Regenerator Site Selection for Mixed Line Rate Optical Networks

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***Abstract*—In this paper, we study the problem of regenerator site (RS) selection for mixed line rate optical networks (MLR-RSS), with the objective of minimizing the number of RSs for a given set of requests. We first provide the problem definition of MLR-RSS and show that the MLR-RSS problem is NP-complete. An integer linear programming model is formulated. We then present two heuristic algorithms, named the independent algorithm and the sequential algorithm, and two approximation algorithms, named the MLR-combined algorithm and the weighted MLR-combined algorithm. The performance of the algorithms is compared via simulation, and results show that the weighted MLR-combined algorithm has the best performance. Results suggest that our proposed MLR algorithm outperforms existing single line rate algorithms by more than 20%. Also, the RS distribution suggests that certain nodes in the network have a much higher probability of being chosen as RSs than the others.**

***Index Terms*—Approximation algorithms; Impairment-aware networking; Mixed line rates; Regenerator site selection.**

I. Introduction

In optical networks, physical degradation effects, such as noise, intra-crosstalk, linear impairments, and nonlinear fiber effects, cause the signal quality to degrade as the signal propagates through the network [1]. Furthermore, higher line rates tend to suffer greater impairments than lower line rates [2]. When the receiving optical signal-to-noise ratio (OSNR) is below a certain threshold, the receiver cannot receive the data correctly. The distance that an optical signal can travel before its quality and the bit error rate degrade to an unacceptable level is called the *reachability.* In order to guarantee successful transmission, 3R regenerators (reamplification, retiming, and reshaping) can be used in the optical network to restore the optical signal quality before the distance of the reachability. Properly selecting a small number of nodes as regenerator sites (RSs) can potentially reduce capital expenditure and operational expenditure compared to placing regenerators anywhere [3]. Expenditure can be reduced by predeploying regenerators at RSs, rather than sending on-site technicians to deploy regenerators on demand. The number of predeployed regenerators also tends to be smaller when there are fewer RSs. Furthermore, predeployed cards can be shared with spare units within the same hardware spare pool, which are generally available at a small number of hub sites. Thus, which nodes to select as RSs for an arbitrary network topology becomes an important problem.

Manuscript received June 19, 2013; revised December 10, 2013; accepted January 21, 2014; published February 20, 2014 (Doc. ID 192515).

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http://dx.doi.org/10.1364/JOCN.6.000291

The network cost can be reduced by assigning high data rate wavelengths to large traffic demands in order to exploit the lower unit cost of high data rate transponders. However, the reachability of such wavelength is significantly limited by physical impairments. Either expensive transmission equipment or more regenerators will be required to increase the reachability of high data rate signals [4]. Moreover, as the Internet continues to develop, traffic volume continues to increase and various new applications start to emerge. This trend requires future telecommunications networks to be more heterogeneous in order to support different applications. Thus, telecommunication networks should be able to support mixed line rates (MLRs) [2,4–7]. Current optical backbone networks support 10–40 Gbps line rates, while the need for 100 Gbps and higher line rates is growing.

A group of previous works attempt to concentrate the RSs when placing regenerators in single line rate (SLR) optical networks. In [8], it is proved that the RS selection problem is NP-complete when routes are not given with each source–destination (s–d) pair, and some heuristic approaches are proposed. In [9], the RS selection problem is considered under four scenarios, depending on whether or not a route is given with the request, and whether or not there is a limit on the number of regenerators at each node. It proves that the RS selection problem is NP-complete even if routes are given with each s–d pair, and that the problem is not approximable when there is a given bound on the number of regenerators that can be placed in a single node. In [10,11], the RSs are concentrated subject to a constraint that every s–d pair does not use more than the minimum number of regenerators of this s–d pair. A greedy heuristic approach is proposed to solve the problem. The work in [12] studies how to select RSs for providing any-to-any optical connectivity when each node pair has only one path to choose. In [13], the work is extended to consider multiple paths; that is, every node pair can choose a path from multiple path candidates. In [14], protection requirements are considered when selecting RSs. The authors try to minimize the number of RSs, subject to the constraint that every s–d pair has two disjoint paths. In [15] and [16], the authors try to minimize the number of required regenerators and concentrate them in a limited number of RSs. All of the above works consider RS selection in SLR optical networks only. Our work is different in that we consider MLR optical networks with different reachabilities, which makes the problem more complex.

Another group of papers considers regenerator placement under different objectives without concentrating regenerators. Among these papers, a group of papers [17–23] considers placing O/E/O 3R regenerators only. The work in [17] studies how to place regenerators to satisfy multiple sets of requests, such that different sets of requests can share a set of regenerators. The work in [18] and [19] jointly considers the placement of regenerators with routing and wavelength assignment (RWA), with the objective of minimizing the number of required regenerators and satisfying as many connection requests as possible, given a limited number of wavelengths. In [20], the authors study the problem of establishing a light-tree and assigning wavelengths with the objective of minimizing the number of regenerators. In [21], Shen *et al.* explore the physical layer heterogeneity of optical networks and develop a heuristic to minimize the number of regenerators under physical layer heterogeneity. The work in [22] studies how to place regenerators and grooming equipment to minimize the total equipment cost under both dedicated and shared connection-level protection. In [23], the authors study the 3R regenerator placement in MLR optical networks with the objective of minimizing the total energy consumption. Another group of papers [24–26] considers mixed regenerator placement, where all-optical 2R (reamplification and reshaping) regenerators are used to partially replace 3R regenerators. In [24], Zhu *et al.* show that using the 2R regenerators can greatly save the energy cost in offline network planning scenarios. They also compare the performance of their proposed algorithms in terms of blocking probability in online provisioning. Their work is extended in [25], where the authors study the mixed regenerator placement problem with a survivability constraint. In [26], the authors address the 2R/3R regenerator placement problem with the objective of minimizing the network cost. Different from their work, we consider how to concentrate the RSs in MLR optical networks. We will show that the number of RSs can be greatly reduced while hardly increasing the number of regenerators.

There are very limited works studying RS selection in MLR optical networks. In [27], the authors address the problem of minimizing the combined cost of RSs, optical switch ports, and regenerators. However, their work is specifically for waveband optical networks. Also, they only propose heuristic approaches without performance guarantees. In our work, we give approximation algorithms to solve the RS selection problem in general MLR optical networks. In [28], heuristic algorithms are developed to minimize the number of RSs in MLR optical networks where routing is not given with a request and any path can be chosen for a request. In [29], the authors extend the work to minimize the combined cost of regenerators and RSs. Our work is different in that the routing is given for each connection request. In practical scenarios, the routing may be predefined considering load balancing, energy consumption, equipment cost, or other factors, and thus it is necessary to study the RS selection problem when routing is given.

Our work considers RS selection for MLR optical networks under impairment constraints that are represented as the reachability for each line rate. The objective of our problem is to minimize the number of RSs. In this paper, we make the following assumptions: 1) the links in the optical network are bidirectional, 2) routing is given for each request, and 3) the number of regenerators in a RS is not limited.

The rest of this paper is organized as follows. In Section II, we provide a detailed description of the RS selection problem in MLR optical networks (MLR-RSS). In Section III, an integer linear programming (ILP) model is formulated for the MLR-RSS problem. In Section IV, two heuristic algorithms and two approximation algorithms are presented. Numerical simulation results are shown in Section V. Finally, we give a summary of our work in Section VI.

II. Regenerator Site Selection in Mixed Line Rate Optical Networks

A. Network Model

The optical network can be represented as a graph $G(\mathbf{V},\mathbf{E})$, where $\mathbf{V}$ is a set of nodes and $\mathbf{E}$ is a set of edges. For each request, a wavelength of the requested line rate is reserved along its given route, and regenerators are placed in the RSs along the route if needed.

In this paper, reachability is used to measure the effect of impairments. The reachabilities of different line rates are different because of different physical impairments and component tolerance. Thus, we use a set of reachabilities $\mathbf{D}$ to denote different line rates' reachabilities. For example, in Fig. 1, suppose we have two different line rates, lower rate l_1 and higher rate l_2, and the reachabilities for l_1 and l_2 are three hops and one hop, respectively. Thus, for Path 1 (4 hops) from Node 1 to Node 5, we need one regenerator for l_1. For Path 2 (four hops) from Node 1 to Node 5, we need three regenerators for l_2.

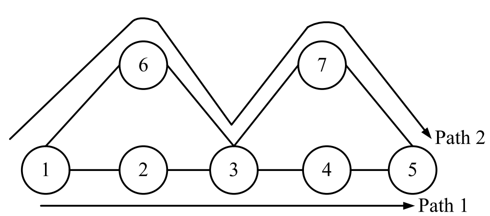


Fig. 1. Example of network and regenerator placement.

B. Problem Formulation

The MLR-RSS can be stated as follows:

Given physical topology $G(\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is a set of nodes and $\mathbf{E}$ is a set of edges; a set of line rates $\mathbf{L}$, $l_k \in \mathbf{L}$, $1 \le k \le |\mathbf{L}|$; a reachability set $\mathbf{D}$, $\delta_k \in \mathbf{D}$, $1 \le k \le |\mathbf{L}|$, where δ_k is the reachability of line rate l_k; and a set of traffic demands Λ in which a request is defined as $R[s, d, l_k, rt]$, where s is a source, d is a destination, l_k is the requested line rate, and rt is the actual route of the request.

Find the placement of RSs at nodes with the objective of minimizing the total number of RSs, such that

1) traffic constraint: all the requests are assigned the requested line rate;
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 δ_k.

An example is shown in Fig. 1. Suppose we have two requests r_1 [1, 5, l_1, (1-2-3-4-5)] and r_2 [1, 5, l_2, (1-6-3-7-5)]. The reachabilities for l_1 and l_2 are three hops and one hop, respectively. For r_1, we can select Node 2, Node 3, or Node 4 as a RS. For r_2, we have no choice but to select Node 6, Node 3, and Node 7 as RSs. Thus, Node 6, Node 3, and Node 7 are the optimal RS selections because only three sites are needed, which is the minimum possible number of RSs.

C. NP-Completeness

The decision version of the problem is as follows: given $G(\mathbf{V}, \mathbf{E})$, $\mathbf{L}$, $\mathbf{D}$, the traffic demand set Λ, and the total number of RSs NR, find the RS selections to meet the constraints such that the total number of RSs is no larger than NR. Given an instance of the problem, we use as a certificate a subset $\mathbf{U} \subseteq \mathbf{V}$. The verification algorithm checks whether all the constraints are satisfied and whether the number of elements in $\mathbf{U}$ is at most NR. This process can certainly be done in polynomial time. Thus, the problem belongs to the NP class.

In [9], it is proved that the RS selection problem in SLR optical networks is NP-complete. Since this problem is a special case of our problem when only a SLR is available, our problem is also NP-complete.

III. ILP Formulation

The ILP model has an input $\mathbf{R} = [r_{k,i,j}^{s,d}]_{|\mathbf{L}|\times|\mathbf{V}|\times|\mathbf{V}|}^{|\mathbf{V}|\times|\mathbf{V}|}$ to denote a modified version of the given path for a request from s to d using line rate l_k. The modified version of a given path is named the *reachability path*. $r_{k,i,j}^{s,d}$ equals 1 if edge (i,j) is on the *reachability path* from s to d using line rate l_k; otherwise it is 0. A *reachability path* is obtained by adding auxiliary links to the original given path. Given an original path as shown in Fig. 2(a), for any two nodes v_i and v_j on the path, if their distance on the given path is not larger than the reachability, an auxiliary link is placed between v_i and v_j. Figure 2(b) shows an example of the reachability path when reachabilities are two hops and three hops, respectively. We can see that for any path from s to d on the reachability path corresponding to line rate l_k, by placing line rate l_k's regenerators at all the intermediate nodes, the line rate l_k's signal is reachable from s to d on the given path.

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

1) Input parameters:
   - $\mathbf{R} = \left[r_{k,i,j}^{s,d}\right]_{|\mathbf{L}|\times|\mathbf{V}|\times|\mathbf{V}|}^{|\mathbf{V}|\times|\mathbf{V}|}$: set of reachability paths;
   - $\mathbf{REQ} = [\text{req}_{s,d,k}]_{|\mathbf{V}|\times|\mathbf{V}|\times|\mathbf{L}|}$: set of requests, $\text{req}_{s,d,k}$, equal to 1 if there is a request from s to d using line rate l_k; otherwise 0;
   - VL: a very large number;
2) Variables of ILP:
   - $\mathbf{X} = \left[x_{k,i,j}^{s,d}\right]_{|\mathbf{L}|\times|\mathbf{V}|\times|\mathbf{V}|}^{|\mathbf{V}|\times|\mathbf{V}|}$: $x_{k,i,j}^{s,d}$ equal to 1 if edge (i,j) on the reachability path from s to d using line rate l_k is selected; otherwise 0;
   - $\mathbf{Y} = [y_{k,i}^{s,d}]_{|\mathbf{L}|\times|\mathbf{V}|}^{|\mathbf{V}|\times|\mathbf{V}|}$: $y_{k,i}^{s,d}$ equal to 1 if a line rate l_k's regenerator is placed at Node i on the path from s to d; otherwise 0;
   - $\mathbf{Z} = [z_i]_{|\mathbf{V}|}$: z_i equal to 1 if Node i is selected as a RS; otherwise 0.
3) Objective:

   The objective of MLR-RSS is

$$\min \sum_{i=1}^{|\mathbf{V}|} z_i. \tag{1}$$

4) Constraints:

$$\sum_{j=1}^{|\mathbf{V}|} x_{k,s,j}^{s,d} - \sum_{j=1}^{|\mathbf{V}|} x_{k,j,s}^{s,d} = \text{req}_{s,d,k}, \quad \forall\ 1 \le s \le |\mathbf{V}|, \quad \forall\ 1 \le d \le |\mathbf{V}|, \quad \forall\ 1 \le k \le |\mathbf{L}|, \tag{2}$$

$$\sum_{j=1}^{|\mathbf{V}|} x_{k,j,d}^{s,d} - \sum_{j=1}^{|\mathbf{V}|} x_{k,d,j}^{s,d} = \text{req}_{s,d,k}, \quad \forall\ 1 \le s \le |\mathbf{V}|, \quad \forall\ 1 \le d \le |\mathbf{V}|, \quad \forall\ 1 \le k \le |\mathbf{L}|, \tag{3}$$

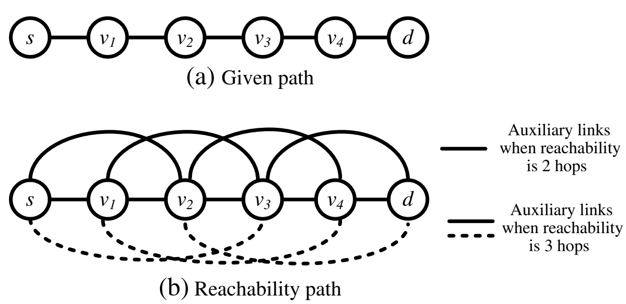


Fig. 2. Example of reachability path.

$$\sum_{i=1}^{|\mathbf{V}|} x_{k,i,j}^{s,d} = \sum_{i=1}^{|\mathbf{V}|} x_{k,j,i}^{s,d}, \quad \forall\, 1 \le s \le |\mathbf{V}|, \quad \forall\, 1 \le d \le |\mathbf{V}|, \quad \forall\, 1 \le k \le |\mathbf{L}|, \quad \forall\, 1 \le j \le |\mathbf{V}|,\ j \ne s, d. \tag{4}$$

Equations (2)–(4) guarantee the traffic constraint. In detail, Eq. (2) guarantees that when there is a request from s to d using line rate l_k, the source node s generates a traffic flow on the corresponding reachability path. Equation (3) guarantees that the traffic flow terminates at destination d on the corresponding reachability path. Equation (4) ensures that, for any intermediate node, the incoming flow and the outgoing flow should be the same:

$$x_{k,i,j}^{s,d} \le r_{k,i,j}^{s,d}, \quad \forall\, 1 \le s \le |\mathbf{V}|, \quad \forall\, 1 \le d \le |\mathbf{V}|, \quad \forall\, 1 \le k \le |\mathbf{L}|, \quad \forall\, 1 \le i \le |\mathbf{V}|, \quad \forall\, 1 \le j \le |\mathbf{V}|. \tag{5}$$

Equation (5) ensures that the routing of the request from s to d using line rate l_k is on the corresponding reachability path. By finding a path on the reachability path from s to d using line rate l_k and placing regenerators in the intermediate nodes, we can guarantee that the line rate l_k's signal is reachable between s and d:

$$y_{k,i}^{s,d} \ge x_{k,i,j}^{s,d}, \quad \forall\, 1 \le s \le |\mathbf{V}|, \quad \forall\, 1 \le d \le |\mathbf{V}|, \quad \forall\, 1 \le k \le |\mathbf{L}|, \quad \forall\, 1 \le i \le |\mathbf{V}|, \quad i \ne s, \quad \forall\, 1 \le j \le |\mathbf{V}|. \tag{6}$$

Equation (6) guarantees that for any edge on the reachability path from s to d using line rate l_k, a line rate l_k's regenerator is placed at the source end of the edge, excluding the source of the request s:

$$z_i \ge \frac{\sum_{s=1}^{|\mathbf{V}|} \sum_{d=1}^{|\mathbf{V}|} \sum_{k=1}^{|\mathbf{L}|} y_{k,i}^{s,d}}{VL}, \quad \forall\, 1 \le i \le |\mathbf{V}|. \tag{7}$$

Equation (7) ensures that for any node where a regenerator is placed, the node is selected as a RS.

IV. Algorithms

A. Approximation Algorithm for Single Line Rate Optical Networks

In [9], an approximation algorithm is proposed for the RS selection problem in SLR optical networks (SLR-RSS). As this algorithm will be used as a subroutine in our heuristic approaches, it is necessary to describe the algorithm in this paper. We call this algorithm the SLR-combined algorithm in the following sections.

The SLR-combined algorithm reduces the SLR-RSS problem to the set cover problem [30]. The input of the algorithm is a network $G(\mathbf{V}, \mathbf{E})$, a set of requests with given routes $\{[s_1, d_1], [s_2, d_2], \ldots, [s_m, d_m]\}$, $s_i \ne d_i$, $s_i, d_i \in \mathbf{V}$, where $[s_i, d_i]$ is a given route from source s_i to destination d_i. The input also includes a reachability $\delta > 0$. Since the SLR-combined algorithm is for SLR optical networks, only one reachability is needed as input. The output of the algorithm is a set of nodes $\mathbf{U} \subseteq \mathbf{V}$ that are selected as RSs. The algorithm process is divided into two cases depending on whether δ is odd or even.

If δ is odd, let $\mathbf{A} = \{a_{v,i} | v \in \mathbf{V}, v \in [s_i, d_i]\}$, and $\mathbf{B} = \cup\{b_v | v \in \mathbf{V}\}$. Let P_v be the set of paths that cross node v. For every path $p \in P_v$, the set b_v includes the following two types of elements: 1) all the elements in $\mathbf{A}$ corresponding to the nodes of p having a distance from v that is less than or equal to $(\delta - 1)/2$, and 2) if the distance between either endpoint of path p and node v is less than or equal to δ, then add to set b_v all the elements in $\mathbf{A}$ corresponding to all the nodes of p between v and such an endpoint.

If δ is even, let $\mathbf{A} = \{a_{j,i} | e_j \in \mathbf{E}, e_j \in [s_i, d_i]\}$, and $\mathbf{B} = \cup\{b_v | v \in \mathbf{V}\}$. Let P_v be the set of paths that cross node v. We define the distance between a node and the edges incident to it to be 1. For every path $p \in P_v$, the set b_v includes the following two types of elements: 1) all the elements in $\mathbf{A}$ corresponding to the edges of p having a distance from v that is less than or equal to $\delta/2$, and 2) if the distance between either endpoint of path p and node v is less than or equal to δ, then add to set b_v all the elements in $\mathbf{A}$ corresponding to all the edges of p between v and such an endpoint.

After $\mathbf{A}$ and $\mathbf{B}$ are found, the set cover algorithm in [30] is applied to find the minimum number of subsets $\mathbf{G} \subseteq \mathbf{B}$ that cover $\mathbf{A}$. If the solution obtained is $\mathbf{G} = \{b_{v_1}, b_{v_2}, \ldots, b_{v_t}\}$, then nodes $\mathbf{U} = \{v_1, v_2, \ldots, v_t\}$ are selected as RSs.

In [30], it is proved that the ratio between the results obtained by the set cover algorithm and the optimal value grows at most logarithmically in the largest cardinality of the subset; that is, the approximation ratio of the set cover algorithm proposed in [30] is $O(\log(\max_i |b_i|))$. In the SLR-combined algorithm, when node i is on the middle of all the paths of the requests, and both the distance between node i and the source and the distance between node i and the destination are δ, then b_i has the largest possible cardinality, which is $2m\delta$. Thus, the approximation ratio of the SLR-combined algorithm is $O(\log m + \log \delta)$.

An example is shown below to illustrate this algorithm. Consider the topology in Fig. 1. There is only one line rate l in the network. There are two requests, r_1 [1, 5, l, (1-2-3-4-5)] and r_2 [1, 5, l, (1-6-3-7-5)]. The reachability of a line rate l's signal is three hops. Then, by running the SLR-combined algorithm, we have

$$\mathbf{A} = \{a_{1,1}, a_{2,1}, a_{3,1}, a_{4,1}, a_{5,1}, a_{1,2}, a_{6,2}, a_{3,2}, a_{7,2}, a_{5,2}\},$$
$$b_1 = \{a_{1,1}, a_{2,1}, a_{1,2}, a_{6,2}\},$$
$$b_2 = \{a_{1,1}, a_{2,1}, a_{3,1}, a_{4,1}, a_{5,1}\},$$
$$b_3 = \{a_{1,1}, a_{2,1}, a_{3,1}, a_{4,1}, a_{5,1}, a_{1,2}, a_{6,2}, a_{3,2}, a_{7,2}, a_{5,2}\},$$
$$b_4 = \{a_{1,1}, a_{2,1}, a_{3,1}, a_{4,1}, a_{5,1}\},$$
$$b_5 = \{a_{4,1}, a_{5,1}, a_{7,2}, a_{5,2}\},$$
$$b_6 = \{a_{1,2}, a_{6,2}, a_{3,2}, a_{7,2}, a_{5,2}\},$$
$$b_7 = \{a_{1,2}, a_{6,2}, a_{3,2}, a_{7,2}, a_{5,2}\}.$$

The set cover algorithm in [30] is then applied to **A** and **B**. Obviously, b_3 alone has all the elements in **A**, so b_3 is the solution, which means only Node 3 is selected as a RS.

B. Heuristic Approaches for Mixed Line Rate Optical Networks

To deal with MLR optical networks, the first approach is to run the above SLR-combined algorithm for each of the line rates $l_1, l_2, \ldots, l_n$ to obtain the results $\boldsymbol{U_1}, \boldsymbol{U_2}, \ldots, \boldsymbol{U_n}$. The final result $\mathbf{U}$ is the union of $\boldsymbol{U_1}, \boldsymbol{U_2}, \ldots, \boldsymbol{U_n}$. As this approach deals with each line rate independently, we call it the independent algorithm.

The full algorithm is described in Algorithm 1. The independent algorithm places RSs for each line rate without considering the placement of RSs of other line rates. To improve this, we can place RSs for each line rate sequentially; that is, when placing RSs for one line rate, we consider reusing the already placed RSs first. If one request cannot be satisfied with the already placed RSs, we take the *unsatisfied segment* of the request and put it in a remaining requests set $\boldsymbol{RR}$. The *unsatisfied segment* is defined as follows. Given a request of line rate l_k with the routing $[s, v_1, v_2, \ldots, d]$, s, d, $v_i \in \mathbf{V}$, take any two of the neighboring RSs v_i and v_{i+x}, which are already placed, along this path. If $x > \delta_k$, then $[v_i, v_{i+1}, \ldots, v_{i+x-1}, v_{i+x}]$ is an unsatisfied segment. Also, if the distance between s and its nearest RS v_i or the distance between d and its nearest RS v_j is greater than δ_k, then $[s, v_1, v_2, \ldots, v_i]$ or $[v_j, v_{j+1}, \ldots, d]$ is also an unsatisfied segment. After all the unsatisfied segments of all the requests of a corresponding line rate are found, we run the SLR-combined algorithm again on the remaining request set $\boldsymbol{RR}$ and add the results to the already placed RSs. We call this algorithm the sequential algorithm. If the algorithm starts with the highest line rate, then it is a sequential high line rate first (sequential HLRF) algorithm. Otherwise, if the algorithm starts with the lowest line rate, then it is a sequential low line rate first (sequential LLRF) algorithm.

Algorithm 1 Independent Algorithm

Input: graph $G(\mathbf{V}, \mathbf{E})$, the available line rate set $\mathbf{L}$, the reachability set $\mathbf{D}$, and the request set Λ.
Output: a subset $\mathbf{U} \subseteq \mathbf{V}$ that denotes the nodes selected as RSs.
//Main procedure
Begin
for all line rate l_i, $l_i \in \mathbf{L}$ **do**
  Run the SLR-combined algorithm and obtain the result $\boldsymbol{U_i}$.
end for
$\mathbf{U} = \bigcup \boldsymbol{U_i}$.
End

The full sequential HLRF algorithm is described in Algorithm 2.

Algorithm 2 Sequential HLRF Algorithm

Input: graph $G(\mathbf{V}, \mathbf{E})$, the available line rate set $\mathbf{L}$, the reachability set $\mathbf{D}$, and the request set Λ.
Output: a subset $\mathbf{U} \subseteq \mathbf{V}$ that denotes the nodes selected as RSs.
//Main procedure
Begin
$\mathbf{U} = \varnothing$.
for line rate l_i from l_n (highest rate) to l_1 (lowest rate) **do**
  for all paths p of line rate l_i **do**
    if path p cannot be satisfied with the already placed RSs $\mathbf{U}$ **then**
      Take the unsatisfied segment of p and add it to set $\boldsymbol{RR_i}$.
    end if
  end for
  Run the SLR-combined algorithm on $\boldsymbol{RR_i}$ and obtain the result $\boldsymbol{U_i}$.
  $\mathbf{U} = \mathbf{U} \cup \boldsymbol{U_i}$.
end for
End

C. Approximation Algorithms for Mixed Line Rate Optical Networks

The third approach places RSs neither from the highest line rate nor from the lowest line rate, but combines these two. This approach is called the MLR-combined algorithm. The MLR-combined algorithm differs from the SLR-combined algorithm in that for each element in sets **A** and b_v, $v \in \mathbf{V}$, we add one more index to denote the line rate. For line rate l_k, $\mathbf{A} = \{a_{v,i,k} | v \in \mathbf{V}, v \in [s_i, d_i]\}$ (when δ_k is odd), or $\mathbf{A} = \{a_{j,i,k} | e_j \in \mathbf{E}, \in [s_i, d_i]\}$ (when δ_k is even), where k is the index of line rate l_k. Then for each line rate, we add to set b_v the above mentioned two types of elements of the corresponding line rate. At the end, the set cover algorithm in [30] is applied to obtain the solution.

The full algorithm is described in Algorithm 3. Let $m_1, m_2, \ldots, m_n$ denote the number of paths of line rates $l_1, l_2, \ldots, l_n$. Since the largest possible cardinality of each set of **B** is $\sum_{i=1}^{n} 2m_i\delta_i$, the approximation ratio of the MLR-combined algorithm is $O(\log(\sum_{i=1}^{n} 2m_i\delta_i))$.

Algorithm 3 MLR-Combined Algorithm

Input: graph $G(\mathbf{V}, \mathbf{E})$, the available line rate set $\mathbf{L}$, the reachability set $\mathbf{D}$, and the request set Λ.
Output: a subset $\mathbf{U} \subseteq \mathbf{V}$ that denotes the nodes selected as RSs.
Begin
//Initial phase
if δ_k is odd **then**
  Let $\mathbf{A} = \{a_{v,i,k} | v \in \mathbf{V}, v \in [s_i, d_i], l_k \in \mathbf{L}\}$ for all v, i, k.
else
  Let $\mathbf{A} = \{a_{j,i,k} | e_j \in \mathbf{E}, e_j \in [s_i, d_i], l_k \in \mathbf{L}\}$ for all j, i, k.
end if
//Main procedure
for line rate l_k from l_1 to l_n **do**
  if δ_k is odd **then**

for all $v \in \mathbf{V}$ **do**
Let P_v be the set of paths that cross node v.
for all $p \in p_v$ **do**
add to set b_v two types of elements
1) all the elements in $\mathbf{A}$ corresponding to the nodes of p having a distance from v that is less than or equal to $(\delta_k - 1)/2$;
2) if the distance between either endpoint of path p and node v is less than or equal to δ_k, then add to set b_v all the elements in $\mathbf{A}$ corresponding to all the nodes of p between v and such an endpoint.
end for
end for
else if δ_k is even **then**
for all $v \in \mathbf{V}$ **do**
Let P_v be the set of paths that cross node v.
for all $p \in P_v$ **do**
add to set b_v two types of elements
1) all the elements in $\mathbf{A}$ corresponding to the edges of p having a distance from v that is less than or equal to $\delta_k/2$;
2) if the distance between either endpoint of path p and node v is less than or equal to δ_k, then add to set b_v all the elements in $\mathbf{A}$ corresponding to all the edges of p between v and such an endpoint.
end for
end for
end if
end for
//Apply set cover algorithm
while $b_v \neq \emptyset$ for any $v \in \mathbf{V}$ **do**
Find a set b_v with the maximum cardinality $|b_v|$;
Add v to set $\mathbf{U}$, replace each b_i, $i \in \mathbf{V}$, by $b_i - b_v$.
end while
End

In the set cover algorithm part of the MLR-combined algorithm, we select the set b_v with the maximum cardinality without considering what line rates' elements are included in this set. Suppose a high line rate request and a low line rate request pass the same node v. There may be more elements of the low line rate request in the set b_v than the high line rate request, since the low line rate usually has longer reachability than the high line rate. If cardinality is the only metric when selecting the next set, then we indeed give low line rate a higher priority, especially when the reachability of low line rate is much longer than the high line rate. An example is shown in Fig. 3. In this example, we have two requests, r_1 [1, 7, l_1, (1-2-3-4-5-6-7)] and r_2 [1, 7, l_2, (1-8-3-9-5-6-7)]. Assume the reachabilities of l_1 and l_2 are three hops and one hop, respectively. Then we have

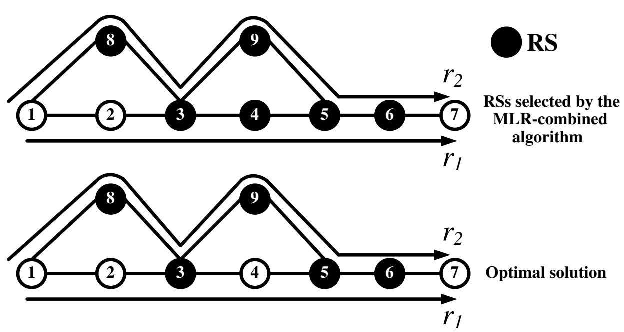


Fig. 3. Example of a suboptimal solution obtained by the MLR-combined algorithm.

$$
\begin{aligned}
\mathbf{A} = \{&a_{1,1,1}, a_{2,1,1}, a_{3,1,1}, a_{4,1,1}, a_{5,1,1}, a_{6,1,1}, a_{7,1,1},\\
&a_{1,2,2}, a_{8,2,2}, a_{3,2,2}, a_{9,2,2}, a_{5,2,2}, a_{6,2,2}, a_{7,2,2}\},\\
b_1 &= \{a_{1,1,1}, a_{2,1,1}, a_{1,2,2}\},\\
b_2 &= \{a_{1,1,1}, a_{2,1,1}, a_{3,1,1}\},\\
b_3 &= \{a_{1,1,1}, a_{2,1,1}, a_{3,1,1}, a_{4,1,1}, a_{3,2,2}\},\\
b_4 &= \{a_{1,1,1}, a_{2,1,1}, a_{3,1,1}, a_{4,1,1}, a_{5,1,1}, a_{6,1,1}, a_{7,1,1}\},\\
b_5 &= \{a_{4,1,1}, a_{5,1,1}, a_{6,1,1}, a_{7,1,1}, a_{5,2,2}\},\\
b_6 &= \{a_{5,1,1}, a_{6,1,1}, a_{7,1,1}, a_{6,2,2}, a_{7,2,2}\},\\
b_7 &= \{a_{6,1,1}, a_{7,1,1}, a_{7,2,2}\},\\
b_8 &= \{a_{1,2,2}, a_{8,2,2}\},\\
b_9 &= \{a_{9,2,2}\}.
\end{aligned}
$$

The MLR-combined algorithm selects b_4 first, but as shown in Fig. 3, this is not the optimal solution. Although b_4 has the largest cardinality, its elements are all low line rate's elements. Since low line rate has more elements than high line rate, we should not simply choose the set with the largest cardinality. A solution to solve the problem is assigning different weights to different line rates to compensate for the difference in reachabilities.

We associate a weight α_i with each line rate l_i. The total weight of set b_v is $W_v = \alpha_1 N_1 + \alpha_2 N_2 + \cdots + \alpha_n N_n + \epsilon |b_v|$, where N_i is the number of elements corresponding to line rate l_i in b_v, $\sum_i \alpha_i = 1$, and ϵ is a very small constant value. The optimal values of $\alpha_1, \alpha_2, \ldots, \alpha_n$ can be found through experiments. By adding a weight to each line rate, we have the weighted MLR-combined algorithm. This algorithm differs from the MLR-combined algorithm only in the final set cover algorithm. In the MLR-combined algorithm, a set b_v with the maximum cardinality $|b_v|$ is selected, while in the weighted MLR-combined algorithm, a set b_v with the maximum weight $W_v = \alpha_1 N_1 + \alpha_2 N_2 + \cdots + \alpha_n N_n + \epsilon |b_v|$ is selected. Since the MLR-combined algorithm is a special case of the weighted MLR-combined algorithm when the weights of all line rates are equal, the performance of the weighted MLR-combined algorithm will not be worse than that of the MLR-combined algorithm. Thus, the approximation ratio of the weighted MLR-combined algorithm is also $O(\log(\sum_{i=1}^{n} 2m_i\delta_i))$.

V. Numerical Results

In this section, we present some numerical results in order to compare the performance of the independent, sequential HLRF, sequential LLRF, MLR-combined, and weighted MLR-combined algorithms, and the ILP model.

The heuristic and approximation algorithms are implemented in Java, and the ILP model is solved by IBM ILOG CPLEX Optimization Studio v12.2. All the simulation experiments are performed on a server with 16×2.4 GHz processors and 12 GB memory. In the simulation, we choose two line rates: 100 and 400 Gbps. Experiments 1 to 4 test the average number of RSs and regenerators under different network loads, different ratios of 100 Gbps requests, different reachabilities of 100 Gbps signal, and different reachabilities of 400 Gbps signal, respectively. Experiments 5 and 6 investigate the RS distribution under uniform traffic and nonuniform traffic, respectively.

For Experiments 1 and 2, the ILP is tested on the 24-node network shown in Fig. 4, while the algorithms are tested on both the 24-node network and the 75-node CORONET [31] shown in Fig. 5. Experiments 3 to 6 are conducted on the 75-node CORONET only. Experiments 1 to 5 are under uniform traffic. When generating uniform traffic, every node in the network has equal probability to be selected as a source or destination. Experiment 6 is conducted on CORONET with nonuniform traffic. When generating nonuniform traffic, we select the 25 most populated cities, and these cities' probabilities of being chosen as sources or destinations are 10 times higher than those of the other 50 cities. For the 24-node network, we precalculate a set of paths for each s–d pair. When generating a request for the 24-node network, we first determine the source node and the destination node, and then a path is randomly chosen from the set of paths, which have hop counts more than the corresponding line rate's reachability, between this s–d pair. When generating a request for the 75-node CORONET, different from the 24-node network, we always use the shortest hop distance path for every s–d pair. If the shortest hop distance is not greater than the corresponding line rate's reachability, we discard this s–d pair and randomly select another s–d pair until its shortest hop distance is greater than the corresponding line rate's reachability. There are no two requests with the same end nodes, unless they require different line rates. The experiment results are average values of more than 50 simulation runs on the 24-node network or more than 1000 simulation runs on the 75-node CORONET. We have fewer simulation runs on the 24-node network due to the long running time of ILP.

The reachabilities of 100 and 400 Gpbs are assumed to be five hops and three hops, respectively, except

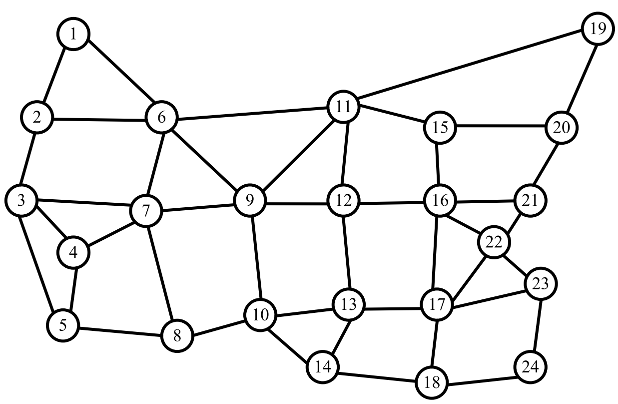


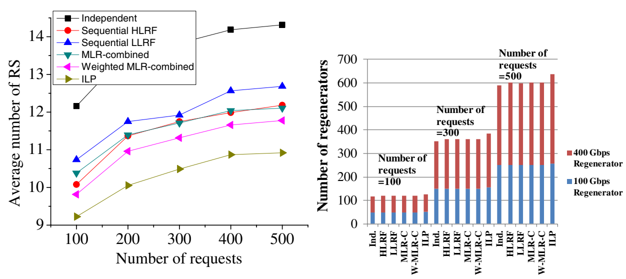
Fig. 4. 24-node network topology.

Fig. 5. 75-node CORONET [31].

Experiments 3 and 4, in which different reachabilities are tested. In the simulation, given a total number of requests, half of them are 100 Gbps requests, and the other half are 400 Gbps requests, except Experiment 2, in which this ratio is changed. For the weighted MLR-combined algorithm, we have a weight α associated with 100 Gbps and a weight $\beta = 1 - \alpha$ associated with 400 Gbps. The value of α is determined as follows: we compare all the results obtained by the weighted MLR-combined algorithm when $\alpha = 0, 0.1, 0.2, \ldots,$ or 1, and choose the α value that leads to the best results. The ϵ value is set to 10^{-4}.

Experiment 1. In the first experiment, we study the average number of RSs and regenerators under different network load.

We first test the algorithms and the ILP on the 24-node network. As Fig. 6(a) depicts, the weighted MLR-combined algorithm has the best performance among all the algorithms, and its performance is only slightly worse than that of the ILP. The difference of the weighted MLR-combined algorithm and the ILP is 7.7% on average, which is not more than one RS in the 24-node network. The performance of the independent algorithm is the worst, as it simply combines the results of two line rates' RS selection without considering sharing RSs among different line rates. The independent algorithm increases the number of RSs by 22.7% on average, compared to the weighted MLR-combined algorithm. This result shows that selecting RSs for all the line rates together is better than selecting RSs for each line rate independently and combining them. Thus, the existing SLR algorithm is not effective for MLR



(a) Number of RSs (b) Number of regenerators

Fig. 6. Average number of RSs and regenerators versus total number of requests for the 24-node network.

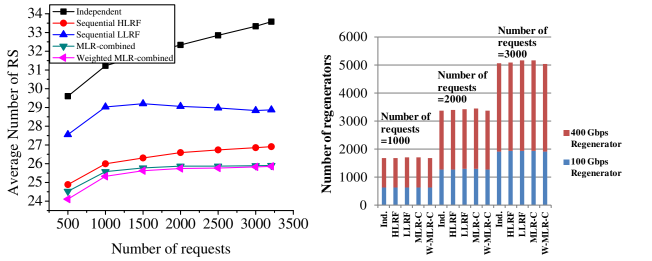
networks, and we need MLR algorithms, such as the weighted MLR-combined algorithm, for MLR networks. The sequential HLRF algorithm outperforms the sequential LLRF algorithm, because under this specific setting, the placement of RSs for the lower line rate has more flexibility due to the longer reachability; thus, starting from the high line rate enables the lower line rate to better reuse those RSs that are placed for the higher line rate.

Figure 6(b) shows the average number of regenerators when the total number of requests is 100, 300, and 500, respectively, under the 24-node network. In Fig. 6(b), “Ind.,” “HLRF,” “LLRF,” “MLR-C,” “W-MLR-C,” and the “ILP” refer to the independent, sequential HLRF, sequential LLRF, MLR-combined, and weighted MLR-combined algorithms, and the ILP model, respectively. These abbreviations apply to the following figures as well. From Fig. 6(b), we can see that the independent algorithm results in the fewest number of regenerators; however, the number of regenerators used by other algorithms is very close to that of the independent algorithm. The ILP model uses the most regenerators. Since the objective of the ILP is just to minimize the number of RSs, it may result in a considerably larger number of regenerators.

We then test the algorithms on the 75-node CORONET. The ILP was not able to obtain a solution for this network. Figure 7(a) shows the average number of RSs. It shows that the weighted MLR-combined algorithm has the best performance. The independent algorithm requires an additional 26.0% more RSs than the weighted MLR-combined algorithm. Figure 7(b) shows the average number of regenerators. From Fig. 7(b), we can see that the weighted MLR-combined algorithm does not use more regenerators than the independent algorithm. Sometimes the number of regenerators used by the weighted MLR-combined algorithm is even lower than that of the independent algorithm. This result shows that the weighted MLR-combined algorithm can select RSs wisely. The number of RSs can be reduced, while the number of regenerators is not increased.

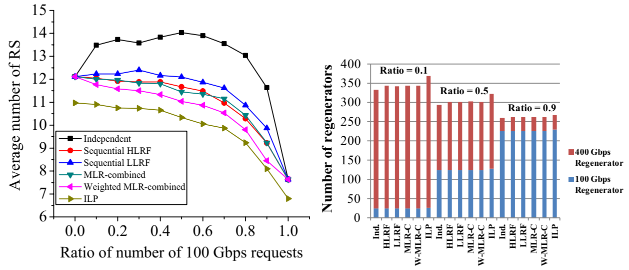
Experiment 2. In the second experiment, we study the average number of RSs and regenerators under different ratios of 100 Gbps requests to the total number of requests.

For the experiment on the 24-node network, the total number of requests in the network is 250. The number of 100 Gbps requests changes from 0% to 100% of the total



(a) Number of RSs (b) Number of regenerators

Fig. 7. Average number of RSs and regenerators versus total number of requests for the 75-node network.

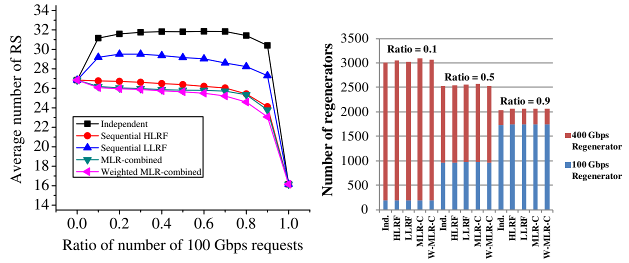


(a) Number of RSs (b) Number of regenerators

Fig. 8. Average number of RSs and regenerators versus different ratios of 100 Gbps requests in total number of requests for the 24-node network.

number of requests. Figure 8(a) shows that, although the ILP has the best performance, the weighted MLR-combined algorithm only increases the number of RSs by 7.6% on average, compared to the ILP; that is, not more than one additional RS is required. Meanwhile, the independent algorithm uses 20.7% more RSs than the weighted MLR-combined algorithm. When the ratio is 0 or 1, all the algorithms, except the ILP, will have the same results. This is because when the ratio is 0 or 1, the requests will all be 400 Gbps requests or 100 Gbps requests. In this case, the independent, sequential HLRF, sequential LLRF, MLR-combined, and weighted MLR-combined algorithms will operate as the SLR-combined algorithm since there are only one line rate's requests. Figure 8(b) shows the average number of regenerators. We can see that the ILP uses more regenerators than the other algorithms, and by around 5.7% on average more than that of the weighted MLR-combined algorithm.

The algorithms are then tested on the 75-node network. The total number of requests in the network is 1500. As Fig. 9(a) depicts, the weighted MLR-combined algorithm still outperforms the other algorithms. Specifically, the weighted MLR-combined algorithm reduces the number of RSs by 20.2% on average compared to the independent algorithm. When the ratio of 100 Gbps requests is low, the average number of RSs obtained by all the algorithms does not change much, because when the ratio of 100 Gbps requests is low, the placement of RSs is mainly for 400 Gbps requests, and these sites are sufficient to satisfy 100 Gbps requests. From Fig. 9(b), we can see that although the weighted MLR-combined algorithm shows a little increase



(a) Number of RSs (b) Number of regenerators

Fig. 9. Average number of RSs and regenerators versus different ratios of 100 Gbps requests in total number of requests for the 75-node network.

in the the number of regenerators compared to that of the independent algorithm, the difference is negligible.

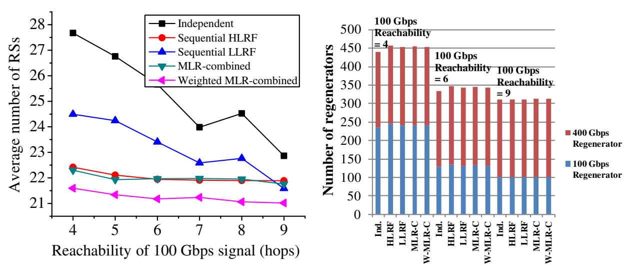
Experiment 3. In the third experiment, we study the average number of RSs and regenerators while varying the reachability of the 100 Gbps signal. The reachability of the 400 Gbps signal is three hops, and the reachability of the 100 Gbps signals ranges from four to nine hops.

The algorithms are tested on the 75-node network. The total number of requests in the network is 200. As Fig. 10(a) shows, the weighted MLR-combined algorithm has the best performance, and it outperforms the independent algorithm by 18.8% on average. The number of RSs obtained by the sequential HLRF, the MLR-combined, and the weighted MLR-combined algorithms almost does not change. The reason is that, under this network load and the reachabilities, the RSs are mainly determined by the 400 Gbps requests. The RSs determined by the 400 Gbps requests are sufficient for 100 Gbps requests, even when the 100 Gbps reachability is four hops. Thus, no matter how the reachability of the 100 Gbps signal increases, the RSs are always determined by the 400 Gbps requests, and thus the number of RSs does not change. However, if we start from the lower rate, the RSs selected by the lower rate may not be reused by the higher rate, thus resulting in more RSs than starting from the higher rate. This is why the sequential LLRF algorithm requires more RSs than the sequential HLRF algorithm when the 100 Gbps reachability is short. When the reachability of the 100 Gbps signal grows, the performance of the sequential LLRF algorithm will become better than that of the sequential HLRF algorithm. Although starting from 400 Gbps requests means that 100 Gbps requests have a higher possibility to reuse those RSs that are placed for 400 Gbps requests, when the need for RSs for 100 Gbps becomes less, the advantage of sequential HLRF over sequential LLRF becomes weaker. On the other hand, when the need for RSs for 100 Gbps requests becomes less, starting from 100 Gbps requests means that we start from a smaller number of RSs, and these RSs are more likely to be reused by 400 Gbps requests; thus, sequential LLRF will outperform sequential HLRF when the reachability of the 100 Gbps signal grows. Figure 10(b) shows that the number of regenerators used by the weighted MLR-combined algorithm is almost the same as that of the independent algorithm.

Experiment 4. In the fourth experiment, we study the average number of RSs and regenerators while varying the reachability of the 400 Gbps signal. The reachability of the 100 Gbps signal is nine hops, and the reachability of the 400 Gbps signals ranges from three to eight hops.

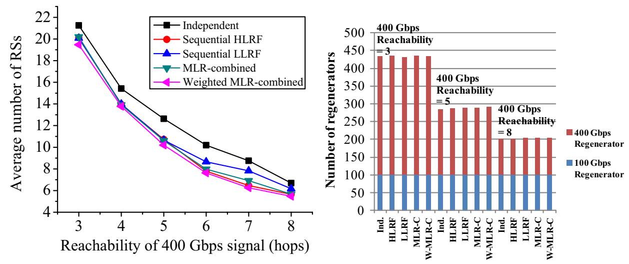
The algorithms are tested on the 75-node network. The total number of requests in the network is 200. Again, as Fig. 11(a) shows, the weighted MLR-combined algorithm has the best performance, and it outperforms the independent algorithm by 23.3%, on average. For all algorithms, the number of RSs decreases as the reachability of the 400 Gbps signal increases. Comparing Figs. 10(a) and 11(a), the number of RSs may not decrease when the reachability of the 100 Gbps signal increases; however, the number of RSs will decrease when the reachability of the 400 Gbps signal increases. Thus, when the number of 100 Gbps requests and 400 Gbps requests is the same, the number of RSs mainly depends on the reachability of the 400 Gbps signal, since the RSs placed by 400 Gbps requests may be reused by the 100 Gbps requests. This result suggests that when the number of different line rates' requests is not much different, the RSs are mostly determined by the higher rates. Figure 11(b) shows that the number of regenerators used by the weighted MLR-combined algorithm is almost the same as that of the independent algorithm, showing that the weighted MLR-combined algorithm can concentrate RSs without using many more regenerators.

Experiment 5. In the fifth experiment, we study how the RSs are distributed in the network under uniform traffic. Specifically, we study whether there are certain nodes in the network that are more likely to be chosen as RSs. We use the results obtained by the weighted MLR-combined algorithm in Experiment 1. The traffic is uniform; i.e., each node has equal probability to be chosen as a source or destination. Let $C_{i,j}$ denote the number of times node i is chosen as a RS under network load j, and let H_j denote the number of simulation runs under network load j. Then, the probability of node i being chosen as a RS under network load j is defined as $\mathrm{prob}_{i,j} = C_{i,j}/H_j$. We then visualize the network based on $\mathrm{prob}_{i,j}$, in which each network node's size, color, and shape are determined by its $\mathrm{prob}_{i,j}$. Figures 12(a)–12(c) show the networks under network load of 1000, 2000, and 3000 total requests, respectively. In the figures, a node is originally a circle. The circle is bigger and



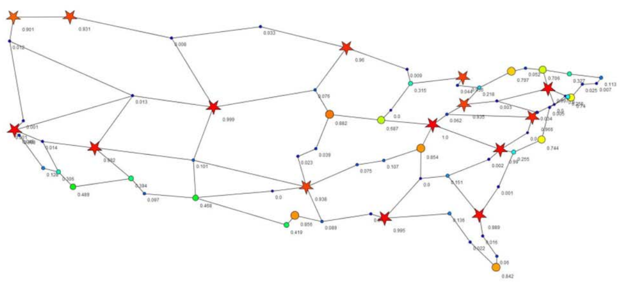
(a) Number of RSs (b) Number of regenerators

Fig. 10. Average number of RSs and regenerators versus different reachabilities of 100 Gbps signal for the 75-node network.

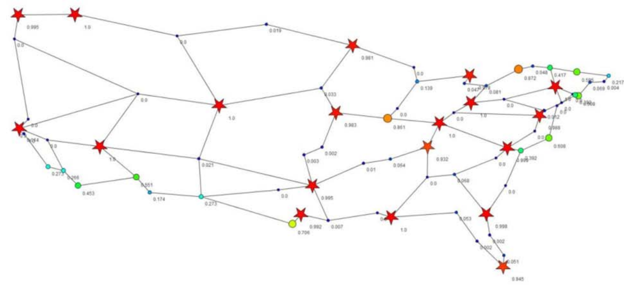


(a) Number of RSs (b) Number of regenerators

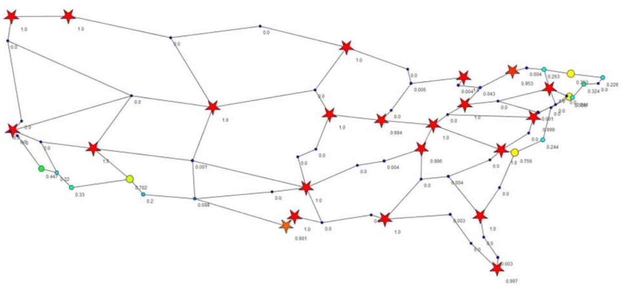
Fig. 11. Average number of RSs and regenerators versus different reachabilities of 400 Gbps signal for the 75-node network.



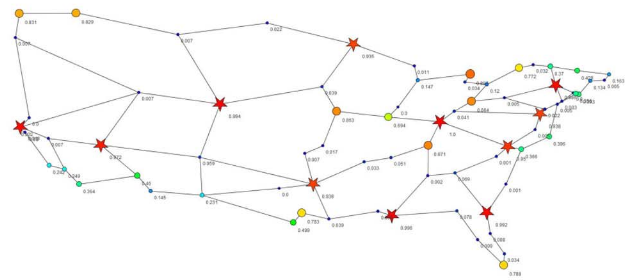
(a) RS distribution (1000 requests)



(b) RS distribution (2000 requests)



(c) RS distribution (3000 requests)



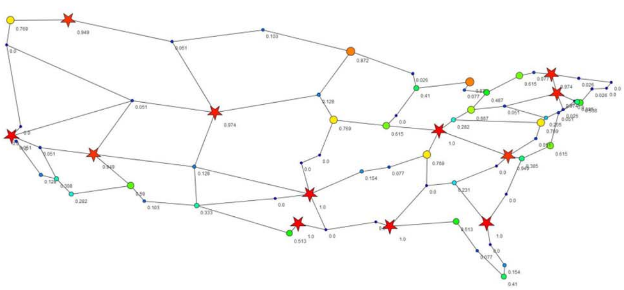
(d) RS distribution (SDPE)

Fig. 12. RS distribution under uniform traffic.

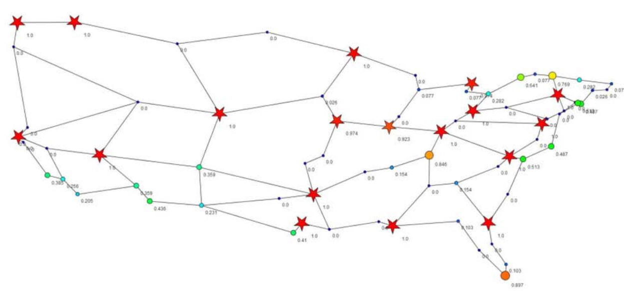
redder with higher $\text{prob}_{i,j}$, and finally, those nodes with $\text{prob}_{i,j}$ larger than 90% are transformed into stars.

From Figs. 12(a)–12(c), we can see that some nodes have extremely high probabilities (more than 90%), while some nodes have very low probabilities (less than 1%). This polarization is even more obvious when the network load increases; that is, the high probability node has even higher probability and the low probability node has even lower probability. The reason is that given a fixed set of s–d pairs to choose, when the network load is high, the traffic pattern is more certain. That is, under high traffic load, the set of requests changes less in different simulation runs than the low traffic load. The RS distribution is more certain when the traffic pattern is more certain.

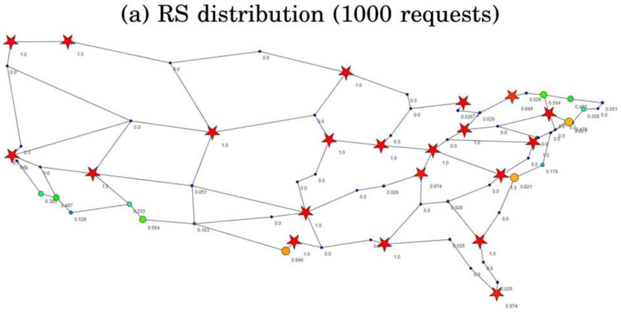
To further evaluate the probabilities under different network load, we have the following statistical calculation. First, we have the average probability of $\text{prob}_{i,j}$ under J different network loads, which is $\text{prob}_i = (\sum_{j=1}^{J} \text{prob}_{i,j})/J$.



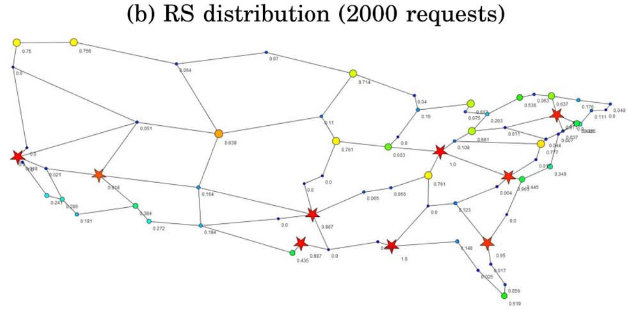
(a) RS distribution (1000 requests)



(b) RS distribution (2000 requests)



(c) RS distribution (3000 requests)



(d) RS distribution (SDPE)

Fig. 13. RS distribution under nonuniform traffic.

Then, we calculate the standard deviation of $\text{prob}_{i,j}$ under J different network loads, which is $\sigma_i = \sqrt{\sum_{j=1}^{J} (\text{prob}_{i,j} - \text{prob}_i)^2 / J}$. Finally, we define the standard deviation-weighted probability expectation (SDPE) of node i as $(1 - \sigma_i) \times \text{prob}_i$. The SDPE combines the average probability and standard deviation of node i under different network load. If a node has high SDPE, it means this node has constantly high probability of being chosen as a RS under different network load. Figure 12(d) shows the network based on SDPE. We can see that the polarization is still obvious in SDPE values. This polarization suggests a way to select RSs when traffic demands are uncertain. We can first choose the nodes with extremely high SDPE as a base, and then add additional RSs according to the real traffic demands.

Experiment 6. In the sixth experiment, we study how the RSs are distributed in the network under nonuniform traffic. The simulation parameters are the same as those of Experiment 5, except that we choose the 25 most populated nodes out of the 75 nodes, and these nodes' probabilities of being chosen as sources or destinations are 10 times higher than the other 50 nodes. Figures 13(a)–13(c) show the RS distribution under network load of 1000, 2000, and 3000 total requests, respectively, with nonuniform traffic. Figure 13(d) shows the RS distribution based on SDPE.

From Figs. 13(a)–13(d), we can see that the observations obtained under uniform traffic are also true under nonuniform traffic. Some nodes have extremely high probabilities of being selected as RSs, while some nodes have very low probabilities. This polarization becomes more obvious when the network load increases. Compare Figs. 12(d) and 13(d); we find that the sets of high probability nodes are very similar under uniform traffic and nonuniform traffic. In Fig. 13(d), there are nine stars, and eight of them are also stars in Fig. 12(d). This further justifies our proposed method of selecting RSs. Since there are certain nodes having high probabilities of being chosen as RSs, under different traffic patterns and different network loads, we can select them as a base and add additional RSs when necessary.

VI. Conclusion

In this paper, we focus on the problem of MLR-RSS, which aims to minimize the number of RSs when a route is given with a request. We show that MLR-RSS is NP-complete, and then formulate an ILP model to solve the problem. Two heuristic algorithms and two approximation algorithms are proposed, named the independent algorithm, the sequential algorithm, the MLR-combined algorithm, and the weighted MLR-combined algorithm. The numerical results show the performance comparison of these algorithms and show that the weighted MLR-combined algorithm outperforms the other algorithms. The weighted MLR-combined algorithm requires not more than one RS than the ILP, showing near optimal performance. It is shown that the MLR approach can save more than 20% compared to using the SLR approach for each line rate independently and then combining them. The RS distribution shows that certain nodes in the network are more likely to be selected as RSs than the other nodes, under both uniform traffic and nonuniform traffic. It suggests a way for selecting RSs, that is, selecting the nodes with high SDPE first, and then adding extra RSs when necessary.

Acknowledgments

A preliminary conference version of this paper appeared in the *IEEE ICC*, Ottawa, Canada, June 2012.

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