Towards Regeneration in Flexible Optical Network Planning

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***Abstract*—In optical networks, the reach of the optical signal is controlled by the receiver's capability to successfully receive the signal, degraded due to optical impairments and noise. This reach can be extended by using regeneration at intermediate nodes. Efficient placement and minimization of the number of regenerators is referred to as the regenerator placement problem. This paper proposes a method to solve the regenerator placement problem in a multiperiod planning scenario with the objective of maximizing throughput with minimum lightpaths. The paper addresses regenerator placement in two phases, a preselection of possible locations for regeneration based on OSNR constraints, and provisioning a combination of regenerated and non-regenerated lightpaths. The provisioning formulation focuses on minimizing the number of transceivers while maximizing the datarate. We demonstrate the advantage of our approach compared to state-of-the-art methods in terms of throughput, underprovisioning and number of transceivers on 3 different topologies. Our results show that the proposed solution is able to meet the dynamic traffic with lower underprovisioning.**

***Index Terms*—Flexible optical networks, elastic optical networks, network planning, regenerator placement, RCSA**

I. Introduction

The core optical networks form the backbone of communication networks. With the constant growth in Internet and bandwidth hungry network services, network operators look for solutions to increase the network utilization with minimal changes in infrastructure. Elastic Optical Networks (EON) introduced a solution with flex-grid channels to increase spectrum efficiency, as opposed to Wavelength Division Multiplexing (WDM) optical networks, which provide inflexible spectrum allocation [1]. EON creates frequency slots, with a granularity of 12.5 GHz, to meet the required bandwidth of each demand. Furthermore, bandwidth variable transceivers (BVTs) allow flexible resource allocation and enables EONs for reducing overprovisioning in the network. The network operators require efficient routing and channel allocation algorithms in EON to achieve the maximum possible throughput, with efficient spectrum allocation. This problem is known as the routing and spectrum assignment (RSA) problem [2]. BVTs allow several transmission parameters, such as datarate, modulation scheme, and FEC overhead, to configure different lightpaths (LPs). Each combination of such parameters is referred to as a configuration. This extends the RSA problem to routing, configuration, and spectrum assignment (RCSA). In a multi-period planning scenario, each demand is routed and assigned a part of the available spectrum for every planning period, where each demand is subject to an increase in traffic [3]. In such cases, the RCSA algorithm must uniformly route and allocate channels, while coping with the increase in yearly traffic.

To maximize throughput in a limited-sized spectrum, configurations with higher datarates (e.g., 500-600 Gbps) are optimal for selection in an LP. The drawback of placing LPs with higher datarates is their lower optical reach: the maximum transparent optical path traversed by the signal to be successfully received. Optical signals suffer from physical layer impairments and non-linear interference (NLI) noise [4], which increase with distance. Similarly, the minimum required received OSNR is directly correlated to the configuration datarate. The use of 3R regeneration (Reshaping, Reamplification and Retiming) [4] in intermediate nodes of the routed path can help in using higher datarate configurations for demands over long paths. 3R regeneration requires splitting of the transparent path into segments by OEO conversions [5]. This split of the LP is considered as 2 sub-LPs. Each regenerator node uses 2 back-to-back (B2B) BVTs for regeneration. Installing additional BVTs will lead to an increase in installation costs. The efficient placement of regenerators, and consequently RCSA algorithm, should be able to meet the traffic demand, and minimize spectrum usage and overall number of BVTs used in the network.

Fig. 1 motivates the advantage of using regenerators in the Abilene-USA network topology with add/drop nodes housing a number of BVTs. We consider 4 available configurations with datarates of 100, 200, 400, and 600 Gbps. In this example, we refer to any configuration in terms of its datarate only. We assume that only a single configuration is used to place the demand. Each configuration has an OSNR requirement, which increases with higher datarates. The OSNR limitation helps us to find the regeneration point(s) for any given path. We want to place a demand of 800 Gbps between Los Angeles (LA) and New York (NYC), with the routed path shown by bold

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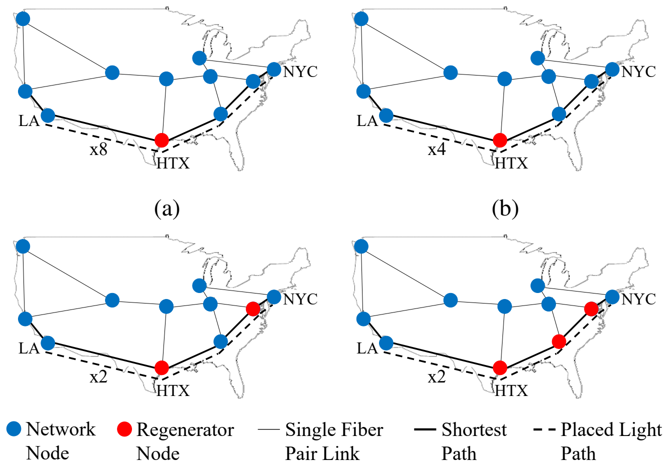

Fig. 1: Regeneration locations required and number of LPs to be placed for configuration of (a) 100 Gbps, (b) 200 Gbps, (c) 400 Gbps, and (d) 600 Gbps

lines in Fig. 1. The shortest path includes a long distance link between LA and Houston (HTX). This link limits the optical reach and does not allow even 100 Gbps LPs to be placed without regeneration, as shown in Fig. 1a. 8 LPs of 100 Gbps are required to place a demand of 800 Gbps using 32 BVTs (16 for source and destination, 16 for regeneration). 200 Gbps configuration requires a single regeneration node, shown in Fig. 1b. We need to place 4 LPs of 200 Gbps to meet the demand traffic of 800 Gbps, requiring deployment of 16 BVTs (8 at source and destination, 8 at regeneration nodes). 2 regenerator locations are used to meet the OSNR requirements for the 400 Gbps configuration (Fig. 1c). To meet the demand, we place 2 LPs using 12 BVTs (4 at source and destination, 8 at regeneration nodes). The 600 Gbps configuration provides the highest datarate, but requires every intermediate node on the routed path be considered as a regeneration node, as shown in Fig. 1d. Since we assume that only a single configuration can be used to place the demand, an 800 Gbps demand requires 2 LPs of 600 Gbps, with an overprovisioning of 400 Gbps. The total number of BVTs required to place the demand are 16 (4 at source and destination, 12 at regeneration nodes). In order to maximize the datarate, configuration 4 is the best. To minimize number of BVTs, configuration 3 should be used. If we want to minimize the number of regeneration BVTs required and remove the restriction of a single configuration per demand, the best combination is 1 LP with 200 Gbps and 1 LP with 600 Gbps. This combination aims to provide both: minimum LPs and minimum BVTs to satisfy the requested demand, which is the objective of our work.

There is extensive literature that shows the advantages of regeneration, and weighs on the importance of their efficient usage in a network. The authors in [6] introduced heuristics for regenerator placement in translucent optical networks to improve spectrum usage. The joint regenerator placement with routing, modulation level, and spectrum assignment (RP-RMLSA) was introduced in [5], where the authors optimize regeneration locations based on the modulation format used by minimizing the cost of installing regenerators with static demands. Another joint optimization approach is proposed in [7] with a focus on energy efficiency. The authors in [8] created a method for efficiently finding regenerator locations in the network. Multiple heuristics for regenerator placement problem based on path length and number of hops are proposed in [9].

The main contribution of this work is to investigate the advantage of regeneration in C-band in a multi-period planning scenario. The paper intends to improve the performance of the existing RCSA model by placing a combination of regenerated and nonregenerated LPs for each demand. The objective is to minimize the overall number of BVTs with the maximum possible datarate. We compare the results of the algorithm with other RCSA algorithms, which are presented in our previous works [3] [10]. Section II provides a review of our existing work on the RCSA problem. In Section III, we present the methodology of creating efficient path segments for various configurations and introduce the proposed MILP formulation for the combined regeneration placement. Finally, Section IV covers the performance evaluation of the proposed solution using various performance metrics.

II. C-Band RCSA

The baseline RCSA is presented in [3]. The paper presents a multi-period traffic model that accounts for the unexpected increase in traffic. The algorithm solves to meet the requested traffic and minimize the number of LPs placed every planning period. To meet all traffic demands, two methods are applied: *LP upgrade* and *LP addition*. *LP upgrade* upgrades the configuration of existing LP BVTs by calculating the NLI on the path and looking for valid configurations with higher datarate than the current configuration of the LP. *LP addition* is modeled as MILP to add new BVTs (thereby adding new LPs) if existing BVTs cannot meet the requested traffic. The algorithm provisions LPs with the objective of minimizing number of BVTs and maximizing datarate to meet the requested traffic for every demand at each planning period individually. The *LP addition* provides a set of LPs, and their placement relies on spectrum availability, calculated NLI [11] and constraints such as spectrum continuity and contiguity. For the rest of the paper, we will refer to this solution as **Baseline**.

[10] extends the existing RCSA algorithm by adding a rerouting and reconfiguration mechanism to the baseline. The *LP rerouting* uses a spectrum reallocation heuristic, which reallocates existing spectrally adjacent LPs to create free contiguous slots in the spectrum that can be used to upgrade the configuration of the placed LPs.

The network topology is defined as a network graph $G(V, E)$, with V add/drop nodes housing a number of BVTs, and E links with single-mode fiber pairs and heterogeneous span lengths. A set of demands D is considered for planning every period t, with a finite discrete time horizon T. Each demand requests a traffic of DR_d, which increases every

Algorithm 1 Path segmentation

Input: Network $G(V, E)$, Demand $d \in D$ (source src_d, destination dst_d nodes) configuration $c \in C$, required OSNR $reqOSNR_c$, shortest paths $k \in KSpath_{dk}$

Output: Set of path segments $ps_0, ps_1..ps_n \in PS$ and regenerator locations: $r_{cdk} \in V$

```
for link l(src_l, dst_l): KSpath_dk do
    Calculate accumulated ASE and update OSNR OSNR_cdk
    if OSNR_cdk < reqOSNR_c then
        Create path segment ps_i till l_prev : dst_prev = src_l
        Consider src_l as source for ps_i + 1
        Add src_l to r_cdk
        Recalculate OSNR_cdk
        if OSNR_cdk < reqOSNR_c then
            Invalidate c for d on path k
        end if
    end if
end for
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planning period based on the traffic prediction model, and routed using k-shortest paths. The model considers 26 possible configurations C that differ in terms of modulation formats, datarate DR_{lp} and FEC [12]. The demand set is sorted by path length and LPs are upgraded, added, or rerouted sequentially to meet the requested traffic. The objective is to minimize the number of LPs, such that the provisioned datarate is more than or equal to the requested datarate:

$$DR_d \leq \sum_{\forall lp \in LP_d} DR_{lp} \quad (1)$$

Minimizing the number of LPs reduces overprovisioning of demands and ensures fair use of the available spectrum.

III. Problem Formulation

The RCSA solutions discussed in the previous section provide the basis for the proposed solution with regeneration capabilities. The regenerator placement problem is divided into two subproblems: regenerator location selection problem and regenerator assignment problem.

A. Regenerator Location Selection Problem

The regenerator location problem finds all possible regenerator locations given a demand $d \in D$ with source and destination nodes (src_d and dst_d), configuration $c \in C$ and the k-shortest path $k \in KSpath_{dk}$. Each configuration has a maximum optical reach over the routed path due to OSNR limitation. Using the first longest reach (FLR) method [9], the path segments are precalculated to identify the intermediate nodes that should be used as regeneration nodes [8]. Algorithm 1 shows the pseudocode for path segmentation. Starting from the source node, the OSNR is calculated per link by calculating the accumulated ASE noise. Once the OSNR drops below the minimum required OSNR, the previous network node is selected as the regeneration location for the given demand, configuration and k-shortest path. Due to high OSNR restrictions on configurations with high datarate, some configurations are not able to transmit over a long link, rendering the regeneration at the previous node useless. In such cases, the configuration is declared invalid for the demand on the specified routed path.

Symbol	Description
$G(V, E)$	Network topology
V	Set of optical add/drop nodes
E	Set of links with single mode fiber pairs
T	Planning time horizon, $t \in T$
D	Set of demands $d \in D$
C	Set of configurations $c \in C$
K	Set of k-shortest paths $k \in KSpath_{dk}$
DR_d	Requested traffic by demand d
DR_{lp}	Datarate of LP $lp \in LP_d$
LP_d	Set of placed LPs for demand d
CR_c	Datarate provisioned using configuration c
BW_c	Bandwidth requirement of configuration c
$\eta_{NLI_{cdk}}$	NLI coefficient for c on d at k path
R_{cdk}	Set of regenerator locations for c on d at k path
δ	Permissible overprovisioning
S_{dk}	Maximum number of contiguous slots for d on k path, with each slot 12.5 GHz

TABLE I: Notations definition

Once these path segments are calculated, the algorithm ranks the nodes V according to the maximum usage as regeneration location for all possible configurations and shortest paths. This ranking allows us to prioritize locations when selecting regeneration sites. Given the NP-hardness of the problem, our solution provides a simple and fast heuristic, which can be used prior to any LP provisioning. In our study, we assume that all nodes are candidate regeneration locations.

B. Regenerator Assignment Problem

We address the regenerator assignment problem by combining it with the existing RCSA MILP for each demand at every planning period [5]. The proposed model continues with the same notations used in the MILP formulation in Section II, and the extended notations are given in Table I. The model is formulated as a multi-objective MILP model to add LPs, with the primary objective of minimizing the number of BVTs (regenerator and nonregenerator) and the secondary objective of maximizing the datarate for each demand. The MILP is formulated for a single demand, considering all configurations over all k-shortest paths.

At the initial planning period, the demands are sorted by the path length over the k-shortest paths. The requested traffic of each demand is placed sequentially. A preselection of valid configurations over all shortest paths is performed by calculating the $\eta_{NLI_{cdk}}$ coefficient. The $\eta_{NLI_{cdk}}$ coefficient is calculated using the accurate non-linearity fully closed-form enhanced Gaussian noise model [11]. If $\eta_{NLI_{cdk}} \leq 1$, the configuration is considered valid and added to the subset $C_{dk}^{valid} \subset C$. The preselection of the configurations and calculation of $\eta_{NLI_{cdk}}$ coefficient form the precomputation phase and act as inputs for optimization.

Given a demand $d \in D$, the set of its valid configurations $c \in C_{dk}^{valid}$, and all k-shortest paths $k \in KSpath_{dk}$, the objective is to find the number of LPs to be provisioned for each configuration c on all paths k to accommodate the requested traffic. For that purpose, the following single decision variable is defined:

X_{cdk} An integer decision variable to determine number of LPs provisioned for demand d with configuration c on path k

The MILP is formulated as follows:

$$obj1 : \min \sum_{\substack{c \in C_{dk}^{valid} \\ k \in KSpath_{dk}}} 2(1 + |r_{cdk}|)X_{cdk} \quad (2)$$

$$obj2 : \max \sum_{\substack{c \in C_{dk}^{valid} \\ k \in KSpath_{dk}}} CR_c X_{cdk} \quad (3)$$

subjected to the following constraints:

$$\sum_{\substack{c \in C_{dk}^{valid} \\ k \in KSpath_{dk}}} CR_c X_{cdk} \geq DR_d \quad (4)$$

$$\sum_{\substack{c \in C_{dk}^{valid} \\ k \in KSpath_{dk}}} CR_c X_{cdk} \leq DR_d + \delta \quad (5)$$

$$BW_c X_{cdk} \leq 12.5 S_{dk}, \forall c \in C_{dk}^{valid} k \in KSpath_{dk} \quad (6)$$

Objective 1 (Eq. (2)) minimizes the number of BVTs, where $|r_{cdk}|$ represents number of regeneration nodes required for a given configuration and path. $|r_{cdk}| \in R_{cdk}$ provides the number of regenerator BVTs required to place a single LP for demand d on path k, with configuration c. Objective 2 in Eq. (3) maximizes the datarate of each selected configuration and shortest path. The constraint in (Eq. (4)) ensures that the provisioned LPs have a combined datarate greater than the requested traffic for the demand. To restrict number of BVTs, an overprovisioning datarate $\delta = 200\ Gbps$ is used to restrict the provisioned datarate using the constraint in (Eq. (5)). Valid configurations are further filtered using a bandwidth constraint (Eq. (6)). This constraint ensures that the configurations with a required bandwidth lower than the maximum contiguous bandwidth are selected. In case of regenerated LPs, the maximum contiguous bandwidth are found for each sub LP and the minimum of those slots is considered. Once we get the provisioned LPs from the optimization model, a first-fit spectrum allocation method is used for placing the LPs provisioned by the optimization model. This spectrum allocation ensures the spectrum continuity and contiguity constraints.

In the following planning periods, the *LP upgrade* module is used for all LP that can be upgraded. The *LP upgrade* is updated from the previous work for LPs with regeneration. Given the k-shortest path used by the LP, the configurations which require the same regenerator location are considered valid, to ensure that the sub LPs are consistent and BVTs deployed are utilized in the upgrade phase. If the requested traffic cannot be met with *LP upgrade*, the proposed module initiates the addition of LPs with regeneration.

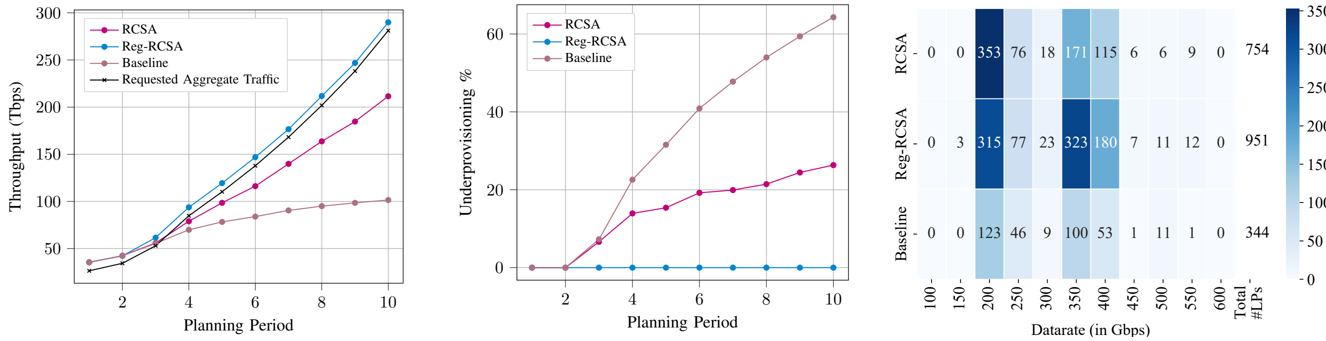
Once the LPs for each demand are added for a given planning period, η_{NLI} and OSNR are calculated for all configured LPs. A 0.5 dB margin is considered in linear OSNR calculation, to compensate for crosstalk. The LPs with OSNR lower than required OSNR by the configuration are blocked. The spectrum occupied by the blocked LP is made available for the following demands, ensuring that the spectrum is used efficiently every planning year.

IV. Results and Discussion

The proposed model is evaluated for 3 topologies: Abilene-USA ($|V| = 12, |E| = 15$ and $|D| = 66$, $diameter = 4714.0\ km$), Nobel-Germany ($|V| = 17, |E| = 26$ and $|D| = 123$, $diameter = 992.20\ km$) and Nobel-Europe ($|V| = 28, |E| = 41$ and $|D| = 378$, $diameter = 3363.741 km$) for a planning period of $|T| = 10$ years. The performance of the RCSA with regeneration (referred to as **Reg-RCSA**) is compared to the previously presented RCSA (referred to as **RCSA**) discussed in Section II and the baseline [3]. The simulation framework has been implemented in Java, and all simulations are run on Intel Core i7-10800H 2.70 GHz, 32 GB of RAM, running Windows 10. We consider 26 possible configurations C with datarate between 100-600 Gbps with steps of 50 Gbps, QPSK, 8QAM, 16QAM, 32QAM, 64QAM, and 7%, 15%, 27% FEC overhead. The minimum received OSNR is defined such that the BER is always below 10^{-9}, in a B2B configuration [13]. The k-shortest paths are calculated using Yen's algorithm with $K = 5$.

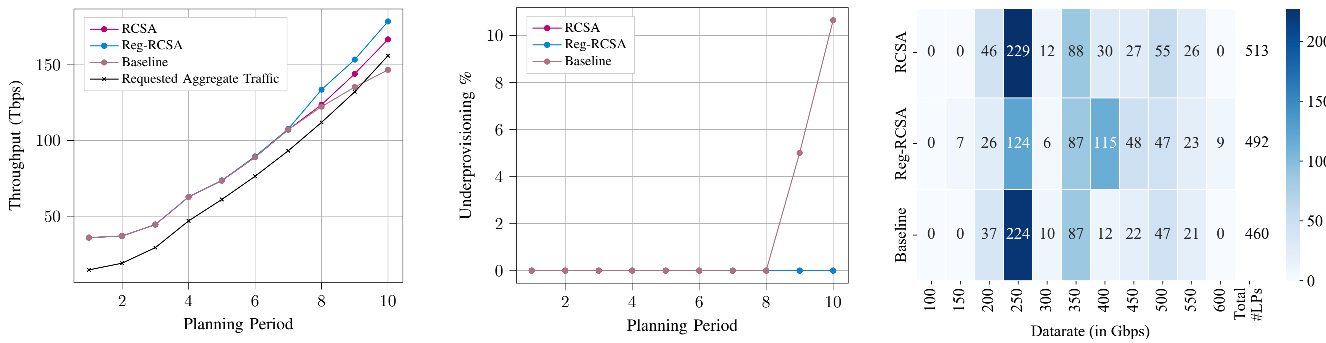
We compare the *Reg-RCSA* and *RCSA* on 4 different metrics: throughput, datarate distribution, underprovisioning, and number of BVTs deployed at every planning period. Throughput represents the total datarate of all placed LPs for a given planning period. The datarate distribution gives the number of LPs being placed with different datarates.

In terms of throughput, *Reg-RCSA* allows coping with the requested demands during all planning time for all topologies as depicted in Figs. 2a, 3a and 4a for Abilene-USA, Nobel-Germany and Nobel-Europe respectively. In case of Nobel-Germany topology (Fig. 3a), the throughput for *Reg-RCSA* and *RCSA* stays above the requested aggregate traffic for all planning periods. All the models follow closely to the *Baseline* until year 7. Post that planning year, *Reg-RCSA* continues the increasing trend, whereas the other models diverge below, with *Baseline* falling below the requested traffic in the last planning year. The difference is more pronounced in Abilene-USA and Nobel-Europe topologies. The throughput in Nobel-Europe (Fig. 4a) is consistently higher than requested traffic for *Reg-RCSA* by 50-100 Tbps. The advantage of regeneration can be observed in Abilene-USA (see Fig. 2a) where both *Baseline* and *RCSA* cannot cope with the requested traffic after the fourth planning year, whereas the use of regeneration allows fulfilling over all the planning period. This limitation



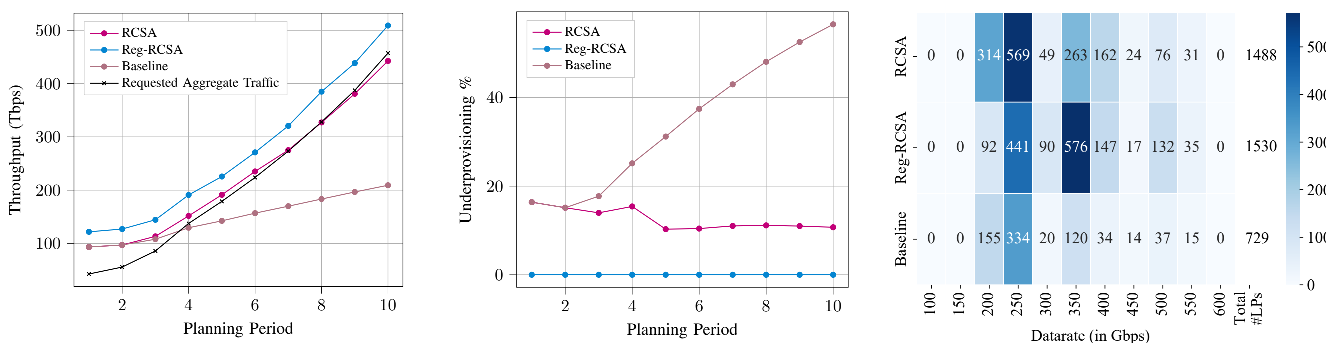
(a) Throughput (b) Underprovisioning (c) DR Distribution

Fig. 2: Comparison of the proposed solution with existing works for Abilene-USA topology.



(a) Throughput (b) Underprovisioning (c) DR Distribution

Fig. 3: Comparison of the proposed solution with existing works for Nobel-Germany topology.



(a) Throughput (b) Underprovisioning (c) DR Distribution

Fig. 4: Comparison of the proposed solution with existing works for Nobel-Europe topology.

can be attributed to the topology, which contains long east-west demands. These demands cannot be configured with LPs with higher datarate configurations and need using many LPs with configurations of 100 Gbps datarate, which saturate the spectrum of those links very fast.

However, looking only at the throughput may lead to misleading conclusions, as it is the aggregated throughput of all the demands. In order to have a more fair comparison, the underprovisioning of the demands has to be evaluated. The underprovisioning quantifies the number of demands that could not be fully satisfied. It is defined as

$$UP = \frac{\sum_{\forall \widetilde{d} \in \widetilde{D}} (DR_{\widetilde{d}} - \sum_{\forall lp \in LP_{\widetilde{d}}} DR_{lp})}{\sum_{d \in D} DR_d} \tag{7}$$

where $\widetilde{D}$ is the set of underprovisioned demands. We include a margin of error of 2% in the calculation of the underprovisioning ratio. As seen in Figs. 2b, 3b and 4b, *Reg-RCSA* provides underprovisioning lower than 2% in all topologies. In case of Nobel-Germany, both *Reg-RCSA* and *RCSA* do not suffer any underprovisioning. In Abilene-USA topology, *RCSA* shows an increasing trend of under-provisioning, rising to 27%. The underprovisioning for *RCSA* at year 4 is higher at 17% as the NLI and OSNR calculation block many of the LPs. The spectrum occupied by the blocked demands is made available for allocation for the next planning year, thereby reducing the underprovisioning to 11% as the LPs utilize the freed spectrum.

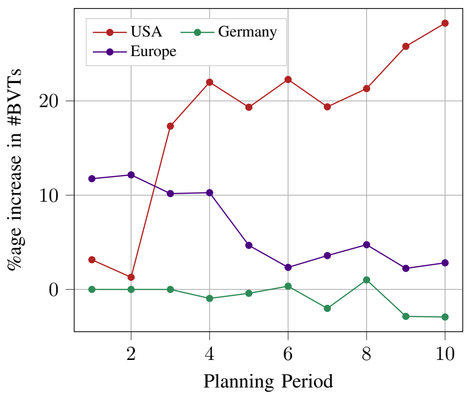


Fig. 5: Percentage change in number of BVTs required with regeneration vs without regeneration for all topologies

Another important parameter to compare is the datarate distribution in the last planning year. The datarate distribution is shown in the form of a heatmap depicting the number of configured LPs with a given datarate. We have grouped all configurations with the same datarate, irrespective of its modulation scheme and FEC. The most important observation for all the topologies is that *Reg-RCSA* uses higher datarate configurations than the other methods. In Nobel-Europe (Fig. 4c), 38% of LPs are 350 Gbps, with more than 100 LPs configured for 400 and 500 Gbps in *Reg-RCSA*. Conversely in *RCSA*, 40% of LPs are configures with 250 Gbps. Abilene-USA topology also shows a similar distribution on a smaller scale in Fig. 2c. Reg-RCSA places more LPs in total than *RCSA* for these two topologies. In case of Nobel-Germany, *RCSA* is able to provide a higher throughput despite placing lesser number of LPs as seen in Fig. 3c. A possible explanation could be that regeneration is able to place LPs with 600 Gbps, where as *RCSA* is not able to place any LP with such datarate. Furthermore, regeneration places more than 100 LPs at 400 Gbps, while *RCSA* is placing only 30. In general, having more LPs with higher configurations also illustrates efficient use of the available spectrum. The downfall of higher configurations can be attributed to number of BVTs deployed for regeneration, as higher configurations would require more number of regeneration locations. However, deploying regenerator BVTs is useful in overcoming underprovisioning issues.

As one of the important aspects for network operators is the number of BVTs required due to their cost, power consumption, etc., let us compare the percentage difference of BVTs used for *Reg-RCSA* with respect to *RCSA* for every planning period (depicted in Fig. 5). It can be observed, that Nobel-Germany requires even a lower number of BVTs similar to the example of Figure 1. However, topologies with larger diameter such as Nobel-Europe and Abilene-USA require more BVTs to cope with the requested traffic thanks to regeneration. In particular, Abilene-USA topology requires more than 25% BVTs to meet the requested traffic in the final planning year. The higher number of BVTs can be addressed as a compromise in order to get maximum possible throughput and lower underprovisioning in the network.

V. Conclusion

In this work, we propose to extend the existing multi-period planning RCSA method by considering regeneration. The results show that the regeneration is able to cope with the requested traffic for all planning periods by enabling usage of configurations with higher datarates. The datarate distribution shows an effective use of the available spectrum, with a high number of LPs with higher datarates $\geq$ 350 Gbps. The cost of additional BVTs required for regeneration, which are incurred for topologies with long diameter, can be clearly compensated by the full provisioning of all the required demands.

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