Joint Banding-Node Placement and Resource Allocation for Multigranular Elastic Optical Networks

Jingxin Wu, Maotong Xu, Suresh Subramaniam, and Hiroshi Hasegawa

***Abstract*—The fine-grained grid of elastic optical networks (EONs) facilitates flexible bandwidth allocation and increased spectrum utilization efficiency and is seen as a promising solution to handle ever-increasing traffic demands. Despite this, fiber capacity exhaustion is imminent, and multifiber links are expected to be prevalent in future optical networks. A challenge this brings about is the high port count of optical cross-connects (OXCs). Conventional OXCs built using flex-grid wavelength selective switches do not scale well. To achieve scalability of OXCs, a flexible wavebanding OXC architecture (FLEX) has been proposed recently. FLEX reduces the complexity and cost of OXCs while sacrificing some performance in terms of limited switching flexibility. Taking the reduced switching capability into consideration, a cost-function pluggable auxiliary layered-graph framework has been proposed in our previous work to solve the routing, fiber, waveband, and spectrum assignment (RFBSA) problem in multifiber-based EONs with flexible wavebanding nodes. In this paper, we address the following problem. Given the total number of available WSSs for the network as a budget, we determine how many FLEX nodes to deploy and where to deploy them, and solve the RFBSA problem jointly to optimize the network performance. An integer linear programming formulation is proposed for a set of traffic requests. We also propose a heuristic algorithm to solve this joint problem efficiently. The results show that our algorithm achieves good network performance, which is indicated by the average maximum spectrum usage as well as considerably reducing hardware costs. We also evaluate our algorithm for dynamically arriving traffic requests in terms of demand blocking ratio.**

***Index Terms*—Elastic optical networks (EON); Flexible waveband; Integer linear programming (ILP); Placement; Resource allocation; Routing and spectrum assignment.**

I. Introduction

According to [1], global Internet traffic is expected to reach more than 60 Tbps in 2020. To accommodate the dramatic growth of traffic demands resulting from emerging applications such as social networks and livestreams, improving spectrum utilization and increasing the number of fibers on the physical links are two promising strategies. Orthogonal frequency division multiplexing (OFDM)-based elastic optical networks (EONs) are designed to enhance the spectrum utilization efficiency [2]. By introducing a fine-grained grid, EON allows for flexible allocation of fiber bandwidth to better support demand requests. One important problem in EON is the routing and spectrum assignment (RSA) problem, with the objective of finding a path and a number of available frequency slots (FSs) to meet traffic demands and establish lightpaths [3,4]. The three constraints of spectrum contiguity, spectrum continuity, and spectrum nonoverlapping should be satisfied in RSA [5,6]. The spectrum contiguity constraint ensures that a set of consecutive FSs should be allocated to a lightpath. The spectrum continuity constraint ensures that the allocated FSs remain the same for every fiber along the route. The spectrum nonoverlapping constraint ensures that no two lightpaths utilize the same FS in the same fiber. For the static RSA problem, the objective is to minimize the maximum slot usage over all fibers while provisioning all traffic requests [7,8]. For the dynamic RSA problem, the objective is to minimize the blocking ratio and demand blocking ratio of traffic requests [9–11].

Even though increasing the number of fibers per link improves network capacity, it also increases the port count of optical cross-connects (OXCs). This, in turn, means that the port counts of wavelength selective switches (WSSs), which are key building blocks of OXCs, also increase. As large WSSs are difficult to construct, typical port counts of commercial WSSs are limited to 4, 9, or 20. Larger WSSs can be implemented by cascading smaller WSSs, leading to power losses and increased hardware costs [12]. A flexible waveband multigranular OXC architecture (FLEX) that utilizes waveband switching to alleviate the node complexity was proposed in [13]. Waveband switching aggregates multiple lightpaths and switches them as a single band in contrast with switching at the lightpath level. The FLEX architecture admits nonuniform and noncontiguous wavebands, i.e., the waveband sizes (in terms of number of FSs in the band) can be varied, and the FSs in a waveband need not be contiguous. Our previous work [14] presents a joint routing, fiber, waveband, and spectrum assignment (RFBSA) algorithm for EONs with multiple fibers per link and FLEX nodes. It utilizes a cost-function-pluggable

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auxiliary layered-graph framework to allocate resources to traffic demands in such networks.

FLEX introduces a constraint in switching capability as a penalty for the reduced hardware requirement. The switching from an input fiber to output fibers might be limited in FLEX nodes compared with the conventional OXC architecture (CONV). Thus, deploying FLEX at some locations may have an impact on network performance. A judicious compromise is to appropriately deploy both CONV and FLEX nodes in the same network. Reference [15] considers waveband switch placement schemes to maximize waveband switching efficiency in a fixed-grid WDM network. In our previous paper [16], given the number of available WSSs as a budget for network planning, we determine the number and placement of FLEX nodes. Also, we jointly consider the RFBSA and the FLEX node placement to minimize the total maximum spectrum usage (MSU), which is the sum of the maximum slot indexes used over all fibers in the network. An integer linear programming model and heuristics are presented to solve this problem. To the best of our knowledge, this is the first work to consider placement of FLEX nodes and the RFBSA problem jointly. In this paper, we extend the work of [16] on three sides: first, we improve the RFBSA algorithm via decreasing its complexity to make it more practical; second, we update the cost functions for both RFBSA and traffic aware node placement scheme; finally, we evaluate the performance of our joint placement and RFBSA algorithm for dynamic instances and conduct sensitivity tests.

The rest of this paper is organized as follows. Section II summarizes important features of the CONV and FLEX node architectures and presents a comparison of these two types of OXCs. Section III presents an integer linear programming model to get both optimal placements of FLEX nodes and resource allocations for requests, and Section IV proposes heuristic solutions. Section V presents simulation results, and Section VI concludes the paper.

II. Background and Problem Statement

In this section, we first describe the CONV and FLEX architectures in detail and present a comparison between them. Then, we introduce the problem.

Consider an OXC node with a physical node degree of D, which is the number of physical nodes connected to this node. Each connectivity is represented by an input or output link. Each physical link contains several fibers. $N = \sum_{i=1}^{D} x_i$ denotes the total number of input/output fibers to/from the node, where x_i denotes the number of parallel fibers on link i.

A. CONV Architecture

The CONV OXC architecture, which is implemented by cascading a number of WSSs, is shown in Fig. 1. A $1 \times N$ WSS is capable of independently switching a wavelength from the input port to any of its N output ports. In EONs, these WSSs are flex-grid in order to switch

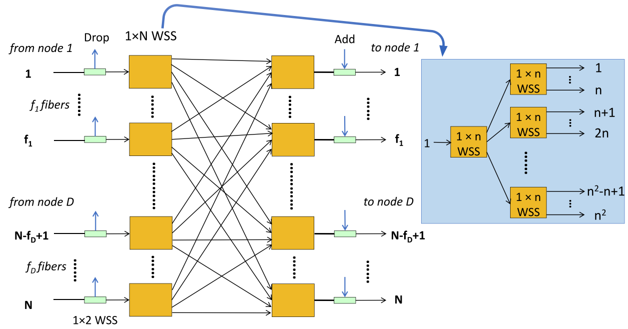

Fig. 1. Conventional node architecture.

frequency slots. Current commercially available flex-grid WSSs typically have a port count limit of 4, 9, or 20, which is not easily scalable. As shown in the inset figure, to implement a large WSS, many smaller WSSs are cascaded [17]. For example, taking 1×4 WSSs as building blocks, approximately $S(N)$ small WSSs are required to build a large $1 \times N$ WSS [18], where:

$$S(N) \approx \frac{N}{4} + \frac{N}{4^2} + \ldots + 1 = \frac{N}{3}\left(1 - (1/4)^{\log_4 N}\right). \quad (1)$$

To implement an $N \times N$ OXC, there will be approximately a square order increment of hardware.

The advantage of this CONV architecture is that there are no switching constraints: any set of FSs on any incoming fiber can be switched to any outgoing fiber of the OXC node at any time.

B. FLEX Waveband Architecture

The FLEX OXC architecture was proposed in [13] to reduce the complexity. As shown in Fig. 2, FLEX is composed of small-port-count $1 \times B$ flex-grid WSSs and B cost-effective matrix switches. FLEX functions by partitioning requests from an input fiber into B groups and switching each group as a whole to one of the output fibers of the node. Note that the flex-grid WSSs are capable of *independently* switching a set of contiguous FSs, which

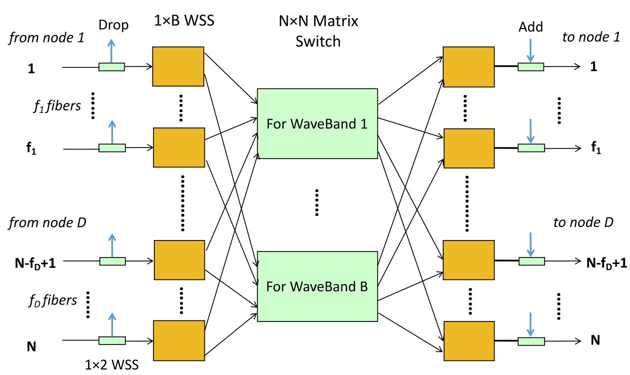

Fig. 2. Flexible waveband node architecture [13].

corresponds to one lightpath to *any* of its output fibers. The size of each set could be different. Therefore, while spectrum contiguity should be met for each lightpath, the sets of lightpaths (different sets of contiguous FSs) that are switched as a band need not occupy a contiguous spectral range in FLEX. This is in contrast with [19], which requires each waveband to be of uniform size and occupy a contiguous spectral range.

Because B is quite small compared with N, the hardware cost can be reduced in terms of fewer number of costly WSSs in this architecture. However, the switching capability is reduced because an entire group of lightpaths needs to be switched as a single entity, and the number of groups that can be switched simultaneously cannot exceed B.

C. Comparison Between Architectures

We compare the two architectures in terms of power consumption and hardware cost. Suppose the port count of the node is N. A CONV node requires $2N$ $1\times N$ WSSs, each of which is constructed with $S(N)$ 1×4 WSSs. A FLEX node consists of $2N$ $1\times B$ WSSs as well as B $N\times N$ cost-effective matrix switches. Each $N\times N$ matrix switch can be constructed with N $1\times N$ MEMS optical switches and N $N\times 1$ optical couplers. We calculate the power consumption and hardware cost of an OXC node by summing up the consumed power and dollar cost of each component. Table I gives a summary of the comparison.

Typically, B equals 4. The power consumption of CONV is higher than that of FLEX with a difference of:

$$8\cdot N\cdot S(N) - 8\cdot N - N^2 = O(N^2). \tag{2}$$

The difference in hardware costs between the two architectures is:

$$8000\cdot N\cdot S(N) - 8000\cdot N - 1800\cdot N^2 = O(N^2). \tag{3}$$

Thus, the power consumption and cost of a FLEX node is $O(N^2)$ better than CONV's. We can see that significant savings can be realized when utilizing the FLEX node architecture.

D. Problem Definition

Due to the switching constraint in the FLEX architecture, deploying FLEX nodes in the network may cause worse performance than utilizing CONV nodes. To achieve cost efficiency and good performance, the deployment of CONV and FLEX nodes should be carefully addressed. Different node placements may need different numbers of WSSs. If a budget in terms of number of available WSSs is given for network planning, we would like to determine how many FLEX nodes should be deployed and where to place them.

Each request can be represented by a source node, a destination node, and a bandwidth requirement in terms of the number of required FSs. A path (including links and fibers) that satisfies routing constraints caused by limited wavebands and a set of contiguous FSs should be assigned to accommodate the request. The node placement will have a direct impact on the resource assignment and performance of the network, as different FLEX node placements will cause different switching constraints. Thus, we should jointly consider the RFBSA and node placement problem.

For a given set of traffic requests and a network planning budget in terms of the number of WSSs of a given fixed port count, our objective is to find the number and locations of FLEX nodes as well as the resource allocation (FSs on fibers) of requests to minimize the total MSU, which is the sum of the maximum slot indices used on all fibers in the network. In the case of dynamically arriving and departing traffic requests, given a planning budget, our objective is to determine node placements and perform resource allocation to minimize the demand blocking ratio for dynamic traffic requests. The demand blocking ratio is defined as the ratio of the sum of bandwidths of blocked requests to the sum of bandwidths of all requests. Because requests can have different bandwidth requirements, we use a demand blocking ratio instead of lightpath blocking ratio as the performance indicator.

TABLE I
POWER CONSUMPTION AND COST OF THE OPTICAL COMPONENTS IN DIFFERENT ARCHITECTURES

Component	WSS (port)	MEMS Switch (port)	Coupler
Power(Watts) [20]	1	0.25	0
Cost(Dollars) [20]	1000	255	195
CONV	$2N\cdot S(N)\cdot 4$	0	0
FLEX	$2N\cdot B$	$B\cdot N\cdot N$	$B\cdot N\cdot N$

III. INTEGER LINEAR PROGRAMMING MODEL

We now present an ILP formulation for the joint problem. The ILP model can be used to solve small problem instances for a set of static connection requests.

A. Notations

The input parameters to the ILP formulation are shown in Table II. Consider a network $\mathcal{G}=(\mathcal{V},\mathcal{L})$, where $\mathcal{V}$ denotes the set of OXC nodes, and $\mathcal{L}$ denotes the set of unidirectional links.

B. Formulations

We use $\mathcal{J}$ to denote a given set of requests. Request $j\in\mathcal{J}$ requires d^j FSs with source node s^j and destination node t^j. The K shortest paths for each request are precomputed. T denotes the network planning target, which is the total number of available WSSs. Our goal is to determine the placement of FLEX nodes and resource allocation for

TABLE II
NOTATION

Symbol	Meaning
G	the network topology
$\mathcal{V}$	the set of OXC nodes
$\mathcal{L}$	the set of unidirectional links
f_l	the number of parallel fibers on link $l \in \mathcal{L}$
M	number of physical nodes in the network
L	number of physical links in the network
F	total number of fibers in the network
B	the band limit of FLEX nodes
T	the budget, the maximum available number of WSSs
K	the number of predetermined paths between each node pair
v	an arbitrary network node
e	an arbitrary network link
f	an arbitrary network fiber
s	an arbitrary slot
p	an arbitrary path ($p_{s,d,r}$ is the rth shortest path from node s to node d)
$P^e_{s,d,r}$	=1 if link e is on path $p_{s,d,r}$; =0, otherwise
ξ^f_e	=1 if fiber f is on link e; =0, otherwise
IN^f_v	=1 if fiber f is an input fiber of node v; =0, otherwise
OUT^f_v	=1 if fiber f is an output fiber of node v; =0, otherwise
ζ_v	the number of WSSs needed if node v is CONV
Γ_v	the number of WSSs needed if node v is FLEX
Ω	estimated upper bound of maximum slot usage
$\mathcal{J}$	a given set of requests
J	number of requests
j	an arbitrary request
s^j	source node of request j, $s^j \in \mathcal{V}$
t^j	destination node of request j, $t^j \in \mathcal{V}$
d^j	the required number of slots for request j

requests. The MSU for a fiber is defined as the highest slot index utilized to accommodate demands on that fiber.

Variables:

a)

$$\alpha^j_s = \begin{cases} 1, & \text{if starting slot of request } j \text{ is } s; \\ 0, & \text{otherwise} \end{cases},$$

b)

$$z^j_s = \begin{cases} 1, & \text{if request } j \text{ uses slot } s; \\ 0, & \text{otherwise} \end{cases},$$

c)

$$y^j_f = \begin{cases} 1, & \text{if fiber } f \text{ is allocated to accommodate request } j; \\ 0, & \text{otherwise} \end{cases},$$

d)

$$x^j_{f,s} = \begin{cases} 1, & \text{if slot } s \text{ on fiber } f \text{ is allocated to request } j; \\ 0, & \text{otherwise} \end{cases},$$

e)

$$w^{j,v}_{f_a,f_b} = \begin{cases} 1, & \text{if there is a switching from fiber } f_a \text{ to} \\ & \text{fiber } f_b \text{ at node } v \text{ caused by request } j; \\ 0, & \text{otherwise} \end{cases},$$

f)

$$W^v_{f_a,f_b} = \begin{cases} 1, & \text{if there is a switching from fiber } f_a \\ & \text{to fiber } f_b \text{ at node } v; \\ 0, & \text{otherwise} \end{cases},$$

g)

$$C_v = \begin{cases} 1, & \text{if node } v \text{ is chosen to use CONV architecture;} \\ 0, & \text{if node } v \text{ is chosen to use FLEX architecture} \end{cases},$$

h)

$$\lambda^j_r = \begin{cases} 1, & \text{if request } j \text{ uses path } r \text{ of the } K \text{ shortest paths;} \\ 0, & \text{otherwise} \end{cases}.$$

Our objective is to minimize the average MSU or, equivalently, the total MSU over all fibers, as the number of fibers for a single network is constant:

$$\text{Minimize} \sum_{f=1}^{F} \max_s \left(s \cdot \sum_{j=1}^{J} x^j_{f,s} \right).$$

Here, $(s \cdot \sum_{j=1}^{J} x^j_{f,s})$ denotes the index of a slot that is used by some request on fiber f.

Constraints:

a) There is only one starting slot index for each request. For all j,

$$\sum_{s=1}^{\Omega-d^j+1} \alpha^j_s = 1, \qquad \sum_{s=\Omega-d^j}^{\Omega} \alpha^j_s = 0.$$

b) The spectrum contiguity should be met for each request. The slots assigned to accommodate a request must use consecutive slots from its starting slot. For all j, s,

$$\sum_{i=0}^{d^j-1} z^j_{s+i} \geq d^j \cdot \alpha^j_s, \qquad \sum_{s=1}^{\Omega} z^j_s = d^j.$$

c) Only one of the K precomputed shortest paths should be chosen for a request. For all j,

$$\sum_{r=1}^{K} \lambda^j_r = 1.$$

d) Only one fiber on each link along the chosen path is selected to route each request. For all j, e,

$$\sum_{f=1}^{F} \xi^f_e \cdot y^j_f = \sum_{r=1}^{K} P^e_{s,d,r} \cdot \lambda^j_r.$$

e) The value of $x^j_{f,s}$ should be based on both y^j_f and z^j_s. Slot s on fiber f is used by request j if and only if slot s is assigned to j, and fiber f is allocated on the path. For all j, f, s,

$$y_f^j + z_s^j \le 1 + x_{f,s}^j, \qquad y_f^j + z_s^j \ge 2x_{f,s}^j.$$

f) Any slot on any fiber can accommodate at most one request. For all f, s,

$$\sum_{j=1}^{J} x_{f,s}^j \le 1.$$

g) The value of $w_{f_a,f_b}^{j,v}$ is based on the value of $y_{f_a}^j$ and $y_{f_b}^j$. For any two fibers f_a and f_b, there is a switching between them to route request j if f_a is an input fiber and f_b is an output fiber of a node, and both f_a and f_b are allocated to the request. For all j, v, f_a, f_b,

$$y_{f_a}^j \cdot \mathrm{IN}_v^{f_a} + y_{f_b}^j \cdot \mathrm{OUT}_v^{f_b} \le 1 + w_{f_a,f_b}^{j,v},$$
$$y_{f_a}^j \cdot \mathrm{IN}_v^{f_a} + y_{f_b}^j \cdot \mathrm{OUT}_v^{f_b} \ge 2w_{f_a,f_b}^{j,v}.$$

h) There is a waveband from fiber f_a to fiber f_b if at least one request is routed by this switching. For all v, f_a, f_b,

$$\sum_{j=1}^{J} w_{f_a,f_b}^{j,v} \ge W_{f_a,f_b}^v, \qquad \sum_{j=1}^{J} w_{f_a,f_b}^{j,v} \le J \cdot W_{f_a,f_b}^v.$$

i) The total required number of WSSs for the whole network should be no larger than the given budget:

$$\sum_{v=1}^{M} C_v \zeta_v + (1 - C_v)\Gamma_v \le T.$$

j) The routing capacity limit should be satisfied for each input fiber on any FLEX node. Here, Λ is a large value to loosen the constraint for CONV nodes. For all v, f_a,

$$\sum_{f_b=1}^{F} W_{f_a,f_b}^v \le B + \Lambda C_v.$$

IV. Heuristic Solutions

Our proposed heuristics to solve the problem are presented in detail in this section. We first describe our framework to solve the RFBSA problem for static instances. Then, we propose the node placement scheme, which is based on both topology information and results of RFBSA. Finally, we apply the proposed schemes to accommodate dynamic traffic requests.

A. Route, Fiber, Band, and Slot Assignment Framework

For a given set of requests, we first sort them based on the bandwidth requirements in nonincreasing order. The requests are stored in an ordered list $\mathcal{J}$. We consider resource assignments in order from the list, i.e., starting with the request having the highest bandwidth demand.

We start by describing the auxiliary layered-graph framework for solving the assignment problem and refer the reader to [14] for more details. The vertexes in an auxiliary graph represent all input and output fibers (denoted by I vertices and O vertices). The edges between vertexes are classified into two types. The first type of edge is from an I vertex to an O vertex, representing the switching inside a corresponding physical node. Because there is a band limit on FLEX nodes in the network, we define a switching cost between each input fiber and each output fiber on a physical node. The costs of this type of edge are related to the wavebanding status of the node. The other type of edge from an O vertex to an I vertex represent the physical link connection. The costs of such edges are related to the spectrum usage on the particular fiber.

In the following, we briefly describe the algorithm for route, fiber, band, and slot assignment. The pseudocode is shown in Algorithm 1. We modify the algorithm in our previous work [14,16] to reduce the time complexity.

For each request j, we examine the K shortest paths. For each path k, we generate a basic auxiliary graph AG^k based on the links and fibers on this particular path. The algorithm switching cost update is used to update the costs of the first type of edges in AG^k.

The switching cost function is shown in Eq. (4). We denote $C_{v,f_{\mathrm{in}},f_{\mathrm{out}}}$ as the switching cost or cost of the edge from vertex f_{in} to vertex f_{out} in the physical FLEX node v:

$$C_{v,f_{\mathrm{in}},f_{\mathrm{out}}} = \begin{cases} 0, & \text{if waveband is established} \\ \alpha \cdot \frac{b}{B}, & \text{if } b < B \\ \infty, & \text{otherwise} \end{cases}. \tag{4}$$

The basic idea of switching cost update [Eq. (4)] is to give preference to existing wavebands (if any) so as to leave more waveband choices for later requests. When computing the switching cost from an input fiber f_{in} to an outgoing fiber f_{out} of a FLEX node v, we use the following rules. If the waveband from f_{in} to f_{out} already exists, the switching cost from f_{in} to f_{out} is set to 0. Otherwise, if the number of already established wavebands from f_{in} to other outgoing fibers of node v is $b < B$, the switching cost is set to $\alpha \cdot \frac{b}{B}$, where α is a tuning parameter. If the number of established wavebands corresponding to f_i equals B, the switching cost is set to be ∞, which means that no new waveband can be established from f_{in}. If v is a CONV node, the switching costs from any input fiber to any output fiber of that node are set to 0.

Algorithm 1: RFBSA Algorithm

Input: $G = (V, E)$, request j, K shortest paths
Output: $path_j$—Fiber and slot assignment for j
for k: K shortest paths of request j **do**
  Create auxiliary graph AG_k
  Switching cost update along path k
  $C_{\mathrm{total}}^k = \infty$
  for α: outgoing fibers from s^j **do**
    Copy AG_k to create auxiliary graph AG_α^k

$C_a^k = \infty$
for $\widetilde{ss}$: available FS sets of size d^j on a **do**
SI = the start FS index of $\widetilde{ss}$
Create layered graph $AG_{a,SI}^k$
SPECTRUM COST UPDATE
Use Dijkstra's algorithm to find a lightpath with the smallest cost $C_{a,\widetilde{ss}}^k$
if $C_{a,\widetilde{ss}}^k < \infty$ **then**
$C_a^k = C_{a,\widetilde{ss}}^k$
BREAK
end if
end for
if $C_a^k < C_{\text{total}}^k$ **then**
$C_{\text{total}}^k = C_a^k$
end if
end for
end for
$path_r$ = a lightpath p with the smallest C_{total}^k, $\forall\, k$

Then, we copy AG^k to generate an auxiliary graph for each outgoing fiber from s^j in the first link of that path for the request. Each auxiliary graph involves one outgoing fiber from source node s^j and includes all remaining nodes and fibers in the kth shortest path. Let $|f_{l_0}^k|$ denote the number of fibers on the first link of the kth shortest path. In total, we generate $\sum_k |f_{l_0}^k|$ auxiliary graphs.

By fixing one outgoing fiber a in the first link of the path, we only need to consider the available FSs on that fiber, thereby reducing the complexity of searching for a valid lightpath. In an auxiliary graph $AG_a^k = (V_a^k, E_a^k)$, we define a layered graph on FS level $AG_{a,SI}^k = (V_{a,SI}^k, E_{a,SI}^k)$ for a specific spectrum range from FS index SI to $SI + d^j - 1$. Thus, in the layered graphs, the spectrum contiguity, spectrum continuity, and spectrum nonoverlapping constraints are automatically satisfied. For auxiliary layered graph $AG_{a,SI}^k$ corresponding to the outgoing fiber a of s^j, we need to do a switching cost update for the second type of edge, which corresponds to all fibers on the physical links along the path regarding an available slot set $\widetilde{ss}$ on fiber a.

Algorithm 2: SWITCHING COST UPDATE

Input: v, f_{in}, f_{out}
Output: $C_{v,f_{in},f_{out}}$
for f_{in}: all incoming fibers in node v **do**
for f_{out} : all outgoing fibers in node v **do**
b = the number of established wavebands from f_{in}
if the waveband is established **then**
$C_{v,f_{in},f_{out}} = 0$
els if $b < B$ **then**
$C_{v,f_{in},f_{out}} = \alpha \cdot b/B$
else
$C_{v,f_{in},f_{out}} = \infty$
end if
end for
end for

Algorithm 3: SPECTRUM COST UPDATE

Input: f, $\widetilde{ss}$, SI, d^j
Output: $C_{a,\widetilde{ss},f}^k$
m_f = the largest FS index on f
if $\widetilde{ss}$ is not available on f **then**
$C_{a,\widetilde{ss},f}^k = \infty$
else if $SI + d^j \leq m_f$ **then**
$C_{a,\widetilde{ss},f}^k = 1$
else
$C_{a,\widetilde{ss},f}^k = (SI + d^j - m_f)/\Omega + 1$
end if

For each contiguous slot set $\widetilde{ss}$ ranging from SI to $SI + d^j - 1$ that is available on source output fiber a of path k, the spectrum cost is defined in Eq. (5):

$$C_{a,\widetilde{ss},f}^k = \begin{cases} 1, & \text{if } SI + d^j \leq m_f \\ \infty, & \text{if } \widetilde{ss} \text{ is not available on} f \\ (SI + d^j - m_f)/\Omega + 1, & \text{otherwise} \end{cases}. \tag{5}$$

The basic idea of the spectrum cost update [Eq. (5)] is to try to not increase MSU on each fiber after the request is established. We denote m_f as the largest FS index on fiber f and $C_{a,\widetilde{ss},f}^k$ as the spectrum cost on fiber f for the slot set $\widetilde{ss}$ in AG_a^k. If $\widetilde{ss}$ is not available on fiber f, $C_{a,\widetilde{ss},f}^k$ is set to ∞. This means that we cannot establish a lightpath by using the slot set $\widetilde{ss}$ on fiber f. If $\widetilde{ss}$ is available, and the ending FS index is no more than m_f, $C_{a,\widetilde{ss},f}^k$ is set to 1. In this case, the local MSU on fiber f would not increase, and the spectrum cost works as a hop count. Otherwise, $C_{a,\widetilde{ss},f}^k$ is set to be $(SI + d^j - m_f)/\Omega + 1$, which is proportional to the number of slots by which the local MSU increases on that fiber, while taking the hop count into consideration.

For a lightpath l in the kth path, we denote $C_{a,\widetilde{ss}}^k$ as the total cost combining spectrum costs $\sum_f C_{a,\widetilde{ss},f}^k$ of the fiber set F_l and switching costs $\sum_v C_{v,f_{\text{in}},f_{\text{out}}}$ of the node set V_l that the lightpath is going through. Once the costs of all edges in the layered graph are determined, we use Dijkstra's algorithm to find the shortest paths from one output fiber of the source node to different input fibers of the destination node and choose the valid lightpath p with the smallest path cost. In order to decrease the algorithm's complexity, we stop generating further layered graphs for this auxiliary graph and consider p as a *candidate lightpath*. We compare the path costs of all the candidate lightpaths and choose a path with the smallest total cost.

Suppose the total number of links in the network is L, the maximum number of fibers per link is ε, and Ω is an estimated upper bound of the MSU. For each request, the number of hops in the path of a mesh network, denoted as h, is usually small compared with L. For each output fiber of the source node, $O(\Omega)$ auxiliary graphs are created. Because each path is precalculated, each auxiliary graph consists of $O(h\varepsilon)$ vertex and $O(h\varepsilon^2)$ edges [$O(\varepsilon^2)$ first type of edges on each intermediate node of the path and $O(\varepsilon)$ second type of edges on each link of the path]. The dominant part is to find the shortest path in the auxiliary graphs; thus, the time complexity of the algorithm is $O(\Omega h\varepsilon^3 \log(h\varepsilon))$, which is much less than the time complexity of our previous algorithm $O(\Omega L\varepsilon^3 \log(L\varepsilon))$, which generates the auxiliary graphs based on the whole network.

B. Node Placement Schemes

Given only the budget, i.e., the total number of available small-port-count WSSs for the network, the number and location of FLEX nodes should be determined. Assume all nodes are initially CONV nodes; by replacing CONV nodes with FLEX nodes, the required number of WSSs will be decreased. Then, the problem transforms to how many and which CONV nodes should be replaced to meet the budget. Of course, the performance of the network after replacement should be taken into consideration when making the replacements.

Indeed, how many CONV nodes need to be replaced also depends on where they are. Replacing a node with a larger port count may have the same reduction in number of WSSs as replacing two nodes with small port counts. Therefore, we divide the joint placement and assignment problem into two stages. The first stage is to decide the location of FLEX nodes. Then, a routing path, fibers on links along the path, waveband, and a slot set are selected for each request by our RFBSA algorithm.

1) Random Node Placement: We use a random node placement scheme as the baseline. We first try to randomly select a CONV node to replace. The number of required WSSs is reduced accordingly. The procedure of randomly replacing the remaining CONV nodes and updating the required number of WSSs is performed repeatedly until the budget constraint is met.

2) Traffic-Aware Node Placement: For a better node placement scheme, the network topology and the traffic requests should be taken into consideration. The first intuition is that, if fewer CONV nodes are replaced with FLEX, the performance degradation would be less. In this case, we would like to replace the physical nodes with larger port count first. The physical nodes are sorted by their port counts in descending order and replaced one by one to meet the budget.

On the other hand, physical nodes with large port counts usually have more traffic going through them. Replacing these nodes might affect more connection requests and add routing constraints to them, leading to worse performance. Accordingly, the node placement should consider the traffic pattern, as well as the port counts of physical nodes.

We assume all nodes are CONVs initially, and the RFBSA is applied to accommodate all requests in the network. To facilitate node placement, the band usage information and the total number of requests going through each physical node are recorded. A cost function related to the traffic for each node v is defined in Eq. (6). Let $\max b_v$ denote the maximum number of bands originated from all input fibers of node v. $\max b_v$ is related to the waveband usage on each node. Δ_v denotes the number of traffic demands going through node v (excluding requests originating or terminating at this node). Let D_v denote the port count of node v. The larger D_v is, the greater reduction in required number of WSSs is achieved. When $\max b_v$ is not larger than the band limit B, we set the cost to 0; otherwise, we set the cost to the traffic density (Δ_v/D_v) that would be affected by the limited banding. The larger C_v a node has, the more traffic it will affect when replaced by FLEX. Nodes with a small cost C_v are preferred to be replaced. We sort the nodes in ascending order of the costs C_v and replace them one by one until the budget constraint is met:

$$C_v = \begin{cases} 0, & \text{if } \max b_v \leq B \\ \Delta_v/D_v, & \text{otherwise} \end{cases}. \tag{6}$$

When all the FLEX nodes are placed, the route, fiber, band, and slot assignment for each request should be determined in the mixed network. The RFBSA algorithm described in the previous subsection is utilized to assign the route, fibers, wavebands, and a contiguous slot set to accommodate each request. We finally select the node placement by comparing the performance of the above two strategies for each budget.

C. Extension to Dynamic Instances

To accommodate dynamically arriving traffic requests, we should determine the node placements first. Given the information on network topology and traffic (request size distribution and traffic pattern), we first generate a large number of static requests according to the given traffic pattern and use the traffic aware placement introduced in the previous subsection to find appropriate FLEX node deployments. Then, the RFBSA algorithm is applied to the mixed network for the arriving requests. In the dynamic case, the goal is to minimize the demand blocking ratio. We adapt the spectrum cost function in the RFBSA algorithm to achieve good performance. $C^k_{a,\widetilde{ss},a} = SI$ denotes the spectrum cost on one outgoing fiber a from the source node for its available slot set $\widetilde{ss}$ and $C^k_{a,\widetilde{ss},f} = 1$ if $\widetilde{ss}$ is available on fiber f along the path k. Here, we try to compact the total utilized network resources to leave more resources for later requests. The cost function emphasizes both starting slot and hop count of the path.

V. Simulation Results

In this section, we present performance evaluation results for static and dynamic instances to demonstrate the effectiveness of our proposed method. ILP results for small network instances and simulation results for large network instances are generated to examine the effects of changing budget on the performance of the network.

Given a set of connection requests and a budget for the network, the number and locations of FLEX nodes should be determined, and networking resources need to be allocated to the requests. Each request represents a connection from a source node to a destination node with a demand size requirement. A uniform traffic pattern means the source/destination nodes are randomly selected from the physical nodes of the network. We assume three types of demands in terms of the number of required FSs [13], with the following distribution: three slots (40 Gbps) with probability 0.2; four slots (100 Gbps) with probability 0.5; and seven slots (400 Gbps) with probability 0.3. For the FLEX nodes, the maximum number of wavebands B is assumed to be four or nine.

For a given set of static traffic requests, we record the total MSU. The average MSU over the total number of fibers is used as the performance measure. The parameter α is set to 1 for RFBSA.[1] In the node selection scheme, both band usage and the traffic distribution are considered. RP is used to denote the random node placement strategy, while TAP represents the traffic aware node placement strategy in the following results.

A. Results for a Small Network

We get single-run ILP results for a five-node small network, as shown in Fig. 3. The number of parallel fibers, x, on each link is randomly distributed between two and three ($x = [2, 3]$ per link). The band limit $B = 4$.

Table III shows the average MSUs over all fibers achieved by the ILP and our proposed heuristics for different numbers of requests in the five-node small network. The given budget is 89 WSSs (which is between the required number of WSSs for all FLEX nodes—64, and all CONV nodes—125). We only simulate the $K = 1$ case here due to the complexity of the ILP. For example, the execution time of the heuristics is a few seconds, while that of ILP is more than 6 h. We can see that the results from TAP are better than for RP and are not far from the ILP's results.

B. Results for Larger Topologies

The larger topologies used for simulations are the NSFNET network and pan-European network. The NSFNET as shown in Fig. 4 has 14 physical nodes and 22 bidirectional links [12], while the pan-European network as shown in Fig. 5 consists of 28 physical nodes and 43 bidirectional links [21]. The number of fibers, x, on each link is randomly distributed between three and five ($x = [3, 5]$ per link). The network topology is fixed for every run of the simulation.

Figures 6 and 7 show the performance change in the NSF network as the given budget changes. We conducted 50 trials of simulation, each consisting of 3000 traffic requests, and show the average results with 95% confidence intervals. Figure 6 shows the comparison results when $B = 4$, while Fig. 7 is for $B = 9$. We use $K = 3$ for all

[1]This was chosen based on observed performance for a large set of parameters.

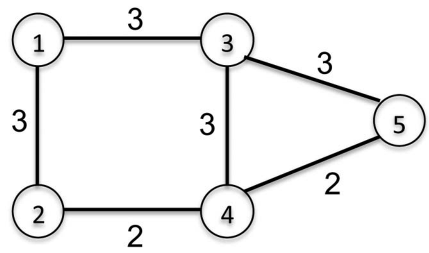

Fig. 3. Small network. Numbers are the number of fibers on the links.

TABLE III
AVERAGE MSU RESULTS FOR THE SMALL NETWORK

Number of Requests	RP	TAP	ILP
40	10.25	9.5	9.03125
50	13.53125	12.46875	12.125
60	15.8125	14.96875	14
100	24.75	23.0625	22.21875

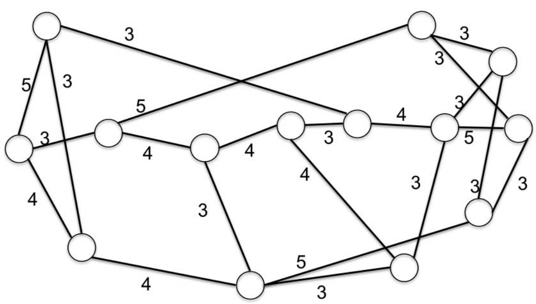

Fig. 4. NSF network. Numbers are the number of fibers on the links.

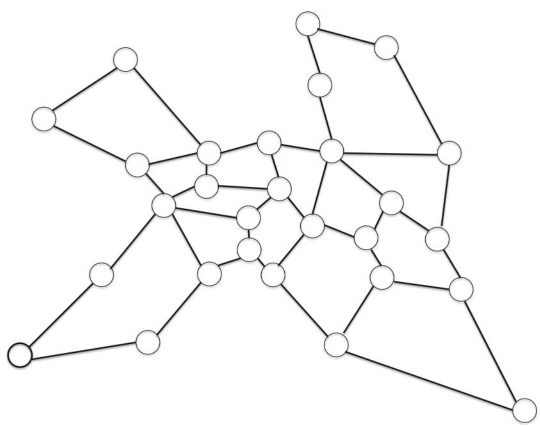

Fig. 5. Pan-European network. The number of fibers on the link is not shown for clarity.

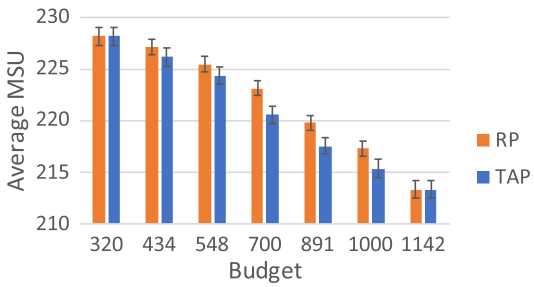

Fig. 6. Network performance versus budget for NSF network ($B = 4$).

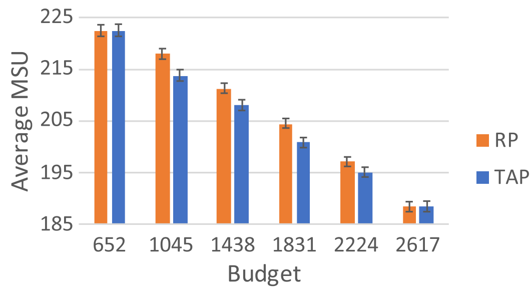

Fig. 8. Network performance versus budget for pan-European network ($B = 4$).

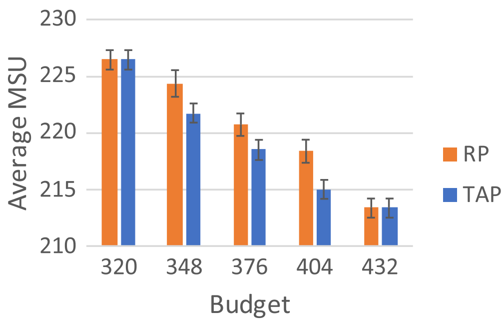

Fig. 7. Network performance versus budget for NSF network ($B = 9$).

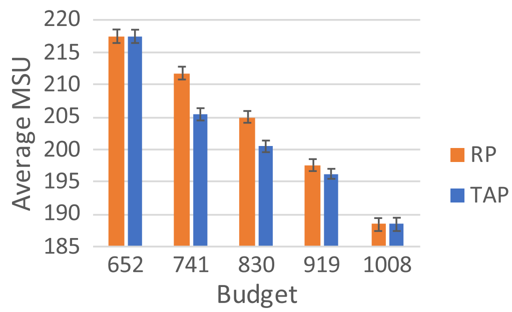

Fig. 9. Network performance versus budget for pan-European network ($B = 9$).

TABLE IV
AVERAGE NUMBER OF FLEX NODES FOR NSF NETWORK ($B = 4$)

	Budget					
Schemes	320	434	548	700	891	1000
TAP	14	11.66	9.52	6.36	3.98	2.68
RP	14	12.436	10.52	8.03	4.78	2.838

simulations. The range of the budget (number of available WSSs) for the network varies from 320 (all nodes are FLEX) to 1142 (all nodes are CONV) when $B = 4$ and to 432 when $B = 9$. Table IV shows the illustrative results depicting the average number of FLEX nodes for each budget in the 14-node NSF network when $B = 4$.

Similarly, Figs. 8 and 9 show the performance change in the pan-European network as the given budget changes. We use similar settings for the simulations. Figure 8 shows the comparison results when $B = 4$, while Fig. 9 is for $B = 9$. The range of the budget (number of available WSSs) for the network varies from 652 (all nodes are FLEX) to 2617 (all nodes are CONV) when $B = 4$ and to 1008 when $B = 9$.

As expected, the average MSU increases, which means network performance degrades as the budget decreases (more FLEX nodes and fewer CONV nodes). The comparison of the two node placement strategies is shown in the figures. When all nodes are FLEX or CONV, there is no difference between RP and TAP as the network is the same for both policies. In general, TAP performs better than RP in the sense that fewer slots are required to accommodate all requests. However, even in the worst case, the degradation of network performance is relatively small, which means that it may be possible to replace most CONV nodes with FLEX nodes in the network without a significant penalty. We note that the MSU is increased by 10% to 15% for the two topologies when all CONV nodes are replaced by FLEX nodes. However, the number of WSSs needed can be reduced by a factor of 2 or more in many cases. These results suggest that the slight increase in spectrum cost is more than offset by the savings in WSSs.

C. Results for Dynamic Requests

The traffic demand is a set of dynamically arriving connection requests. Connection requests arrive to the network according to a Poisson process. Each request has a mean holding time of 1 (arbitrary time unit), and the arrival rate of traffic requests is varied in order to examine the network performance under varying offered loads (denoted by L). We use the demand blocking ratio of dynamic traffic requests to indicate the network performance. The parameter α is set to 100[2] for RFBSA. For each simulation, the results of 200,000 dynamic requests excluding 10,000 warm-up requests are recorded.

[2]This was chosen based on observed performance for a large set of parameters.

The NSNET topology is used for this set of simulations. Each link has a random number of fibers, x, that are uniformly distributed between five and 10 fibers ($x = [5, 10]$ per link). We assume the fiber capacity of 352 frequency slots, with each slot having a bandwidth of 12.5 GHz. The banding limit of FLEX nodes is assumed to be 4 (i.e., $B = 4$). The range of the budget for the network varies from 660 (all nodes are FLEX) to 5137 (all nodes are CONV).

We first show a set of simulation results for the uniform traffic pattern. A set of static connection requests is first generated according to this traffic pattern in order to determine the node placement to satisfy a given budget of the network. Then, the demand blocking ratio of dynamic requests is evaluated. Figures 10 and 11 show the performance change in the NSF network as the given budget changes for different traffic loads. We can see that the network performance degrades (demand blocking ratio increases) as the budget decreases. In general, TAP performs better than RP (lower demand blocking ratio under each budget). When the traffic load is small, the difference between TAP and RP is more obvious.

We also conduct simulations for a nonuniform traffic pattern. We assume that nodes with higher connectivity have a greater opportunity to send and receive traffic and choose the probability that a node v is selected as a source or destination, u_v, in proportion to the node's physical degree. Again, a set of static connection requests of this traffic pattern is generated in order to determine the node placement for each budget. The comparison results for different network loads are shown in Figs. 12 and 13. We can see similar trends as in previous results.

We also conduct sensitivity tests to see how well our TAP scheme performs when the actual traffic pattern is slightly different from what the network was planned for. Here, we perturb the source/destination selection probabilities u_v by a factor η_v (η_v could be either positive or negative, with the average of $|\eta_v|$ being η). In other words, we set the node selection probabilities to be $(u_1(1+\eta_1), u_2(1+\eta_2), \ldots, 1-\sum_{v=1}^{N-1} u_v(1+\eta_v))$. Then, we compare the performance obtained by applying the original node placement to the changed traffic pattern with the performance obtained by applying the node placement for the changed traffic pattern. Figure 14 shows results for $\eta = 0.1$.

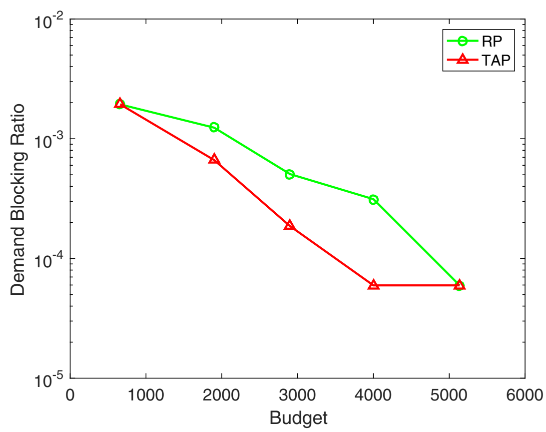

Fig. 10. Network performance versus budget for NSF network with uniform traffic pattern ($L = 6900$).

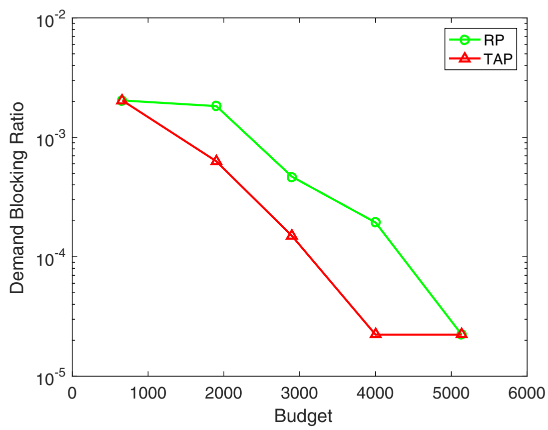

Fig. 12. Network performance versus budget for NSF network with nonuniform traffic pattern ($L = 7100$).

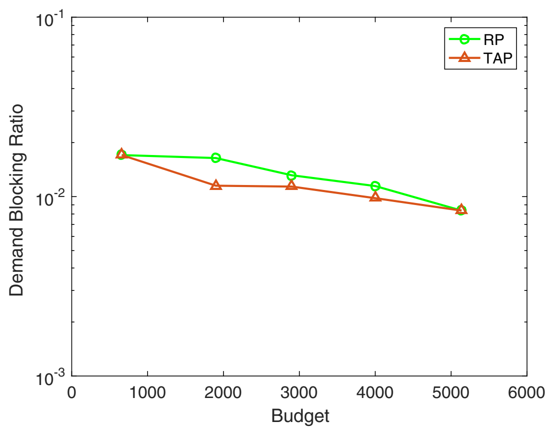

Fig. 11. Network performance versus budget for NSF network with uniform traffic pattern ($L = 7400$).

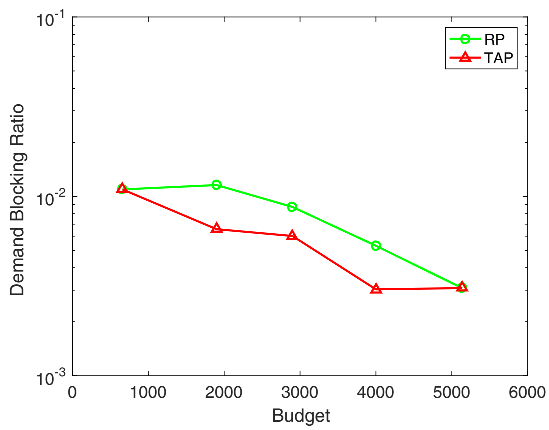

Fig. 13. Network performance versus budget for NSF network with nonuniform traffic pattern ($L = 7400$).

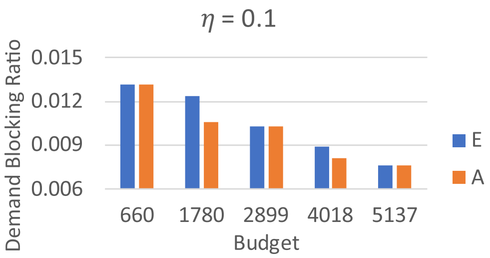

Fig. 14. Sensitivity test for traffic pattern with a perturbation of 0.1.

The results are represented by “A” (with placement based on exact information) and “E” (without exact information). There is no performance difference between “E” and “A” when all nodes are FLEX or CONV because the node placements are the same. For other budgets, the difference in performance between “E” and “A” is relatively small, indicating that the algorithm is not sensitive to small changes in traffic pattern.

VI. Conclusion

Flexible waveband OXCs require much less hardware cost than conventional OXCs, with the penalty of some switching constraints. An RFBSA problem for a network with FLEX nodes was described in [14]. In this paper, we jointly consider RFBSA and FLEX node placement to satisfy a network planning budget in terms of the total number of available WSSs. In addition to an integer linear programming formulation, we present node placement schemes and extend the cost-function-pluggable auxiliary layered-graph framework in our previous paper to solve this problem. The simulation results demonstrate that our heuristic solution saves network resources and achieves good network performance, as indicated by the average maximum spectrum usage. The framework is also demonstrated to have good performance for dynamic traffic requests.

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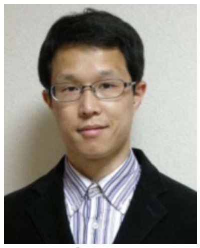

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