Cost-Optimized Design of Flexible-Grid Optical Networks Considering Regenerator Site Selection

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***Abstract*—In this paper, we aim to minimize the total network cost in flexible-grid optical networks with multiple line rates. Besides transponder cost, regenerator cost, and shared infrastructure cost, the cost of regenerator sites is also considered. We first provide the problem definition and formulate the problem as an integer linear program (ILP). We also propose a heuristic algorithm considering both selection and placement of equipment to minimize the total network cost. Simulation results show the heuristic algorithm results in up to 28% cost saving, with no significant increase in spectrum usage.**

I. Introduction

The optical backbone network is now evolving towards flexible-grid optical networks, where optical channels may be assigned different number of spectrum slots according to their transmission parameters [1]. Flexible-grid networks not only provide a more efficient capacity utilization through tighter channel spacing, but also serve as an enabler to data rates beyond 100 Gbps (e.g., 400 Gbps, 1000 Gbps).

In any optical network, the optical signal may suffer physical impairments, such as noise, intra-crosstalk, linear impairments, and nonlinear fiber effects. In general, higher rates may suffer greater impairments. 3R regenerators can be used to restore the optical signal quality in order to guarantee successful transmission. Properly selecting a small number of nodes as regenerator sites (RS) can potentially reduce capital expenditure and operational expenditure compared to placing regenerators anywhere [2]. Expenses can be reduced by pre-deploying regenerators at RSs, rather than sending onsite technicians to deploy regenerators on demand. The number of pre-deployed regenerators also tends to be smaller when there are fewer RSs. Furthermore, pre-deployed cards can be shared with spare units within the same hardware spare pool, which are generally available at small number of hub sites.

The RS selection problem has been studied in single line rate optical networks [3]–[5]. Another group of papers studies the RS selection problem in mixed line rate optical networks with either fixed routing or flexible routing [6], [7]. However, work on RS selection is still missing in flexible-grid optical networks, where both network deployment costs and spectrum usage should be analyzed. In [8], a cost/spectrum design trade-off is shown in flexible-grid DWDM networks. Our work differs in that we consider the cost of RS and the placement of regenerators, which makes the network design problem more complete, especially when the reachability of the optical signal is short or the optical signal needs to traverse long distances.

Our work considers regenerator placement for flexible-grid optical networks under impairment constraints that are represented as the reachability for each line rate. For a given set of connection requests, we need to find a path (or multiple paths) for each connection request, decide the line rate of each path, and place regenerators along each path if the distance is longer than the reachability for the chosen line rate. The objective of our problem is to minimize the total network cost, which includes the cost of transponders, regenerators, RSs, and the other shared infrastructure. In this paper, we make the following assumptions: 1) the links in the optical network are bidirectional; 2) all requests are bidirectional; 3) sufficient link resources (e.g. spectrum) and node resources (e.g. transponders and regenerators) are available in the optical network, which means that no connection request will be blocked.

The rest of this paper is organized as follows. In Section II, a detailed problem description is provided. In Section III, we propose an ILP formulation of the problem. In Section IV, a heuristic algorithm is presented. In Section V, we show some numerical results for both ILP and the heuristic algorithm. Finally, we give a summary of our work in Section VI.

II. Problem Description

A. Network Model and Cost Model

The optical network can be represented as a graph G(**V**, **E**, **D**), where **V** is a set of nodes, **E** = $[e_{i,j}]$ is an adjacency matrix representing edges of **G**, and **D** = $[d_{i,j}]$ is the set of distances corresponding to the edge set **E**, where $d_{i,j}$ is the link length of $e_{i,j}$. For each connection request, the requested traffic is broken down into multiple optical channels of different line rates. These optical channels are reserved along paths, and

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regenerators are placed at the regenerator sites along the paths if needed.

In this paper, we use reachability in actual distance (km) to measure the effect of impairments. The reachabilities of different line rates vary due to different physical impairments. Thus, we use a set of reachabilities **A** to denote the reachabilities for different line rates.

The total network cost consists of the following four elements:

1. The transponders of different line rates;
2. The 3-R regenerators of different line rates;
3. Regenerator sites;
4. The other shared infrastructure (SI) such as the fiber, inline optical amplifiers, and ROADMs. The unit SI cost is the average cost of all shared infrastructure for 1 km of transmission distance and for consuming 1 GHz of optical bandwidth, i.e., $/(km*GHz) [9].

Given an optical channel of certain line rate l_k and its path *P*, the cost of this optical channel is 2*ct_k + *NR(P)**cr_k + C_U*$Dist(P)$*f_k, where ct_k is the cost of line rate l_k's transponder, *NR(P)* is the number of required line rate l_k's regenerators along the path *P*, cr_k is the cost of line rate l_k's regenerator, C_U is the unit SI cost, $Dist(P)$ is the distance of *P*, and f_k is the channel width of line rate l_k. The total network cost is the summation of all the optical channels' costs plus the cost of regenerator sites.

B. Problem Statement

Given physical topology *G*(**V**, **E**, **D**), where **V** is a set of nodes, **E** is a set of edges, **D** is a set of distance according to the edge set **E**, a set of line rates **L**, $l_k \in \mathbf{L}$, $1 \leq k \leq |\mathbf{L}|$, a reachability set **A**, $a_k \in \mathbf{A}$, $1 \leq k \leq |\mathbf{L}|$, where a_k is the reachability of line rate l_k, a set of transponder costs **CT**, $ct_k \in \mathbf{CT}$, $1 \leq k \leq |\mathbf{L}|$, where ct_k is the cost of a line rate l_k's transponder, a set of regenerator costs **CR**, $cr_k \in \mathbf{CR}$, $1 \leq k \leq |\mathbf{L}|$, where cr_k is the cost of a line rate l_k's regenerator, a set of channel width **F**, $f_k \in \mathbf{F}$, $1 \leq k \leq |\mathbf{L}|$, where f_k is the channel width of a line rate l_k's optical channel, the cost of a regenerator site C_{RS}, the unit SI cost C_U, and a set of traffic demands **R**, $r_{s,t} \in \mathbf{R}$, where $r_{s,t}$ is the requested aggregated traffic from s to t.

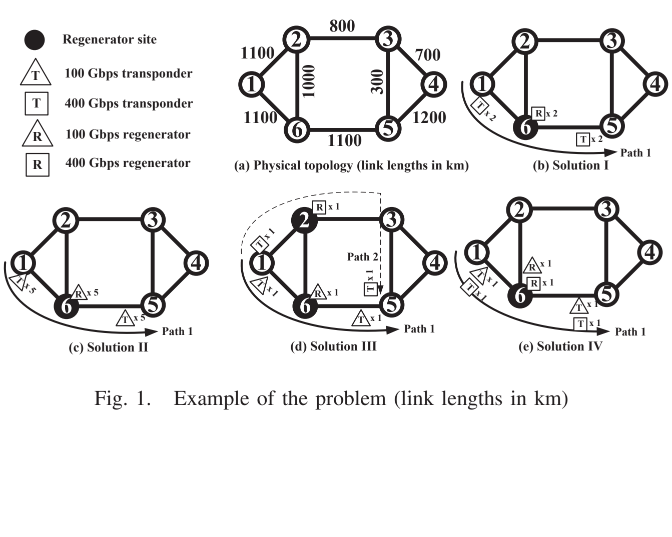

Fig. 1. Example of the problem (link lengths in km)

Find: (1) the line rate selection for each connection request; (2) the routing for each optical channel; (3) the regenerator placement and RS selection.

Our objective is to minimize the total network cost, subject to the following constraints:

1. traffic constraint: every connection request is assigned one or several line rates, and the combined traffic of these assigned line rates is not smaller than that of the connection request;

2. impairment constraint: along any path, the length of each segment without regenerators does not exceed the corresponding line rate l_k's reachability limit a_k.

An example is shown in Fig. 1. Suppose we have a traffic demand of 500 Gbps from Node 1 to Node 5. The available line rates, their corresponding costs, and corresponding channel width are shown in Table I. The cost of a RS is assumed to be 10. The unit SI cost is assumed to be 10^{-5}/km*GHz. As shown in Fig. 1(b), We can choose two 400 Gbps channels along Path 1 with a total cost of 63.5, and select Node 6 as a RS. Or we can choose five 100 Gbps channels along Path 1 with a total cost of 55.5 by selecting Node 6 as a RS, as shown in Fig. 1(c). Now we consider the case where both 400 Gbps and 100 Gbps are used. As Fig. 1(d) shows, if we choose one 400 Gbps channel along Path 2, and one 100 Gbps channel along Path 1, the total cost is 55.85. Node 2 and Node 6 are selected as RSs. The cost can be decreased by choosing Path 1 for both 400 Gbps and 100 Gbps channels, as shown in Fig. 1(e). The total cost is 45.85, and only Node 6 is selected as a RS. This is the optimal solution for this case. Thus, different line rate selection, routing, and regenerator placement will lead to different total cost.

III. ILP Formulation

The ILP model is based on a reachability graph in which a pair of directed auxiliary links are constructed between node pairs whose shortest path distance is shorter than or equal to the reachability. Fig. 2 shows an example of the reachability graphs of the physical topology shown in Fig. 1, when the reachablities are 1200 km and 2000 km, respectively. Under different reachability a_k, a given physical topology can have different reachability graphs. A shortest path in this auxiliary graph is a min-regenerator path in the network.

Next, we present the ILP formulation for the problem. First, we define some useful notations and variables.

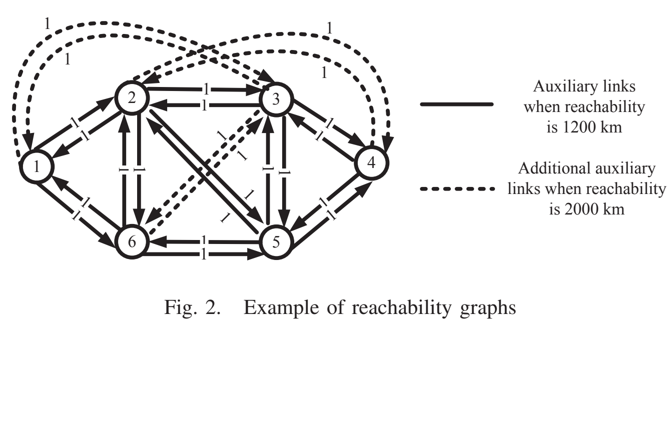

Fig. 2. Example of reachability graphs

1) Input parameters:

- $\mathbf{L} = [l_k]_{|\mathbf{L}|}$: set of line rates;
- $\mathbf{R} = [r_{s,t}]_{|\mathbf{V}|\times|\mathbf{V}|}$: set of connection requests;
- $\mathbf{E'} = [e'_{k,i,j}]_{|\mathbf{L}|\times|\mathbf{V}|\times|\mathbf{V}|}$: $e'_{k,i,j}$ equals to 1 if there is an auxiliary link between i and j in the auxiliary graph corresponding to line rate l_k, otherwise 0;
- $\mathbf{D} = [d_{i,j}]_{|\mathbf{V}|\times|\mathbf{V}|}$: shortest distance between i and j in the physical topology;
- $\mathbf{CT} = [ct_k]_{|\mathbf{L}|}$: set of costs of transponders;
- $\mathbf{CR} = [cr_k]_{|\mathbf{L}|}$: set of costs of regenerators;
- $\mathbf{F} = [f_k]_{|\mathbf{L}|}$: set of channel width;
- C_{RS}: cost of a regenerator site;
- C_U: unit SI cost;
- P: maximum number of paths for a connection request;
- *VL*: a pre-defined very large number.

2) Variables of ILP:

- $\mathbf{X} = [x^{s,t,p}_{k,i,j}]^{|\mathbf{V}|\times|\mathbf{V}|\times P}_{|\mathbf{L}|\times|\mathbf{V}|\times|\mathbf{V}|}$: $x^{s,t,p}_{k,i,j}$ equals to 1 if edge $e'_{k,i,j}$ is along the path p from s to t on line rate l_k's reachability graph, otherwise 0;
- $\mathbf{Y} = [y^{s,t,p}_{k,i}]^{|\mathbf{V}|\times|\mathbf{V}|\times P}_{|\mathbf{L}|\times|\mathbf{V}|}$: $y^{s,t,p}_{k,i}$ equals to 1 if a line rate l_k's regenerator is placed at node i on the path p from s to t, otherwise 0;
- $\mathbf{Z} = [z^{s,t}_k]^{|\mathbf{V}|\times|\mathbf{V}|}_{|\mathbf{L}|}$: number of required line rate l_k's transponder pairs from s to t;
- $\mathbf{S} = [s_i]_{|\mathbf{V}|}$: equals to 1 if node i is selected as a regenerator site, otherwise 0.

3) Objective:

The objective is to minimize the following function:

$$\textit{min obj} = \sum_{k,s,t} 2 \cdot ct_k \cdot z^{s,t}_k + \sum_{s,t,p,k,i} cr_k \cdot y^{s,t,p}_{k,i} + \sum_i C_{RS} \cdot s_i + \sum_{s,t,p,k,i,j} C_U \cdot f_k \cdot x^{s,t,p}_{k,i,j} \cdot d_{i,j} \quad (1)$$

Note that the first part of the objective is the total cost of the transponders; the second part is the total cost of the regenerators; the third part is the total cost of regenerator sites; and the fourth part is the total cost of other shared infrastructure.

4) Constraints:

$$\sum_{p,k,j} l_k \cdot (x^{s,t,p}_{k,s,j} - x^{s,t,p}_{k,j,s}) \geq r_{s,t}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}| \quad (2)$$

$$\sum_{p,k,j} l_k \cdot (x^{s,t,p}_{k,j,t} - x^{s,t,p}_{k,t,j}) \geq r_{s,t}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}| \quad (3)$$

$$\sum_i x^{s,t,p}_{k,i,j} = \sum_i x^{s,t,p}_{k,j,i}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}|, \forall 1 \leq p \leq P, \forall 1 \leq k \leq |\mathbf{L}|, \forall 1 \leq j \leq |\mathbf{V}|, j \neq s, t \quad (4)$$

Eqn. (2) guarantees that the source node generates a traffic flow greater than or equal to the requested traffic. Eqn. (3) guarantees that the destination receives the same amount of data generated at the source node. Eqn. (4) guarantees that for any intermediate node, the incoming and outgoing flows should be the same.

$$x^{s,t,p}_{k,i,j} \leq e'_{k,i,j}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}|, \forall 1 \leq p \leq P, \forall 1 \leq k \leq |\mathbf{L}|, \forall 1 \leq i \leq |\mathbf{V}|, \forall 1 \leq j \leq |\mathbf{V}| \quad (5)$$

Eqn. (5) ensures that the route of line rate l_k's channel is on the reachability graph of line rate l_k.

$$y^{s,t,p}_{k,i} \geq x^{s,t,p}_{k,i,j}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}|, \forall 1 \leq p \leq P, 1 \leq k \leq |\mathbf{L}|, \forall 1 \leq i \leq |\mathbf{V}|, i \neq s, \forall 1 \leq j \leq |\mathbf{V}| \quad (6)$$

Eqn. (6) guarantees that a regenerator is placed for every hop of a path p, excluding the source and destination of paht p, on the reachability graph.

$$z^{s,t}_k = \sum_{p,j} x^{s,t,p}_{k,s,j}, \forall 1 \leq s \leq |\mathbf{V}|, \forall 1 \leq t \leq |\mathbf{V}|, \forall 1 \leq k \leq |\mathbf{L}| \quad (7)$$

Eqn. (7) is to calculate how many line rate l_k's transponder pairs are needed between each s-t pair.

$$s_i \geq \frac{\sum_{s,t,p,k} y^{s,t,p}_{k,i}}{VL} \quad (8)$$

Eqn. (8) ensures that a node is selected as a regenerator site when there is regenerator placed in this node.

IV. Heuristic Approach

Our heuristic algorithm is based on three steps: (1) line rate selection; (2) routing and regenerator placement; (3) post processing.

A. Line Rate Selection

Given a connection request, we can obtain the cost of a line rate l_k's channel between the source and destination of this connection request by the following formula: $TC_{s,t,k}$ = 2*ct_k + ($LHP_{s,t,k}$ - 1)*cr_k + C_U*$SP_{s,t}$*f_k, where $TC_{s,t,k}$ is the total cost of a line rate l_k's channel from s to t, $LHP_{s,t,k}$ is the least hop count from s to t in the reachability graph corresponding to line rate l_k, and $SP_{s,t}$ is the shortest path distance from s to t in the physical topology. Based on the traffic demand and the cost of each line rate's channel, we can determine the number of lightpaths together with the proper line rate for each path so that the total cost for the traffic demand is minimized. If the number of rates is given, this process can be done and achieve the optimal solution in polynomial time through dynamic programming. Due to space limitations, the proof is omitted.

B. Routing and Regenerator Placement

After line rates are selected, we create $|\mathbf{L}|$ matrices $[T_k]_{|\mathbf{L}|}$, where $T_k = [t_{s,d}]_k$ contains the number of channels from s to d using line rate l_k. We start from the highest line rate's matrix. In a matrix, we start from the largest demand. If a node is not a RS, the weights of all egress links of this node in line rate l_k's auxiliary graph are set to $t_{s,d}$ * cr_k + C_{RS}. If a node is already selected as a RS, the weights of its egress links are set to $t_{s,d}$ * cr_k. Then we run shortest path algorithm to find a path on line rate l_k's auxiliary graph for the channels from s to d using line rate l_k. All the internal nodes in this shortest path are selected as RSs. Regenerators of corresponding line rate are placed along this path in RS. The same procedure is applied to the next set of channels, and the weights of the links in the auxiliary graph are updated according to number of channels and the existing RSs.

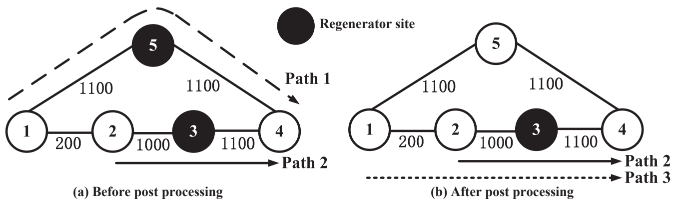

Fig. 3. Example of post processing

C. Post Processing

The above routing and regenerator placement step only adds RSs without deleting any of them. However, it is possible that some earlier selected RS v may become unnecessary when one or several later selected RSs can cover the source-destination pairs that v originally covered with an even lower cost. An example is shown in Fig. 3. Suppose we have two sets of optical channels: Set 1 from Node 1 to Node 4 with two 400 Gbps channels and Set 2 from Node 2 to Node 4 with one 400 Gbps channel. Suppose the costs and the reachabilities are the same as that in Section II.B. Using the routing and regenerator placement approach presented above, the results will be

Algorithm 1 FlexGrid-MinCost (FG-MC)

Input: physical topology G(**V**, **E**, **D**), the reachability set **A**, the connection request set **R**, regenerator cost set **CR**, transponder cost set **CT**, regenerator site cost C_{RS}, and unit SI cost C_U
Output: total cost *TC*
//Main procedure
Begin
$[T_k]_{|\mathbf{L}|}$ = **0**
//Line rate selection
for all $r_{s,t} \in$ **R do**
  Calculate $TC_{s,t,k}$ for all $1 \le k \le |\mathbf{L}|$
  Use dynamic programming to determine the line rate set $\boldsymbol{LR}$ = $[lr_k]_{|\mathbf{L}|}$ with minimum cost
  for all $1 \le k \le |\mathbf{L}|$ **do**
    $[t_{s,t}]_k$ = $[t_{s,t}]_k$ + lr_k
  end for
end for
//Routing and regenerator placement
for all T_k from T_1 (highest rate) to $T_{|\mathbf{L}|}$ (lowest rate) **do**
  Pick the maximum $[t_{s,t}]_k$
  Update the reachability graph corresponding to line rate l_k
  Run shortest path algorithm on the reachability graph corresponding to line rate l_k
  The intermediate nodes of the path found are selected as RSs
  $[t_{s,t}]_k$ = 0
end for
Post processing
Calculate total cost *TC*
End

choosing Path 1 for Set 1 and choosing Path 2 for Set 2, while Node 5 and Node 3 are selected as regenerator sites with a total cost of 100.125, as shown in Fig. 3(a). However, as Fig. 3(b) shows, if we change Set 1 from Path 1 to Path 3, the total cost will be reduced to 90.375, so choosing Node 5 as a RS becomes less cost-efficient.

Thus we propose a post processing approach to improve our solutions. For every RS v in the output of the routing and regenerator placement step, we delete v and check the lightpaths passing through v. These lightpaths have to be switched to other paths. The new lightpaths are found through the routing step described in Section IV. B, except that the weights of the egress links of a RS are set to a very small number, while the weights of the egress links of an non-RS node are set to a very large number. After the new lightpaths are found, the total cost is re-calculated. If the new lightpahts have lower cost and no additional RS is added, then v is deleted, otherwise v remains in the set of RSs. This process is repeated for every RS.

D. Complete heuristic approach

Our heuristic approach follows the three-step process: line rate selection, routing and regenerator placement, and post processing. We name this approach the FlexGrid-MinCost (FG-MC) algorithm. The full FG-MC algorithm is shown in Algorithm 1.

For comparison with our heuristic, we have the FlexGrid-ShortestPath (FG-SP) algorithm, which uses the same line rate selection and post processing approaches as our heuristic, but always uses shortest paths in the physical topology to route the optical channels. We also compare with a Single Line Rate (SLR) algorithm that does not consider line rate selection. In our simulation, the SLR algorithm uses either all 400 Gbps line rate (SLR-400G) or all 100 Gbps line rate (SLR-100G), and the routing is always shortest path in the physical topology. The FG-MC, FG-SP, SLR-400G, and SLR-100G algorithms allow regenerators to be placed anywhere. Any node with regenerators placed becomes a RS.

V. Numerical Results

In this section, we present some numerical examples to show that the ILP can solve small-scale problems very well, while our heuristic algorithm can achieve good performance for both small-scale and large-scale networks. The ILP model

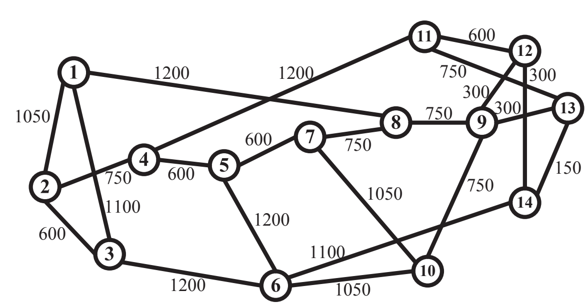

Fig. 4. 14-node NSFNet (link lengths in km)

TABLE I
SIMULATION PARAMETERS

Line Rate (Gbps)	Reach (km)	Transponder Cost	Regenerator Cost	Channel Width (GHz)
100	2000	2	4	50
400	1200	6	12	125

was solved using IBM ILOG OPL *v*12.2. We use two line rates: 100/400 Gbps. The reachabilities, transponder costs, regenerator costs, and channel width are shown in Table. I, which are referred to [8]. The unit SI cost is 10^{-5}/GHz*km, which is refered to [9].

Experiment 1. In the first experiment, we compare the performance of the ILP model with our heuristic algorithm. The experiment is conducted on the 14-node NSFNet topology shown in Fig. 4. The total costs of ILP and heuristic algorithm are compared under different network load, and under different costs of a RS. The average traffic between each node pair grows from 100 Gbps to 600 Gbps. The costs of a RS are 0.01, 1, and 100, respectively.

From Table II, we can see that when the cost of a RS is low, the total costs obtained by our algorithm are almost the same as those of the ILP. When the cost of a RS is 100, the difference between the total costs of our heuristic algorithm and the ILP becomes bigger, but the difference is only 8.3% on average. Fig. 5 shows different network equipment's costs under different cost of a RS, when the average node-pair traffic is 600 Gbps. From Fig. 5, we can see that when the cost of a RS is 100, compared to our heuristic, the ILP decreases the regenerator site cost while slightly increases the transponder and regenerator costs. This is the reason why ILP outperforms the heuristic when the cost of a RS is high.

Experiment 2. In the second experiment, we investigate the performance of our heuristic algorithm under a large-scale network, and study how the total cost changes when the cost of a RS changes. The experiment is conducted on the 75-node CORONET CONUS topology [10]. The average traffic between each node pair is 600 Gbps.

From Fig. 6, we can see that the FG-MC algorithm has the best performance, while FG-SP has better performance than the SLR-100G and SLR-400G algorithms. When the cost of a RS is low, since the cost of a regenerator is much higher than that of a RS, FG-MC uses shortest path routing, and thus the performance of FG-MC and FG-SP are very close.

TABLE II
TOTAL COST VS. AVERAGE TRAFFIC (GBPS) BETWEEN EACH NODE PAIR UNDER DIFFERENT PER RS COST

Traffic	Per RS cost = 0.01		Per RS cost = 1		Per RS cost = 100	
	ILP	FG-MC	ILP	FG-MC	ILP	FG-MC
100	768.2	772.4	774.8	777.4	989.5	1080.6
200	1306.2	1319.2	1316.7	1324.1	1544.3	1634.3
300	1712.2	1726.0	1722.0	1730.9	2019.7	2109.5
400	2119.7	2124.6	2127.6	2132.5	2476.9	2837.7
500	2663.4	2669.8	2671.3	2677.8	3034.8	3383.5
600	3201.4	3215.1	3209.3	3223.0	3589.6	3929.3

However, along with the increase of the RS cost, the total cost obtained by FG-MC increases much slower than the other three approaches. The FG-MC algorithm can concentrate regenerators to form fewer RSs when the RS cost is high. The cost saving is around 22.0% when the cost of a RS is 1000.

Fig. 7 shows different equipments' costs when the costs of a RS are 1 and 1000, respectively. When the cost of a RS is 1, the cost of regenerator sites is low compared to other costs. The regenerator cost and transponder cost of the FG-MC are almost the same as those of the FG-SP, showing that FG-MC mostly chooses shortest paths under this situation. When the cost of a RS is 1000, FG-MC has a slight increase in the regenerator cost but saves a lot in regenerator site cost compared to the FG-SP, showing that in order to be cost-efficient, the FG-MC selects fewer regenerator sites by slightly increasing the path lengths.

Experiment 3. In the third experiment, we study the total cost under different network load in a large-scale network. The experiment is conducted on the 75-node CORONET CONUS topology [10]. The average traffic between each node pair ranges from 100 Gbps to 700 Gbps. The cost of a RS is 1000.

Fig. 8 shows that FG-MC has the best performance. Compared to the FG-SP algorithm, the average saving is around 28.5%. The SLR-400G approach has a stair-stepping increase in the total cost. The reason is that when the average traffic between each node pair increases by 100 Gbps, the 400 Gbps channel may still have vacant space for the increased traffic, thus no additional 400 Gbps channels are needed and the total cost remains the same.

Fig. 9 shows the spectrum usage of the network under different network load. Each link's spectrum usage is the total occupied channel width on the link times this link's distance. The spectrum usage of the network is the summation of all the links' spectrum usage. We can see that the SLR-400G approach has the least spectrum usage in most cases, since 400 Gbps is more spectrum-efficient than 100 Gbps in high network load. However, considering the extreme high costs as shown in previous figures, the SLR-400G approach is not practical. We can also see that our heuristic only increases the spectrum usage of the FG-SP algorithm by averagely 7.2%. Thus, our heuristic can save cost while not significantly

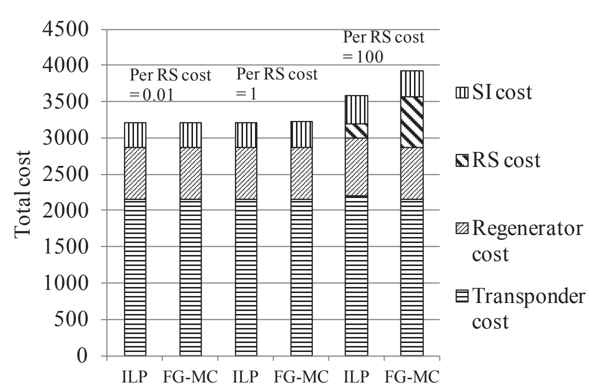

Fig. 5. Network equipment costs

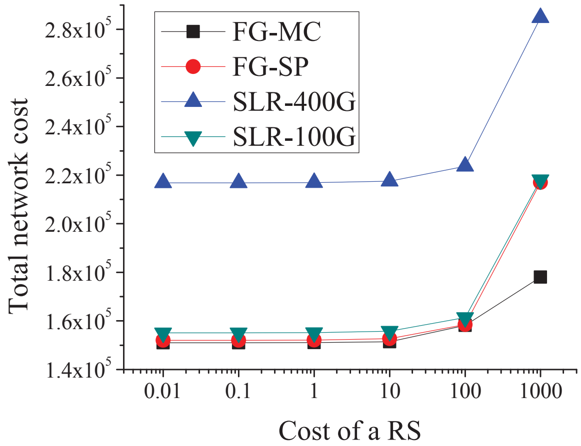

Fig. 6. Total cost vs. cost of a RS

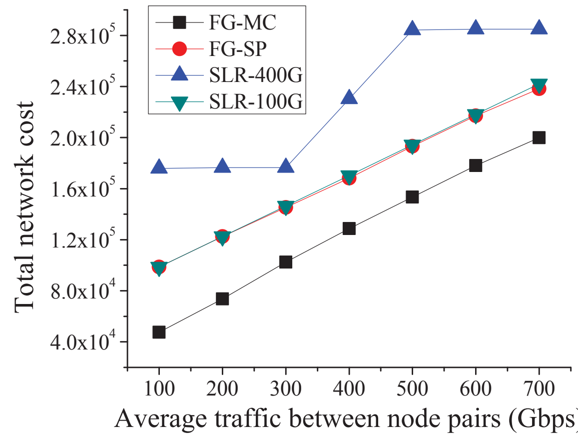

Fig. 8. Total cost vs. network load

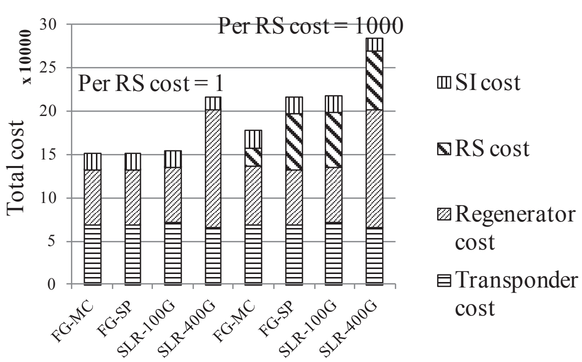

Fig. 7. Network equipment costs

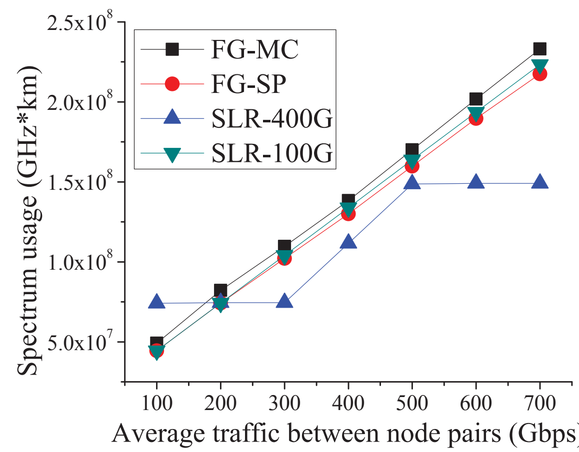

Fig. 9. Spectrum usage vs. network load

increasing the spectrum usage.

VI. Conclusion

In this paper, we focus on the problem of designing a cost-efficient flexible-grid optical network, which aims to minimize the total network cost including transponder cost, regenerator cost, RS cost, and the other shared infrastructure cost. The problem is formulated as an integer linear programming (ILP) model. We also propose a heuristic approach, named FG-MC, to solve large-scale cases. The numerical results show that the ILP can solve small-scale problems properly and that the total cost obtained by FG-MC is only slightly higher than that of the ILP model. Furthermore, we show that RS selection also plays an important role in designing economical flexible-grid optical networks. Selecting the RSs properly can save up to 28% in total network cost, while the spectrum usage is not significantly increased. One possible area of future work is to consider the problem together with protection.

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