Regenerator Site Predeployment in Nonlinear Dynamic Flexible-Grid Networks

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Abstract *A regenerator predeployment algorithm is proposed in dynamic translucent flexible-grid networks based on the GN model. The randomness of traffic bandwidth requests is exploited to allocate regenerators efficiently. Our method accommodates 30% more demands than benchmark methods.*

Introduction

The advent of colorless directionless reconfigurable optical add/drop multiplexers (CD-ROADMs) and software-defined optical networking can support dynamic control, management, and optimization of flexible-grid networks[1], where sparse regenerator sites can be predeployed to enable fast provisioning of services and reconfigurations[2]. To allocate regenerator site (RS) conservatively and effectively, it is necessary to accurately estimate the physical layer impairments (PLIs). Transmission reach (TR) is used in many previous studies[1,2] to guarantee proper quality of transmissions (QoTs). Recently, a more sophisticated RS placement[3] algorithm based on the Gaussian noise (GN) model[4] was proposed to reduce the number of RSs. However, most of the existing algorithms are based on the predicted static traffic demands, whereas the actual bandwidth requests are usually dynamic and random, which can be very different from the predicted data. Therefore, the randomness of traffic demands should be considered to allocate RS efficiently.

In this paper, we propose a new RS placement algorithm for random traffic demands in flexible-grid networks based on the GN model. Assuming a predefined routing scheme, the method obtains the likelihood of being an RS for each network node using Monte Carlo simulations, based on which the RSs are selected.

Problem Statement

The goal is to allocate a limited number of RSs such that the blocking probability (BP) due to the lack of regeneration is minimized in a dynamic flexible-grid network. The network topology is represented as (V, E), where V is the set of CD-ROADM nodes and E is the set of bidirectional links with equal-length fiber spans. The set of RSs is defined as $R \subset V$. The modulation format is used for all the traffic demands. To focus mainly on the PLI-related traffic blocking, unlimited spectrum resources are assumed.

To minimize the communication delay or cost per demand in carrier-grade networks, the shortest-path routing in terms of a certain criterion, e.g., the distance or light path cost, is preferred by all the traffic demands[2]. Constrained by this shortest-path requirement, the light paths for all the possible node pairs are thus determined[2]. Therefore, we assume a predefined routing scheme when assigning RSs.

Proposed Algorithm

The proposed RS allocation algorithm is composed of two stages: we first allocate RSs in Monte Carlo simulations with random bandwidth demands, and then calculate the likelihood of each network node being an RS, according to which permanent RSs are placed to minimize the possible traffic blocking. The algorithm is summarized by a flowchart in Fig. 1.

In the first stage, the statistical network assessment process (SNAP) framework[5] is used to simulate the PLIs generated by random traffic demands. In SNAP, the randomly generated traffic
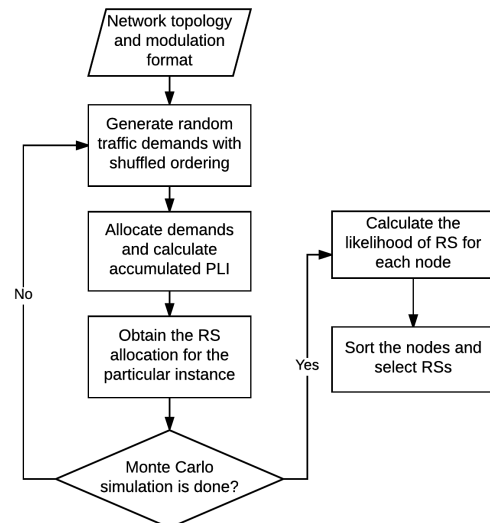

Fig. 1: The flowchart of the proposed algorithm.

demands are shuffled and allocated in the network one by one. The first-fit policy is used for spectrum assignment. At the end of each simulation, the PLI of each traffic demand d on link l, $G_{d,l}^{\text{NLI}}$, is calculated by the GN model. The RS allocation regarding PLIs generated in this specific simulation instance is then optimized by (1).

$$\underset{\substack{N_{d,i},C_{d,i},I_i \\ C_{\text{total}},I_{\text{total}}}}{\text{minimize}} \ \alpha C_{\text{total}} + \beta I_{\text{total}} \tag{1a}$$

subject to

$$N_{d,i} \leq N_{d,\text{src}(i;d)} + L_{d,\text{src}(i;d),i} \quad \forall d \in D, i \in P_d, \tag{1b}$$

$$N_{d,i} \leq M(1 - C_{d,i}) \quad \forall d \in D, i \in P_d, \tag{1c}$$

$$\begin{aligned} N_{d,\text{src}(i;d)} + L_{d,\text{src}(i;d),i} - \\ N_{d,i} \leq MC_{d,i} \end{aligned} \quad \forall d \in D, i \in P_d, \tag{1d}$$

$$N_{d,i} \geq 0 \quad \forall d \in D, i \in P_d, \tag{1e}$$

$$N_{d,\text{src}(i;d)} + L_{d,\text{src}(i;d),i} \leq N_{\text{max}} \quad \forall d \in D, i \in P_d, \tag{1f}$$

$$\sum_{d \in D} C_{d,i} \leq I_i C_{\text{max}} \quad \forall i \in V, \tag{1g}$$

$$C_{\text{total}} = \sum_{d \in D} \sum_{i \in P_d} C_{d,i}, \tag{1h}$$

$$I_{\text{total}} = \sum_{i \in V} I_i. \tag{1i}$$

The parameters and variables in (1) are listed in Tabs. 1 and 2, respectively. By setting $\alpha \ll \beta$, the objective is to first minimize the total number of RSs I_{total}, and secondly minimize the total number of regeneration circuits (RC)[1] C_{total}. Constraints (1b–1d) are equivalent to $N_{d,i} \leq (1 - C_{d,i})(N_{d,\text{src}(i;d)} + L_{d,\text{src}(i;d),i})$, which calculates the accumulated noise of demand d on link $i \in P_d$. Constraint (1f) imposes that the maximum accumulated PLI noise is less than N_{max}. Constraint (1g) ensures that the number of RCs at each RS is lower than the limit C_{max}. Constraints (1h) and (1i) calculate the total numbers of RCs and RSs, respectively. Formulation (1) is a mixed integer linear programming problem with relatively low complexity, which can be solved for a large number of simulations within a short time.

In the second stage, the likelihood of being selected as an RS is calculated for each network node based on the first stage results. We can use either I_i (referred to as RS-based) or $\sum_{d \in D} C_{d,i}$ (RC-based) to calculate the likelihood of being an RS for node i. The former method uses the knowledge of a node being an RS, whereas the latter one provides information about how many traffic demands are regenerated. Finally, the network nodes are sorted in descending order of likelihood and the top ones are selected as permanent RSs.

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[1]The RC is an equipment inside the RS dedicated to the regeneration of one light path. One RC cannot be shared by

Tab. 1: PARAMETERS

Symbol	Meaning
D	the set of demands
P_d	the set of nodes on the path of demand $d \in D$
$\text{src}(i;d) \in P_d$	the node on the path of demand $d \in D$ with node $i \in V$ as the immediate next node
$L_{d,\text{src}(i;d),i}$	PLI noise generated for demand $d \in D$ on the link from $\text{src}(i;d)$ to i, $\text{src}(i;d)$ and i in V, it is calculated by the GN model [4]
N_{max}	the maximum tolerable noise before regeneration
C_{max}	the maximum number of regenerator circuits per RS
M	a number larger than the highest possible accumulated noise of any demand $d \in D$
α, and β	the weight factor for the total number of regeneration circuits and RSs in the objective of (1), respectively

Tab. 2: VARIABLES

Symbol	Meaning
$N_{d,i} \in \mathbb{R}$	accumulated noise for demand $d \in D$ at the egress port of node $i \in V$
$C_{d,i} \in \{0,1\}$	1 if demand $d \in D$ needs a regenerator circuit on node $i \in V$, 0 otherwise.
$I_i \in \{0,1\}$	1 if node $i \in V$ is used as regenerator site
C_{total}	the total number of regenerator circuits in the network
I_{total}	the total number of RSs in the network

Numerical Results

We evaluate the performance of the proposed method using the Coronet CONUS topology[6] with 75 nodes and 99 bidirectional links. The fiber parameters[3] are used in our simulations. Polarization-multiplexed quadrature phase shift keying is used. The min-distance routing scheme[2] is used for all the traffic demands. All-to-all traffic demands, whose bandwidth requests follow a normal distribution with a mean of 200 GHz and a standard deviation of 50 GHz, are generated for all the node pairs[2]. We set $C_{\text{max}} = 1000$, $\alpha = 1$ and $\beta = 0.0001$ such that RC is optimized only after the optimal RSs are found.
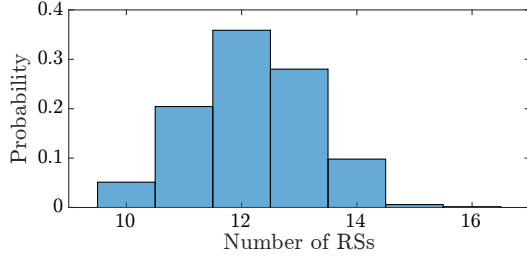
We first compare the number of allocated RSs between the proposed method and the RS planning algorithm[2] with min-distance routing, which is based on the TR constraint and static traffic demands. According to the GN model and the fiber parameters, the TR is calculated to be 2000 km and 20 RSs are needed by the benchmark. For the proposed method, the number of necessary RSs depends on the specific traffic demands and accumulated PLI noise in each Monte Carlo simulation. As is shown in Fig. 2, around 12 RSs are needed on average and the maximum number of RSs is 16. The much lower number of RSs is attributed to the accurate PLI noise estimation by the GN model and optimization in (1).

In Fig. 3, the normalized likelihood of being an RS for each node is calculated based on the simulation results. The RS- and RC-based meth-

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multiple light paths.

[2]Node pairs (s, d) and (d, s) for $s, d \in V$ are different, so there are 5550 node pairs in total in our simulations.

Fig. 2: The histogram of the number of RSs allocated by the proposed method.

Fig. 3: The normalized likelihood of being selected as RS for network nodes. The nodes are sorted in the descending order of the likelihood.

ods are compared with the routing only method[1], which calculates the likelihood of RS for node i by counting the normalized number of demands whose shortest paths go through it. In the RC- and RS-based methods, the normalized likelihoods are concentrated to a relatively small subset of nodes, whereas the routing only method assigns a rather uniform distribution for all the nodes.

**Tab. 3:** Relative gains over benchmark[2] in the # of provisioned demands at different BPs

BP	RS-based	RC-based
0.005	$51.4\% \pm 3.8\%$	$67.0\% \pm 3.2\%$
0.01	$46.2\% \pm 2.6\%$	$62.3\% \pm 2.1\%$
0.02	$38.7\% \pm 1.8\%$	$56.1\% \pm 1.4\%$
0.04	$31.9\% \pm 1.2\%$	$47.5\% \pm 0.9\%$

The top ranked nodes in Fig. 3 can then be selected as RSs. To compare the blocking performance of the proposed methods with the RS allocation benchmark[2], the same number (20) of RSs are chosen for both methods. The relative gains in the number of established demands compared with the benchmark and 90% confidence intervals are shown in Tab. 3. The relative gain is always higher than 30% for both methods and all BPs.

Tab. 4: Relative gains over routing-only[7] in the # of provisioned demands at different RS limits (BP=0.04)

#RSs	RS-based	RC-based
10	13.2%	-4.5%
15	18.7%	43.2%
20	24.7%	10.1%
25	27.9%	14.5%
30	-4.2%	10.5%

Finally, the blocking performance of the proposed method with different number of RSs are compared with the routing only method[1]. As is shown in Tab. 4, the proposed methods achieve significant gains for a large range of RS numbers. The 90% confidence intervals are less than 1% for all the cases. Note that the gains of the proposed methods are relatively low when the number of RSs are too high or too low. Actually, the proposed method is biased towards the minimum numbers of necessary RSs and RCs. Thus the performance of our algorithm would degenerate when the planned number of RSs disagrees
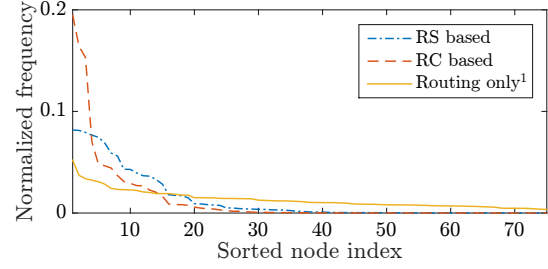
largely with the optimal one, whose statistics are shown in Fig. 2. However, the blocking performance is still improved from a cost and performance perspective.

Conclusion

In this paper, an RS assignment algorithm is proposed for dynamic flexible-grid networks considering nonlinear interference and random bandwidth requests. Numerical results demonstrate that significant gains in the number of provisioned demands ($> 31\%$) is achieved.

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