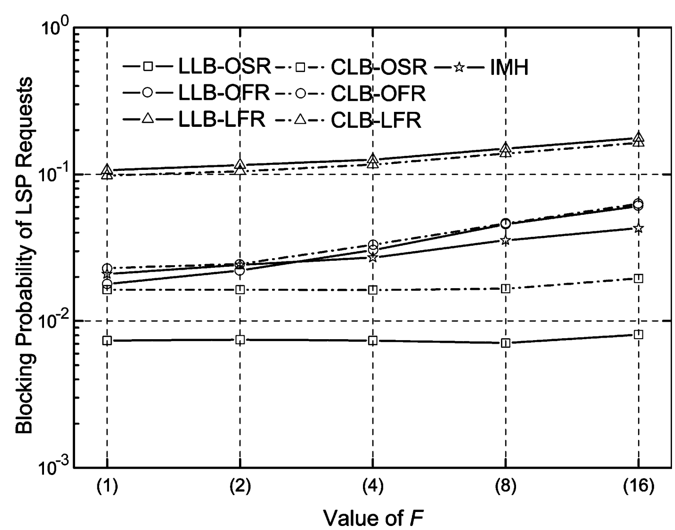

Fig. 10. Blocking probabilities of LSP requests versus the value of F for the NSFNET with $\rho_e = 650$ Erlang and $FW = 16$ under Case 1).

This result can be attributed to the fact that the LSP granularity is very small compared with the wavelength granularity. After a lightpath is established, its residual capacity is still large enough to accommodate many future requests, as long as it is larger than 0.1 and less than 1. Thus, the holding time of a lightpath is much greater than $1/\mu_o$. In other words, once a lightpath is established, it will be a semi-permanent channel compared with the LSP connections. As a result, the traffic load in the optical layer (i.e., ρ_o) is very heavy even though the network traffic load ρ_e is not, i.e., a small ρ_e may incur a large ρ_o. In a heavily loaded optical layer, the wavelength resources are rare. In a wavelength unconvertible (WUC) optical layer, wavelength continuity constraint acts as a protection mechanism that prevents from establishing more lightpaths with long optical hops. However, wavelength conversion tends to establish lightpaths with long optical hops, causing the rejection of *more* subsequent lightpath-connection requests with shorter optical hops. Therefore, when the wavelength resources are rare, the wavelengths can be utilized more efficiently in the WUC optical layer. The WUC optical layer provides more lightpaths than the wavelength convertible (WC) optical layer when ρ_o is very large and no special admission control strategy (e.g., optical hop control) is employed [2]. On the other hand, because the WC optical layer provides less lightpaths to carry ρ_e, the lightpaths created by the WC optical layer have longer average holding time. Thus, the WC optical layer has larger ρ_o than the WUC optical layer, with the same ρ_e offered to the IP/WDM network. All the above mechanisms, consequently contribute to the fact that the WUC optical layer has higher probability to carry the LSPs.

Our analysis can be further proved by the results shown in Figs. 11–13. Figs. 11 and 12 illustrate ρ_o and BPL in the optical layer for the NSFNET, respectively, with $\rho_e = 650$ Erlang. Since it is very difficult to get ρ_os and BPLs for the OSR-based algorithms in the optical layer, we only consider the TSR based algorithms.[2] As shown in Fig. 11, we find that ρ_o is very large and increases with the value of F. For example, ρ_o of CLB-OFR is 5384 Erlang with $F = 1$ and 11 912 Erlang with $F = 16$, even though $\rho_e = 650$ Erlang. In Fig. 12, the BPLs of the algorithms in the optical layer are large $(\mathrm{BPL} > 0.8)$, while the BPLRs of the algorithms are still small in Fig. 10. Also, the BPLs increase with the value of F, indicating that the WUC optical layer provides more lightpaths for the IP layer. The fact that the WUC optical layer is less blocking in the lightpath than the WC optical layer when the optical layer is heavily loaded, can also be proved by the analytical model previously proposed in [22] for the wavelength-routed optical networks. Based on the inclusion-exclusion principle of combinatorics, the model in [22] can be used to obtain fast and accurate estimates of the blocking probabilities for the networks with arbitrary topologies and traffic patterns. Fig. 13 shows the analytical results for a wavelength-routed optical network using the model in [22]. We adopt the topology of NSFNET with $W = 16$ and ρ_o ranging from 0 to 1000 Erlang based on the fixed-routing algorithm, and find that wavelength conversion results in a higher BPL when $\rho_o > 596$ Erlang.

[2]Because both logical-layer links and wavelength-layer links are considered simultaneously in the OSR-based algorithms, it is impossible to know whether new lightpaths should be established before the implementation of the Dijkstra's algorithm. However, in TSR-based algorithms, the logical-layer links and the wavelength-layer links are considered separately, so it is easy to know when the algorithm needs to set up a new lightpath.

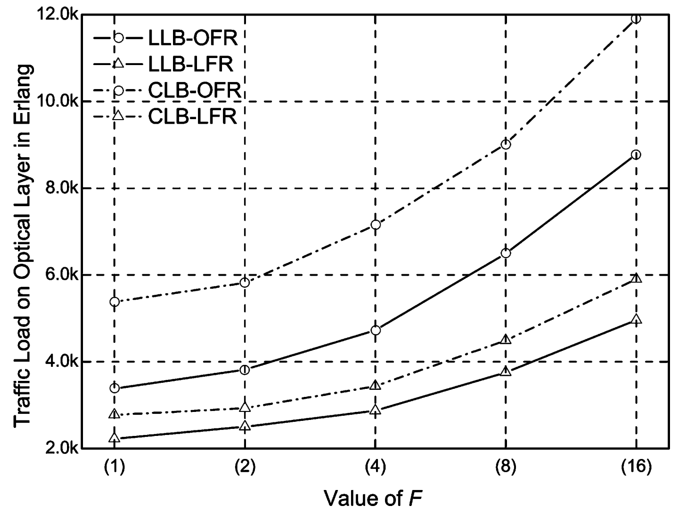

Fig. 11. Traffic load on optical layer versus the value of F for the NSFNET with $\rho_e = 650$ Erlang and $FW = 16$ under Case 1).

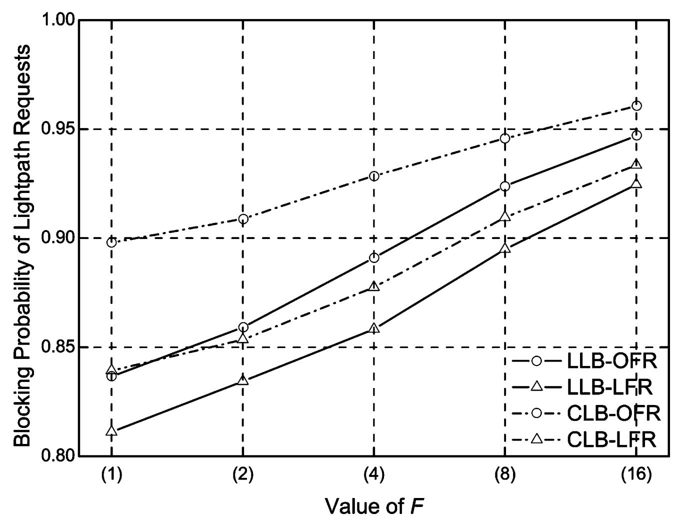

Fig. 12. Blocking probabilities of lightpath requests versus the value of F for the NSFNET with $\rho_e = 650$ Erlang and $FW = 16$ under Case 1).

In summary, our conclusion for Case 1) is as follows. First, a light network traffic load may yield a heavy traffic load in the optical layer, although the LSPs can still be set up on the existing lightpaths. Second, in a heavily loaded optical layer, wavelength conversion could result in higher lightpath blocking probability, as evidenced by a previous numerical study on wavelength-routed optical network [22]. Therefore, an IP/WDM network with wavelength conversion may have a reduced probability to accept LSP requests, even though the network traffic load is low.

2) Case 2): In this case, the bandwidth requirement of each LSP request is greater than 0.5 units. A lightpath can only provide service for one LSP request, and the holding time of a lightpath is equal to $1/\mu_e$. Hence, $\rho_o = \rho_e$.

The TSR-based algorithms are essentially reduced to RWA algorithms. LLB-OFR and LLB-LFR are changed to SPREAD algorithm [14], and CLB-OFR and CLB-LFR are changed to PACK algorithm [14]. Given $\rho_e = 175$ Erlang, the results for this case are shown in Fig. 14. All the TSR-based algorithms

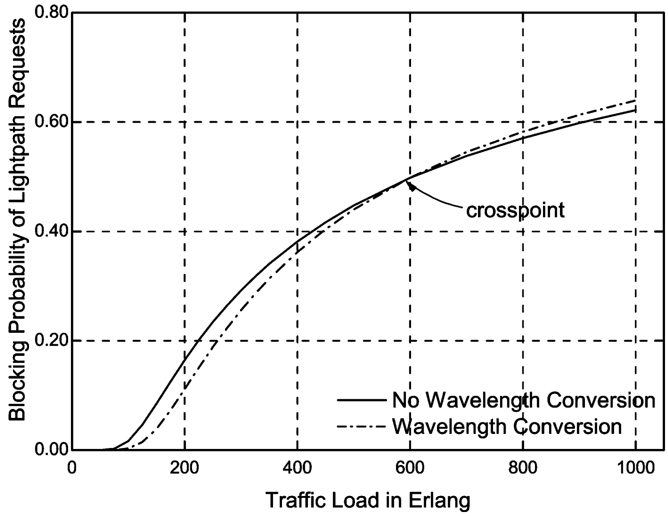

Fig. 13. Blocking probabilities of lightpath requests versus the traffic load for the NSFNET using an analytical model for wavelength-routed optical networks.

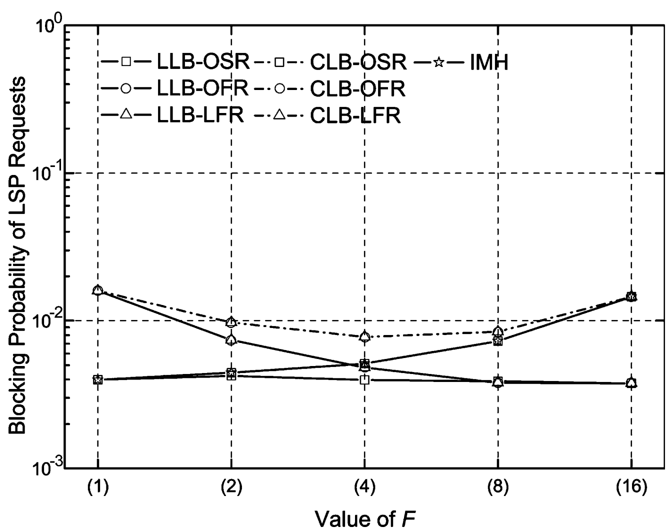

Fig. 14. Blocking probabilities of LSP requests versus the value of F for the CERNET_Like with $FW = 16$ under Case 2).

benefit from wavelength conversion. For example, BPLR of CLB-OFR is 0.015 93 with $F = 1$ and 0.014 55 with $F = 16$.

For all the OSR-based algorithms, IP routers potentially provide wavelength conversion, since they process the traffic electronically. Even though there is no wavelength conversion in the optical layer, the wavelength continuity constraint can be eliminated by the IP routers. Wavelength conversion in the optical layer does not impact the BPLR of LLB-OSR, and LLB-OSR can always balance the traffic along the optical fiber links. IMH herein is completely equal to CLB-OSR, in which the wavelength-layer links have the same cost as long as they have free channels. When $F = 1$, IMH and CLB-OSR are equal to LLB-OSR. When $F = 16$, there is only one wavelength layer in the layered-graph, and IMH and CLB-OSR utilize wavelength resources without difference from CLB-OFR and CLB-LFR. Therefore, the BPLRs of IMH and CLB-OSR increase with F.

V. Conclusion

In this paper, dynamic integrated routing issues in multifiber IP/WDM networks are studied. A layered-graph model is developed to describe the multifiber IP/WDM network. Base on the layered-graph, two resource assignment strategies, CLB and LLB, are proposed for the integrated routing. LLB and CLB balance the traffic in the network at the link level and channel level, respectively. Our analysis shows that LLB requires more link-state information exchange than CLB. These two strategies can be combined with OSR or TSR approach. Simulation results show that LLB can achieve better blocking performance than CLB in most cases, and LLB combined with OSR performs the best in the cases studied. A trade-off parameter $\mathcal{K}$ is introduced to optimize the performance of CLB and LLB combined with the OSR approach. Moreover, we use r_l to define the resource richness of the IP/WDM network, and find that the resource assignment strategy and the routing approach play different roles with various values of r_l.

Finally, we investigate the effects of wavelength conversion by studying the multifiber IP/WDM networks. Our analysis shows that the effects of wavelength conversion are sensitive to the granularities of the LSP requests. When the granularity of each LSP request is much smaller than the wavelength granularity wavelength conversion may degrade the blocking performance in the IP/WDM networks if no special admission control strategies are employed.

Acknowledgment

The authors would like to thank Dr. Y. Xiong and Dr. S. Xu for many useful discussions during the course of the work, and the anonymous reviewers for their invaluable comments.

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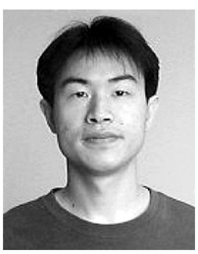

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