Improving Spectrum Efficiency with Adaptive Regenerations in Elastic Optical Networks

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***Abstract*—This paper addresses the persistent challenge of optimizing optical transport networks amidst the growing demand for the Internet and bandwidth-intensive services. The focus is to enhance spectrum efficiency through flexgrid channels, presenting heuristic approaches for Routing, Configuration Selection, and Spectrum Allocation (RCSA) with regeneration. Acknowledging the saturation of commercial optical networks in the C-band, the paper proposes two key heuristics, "Upgrade LP with Regeneration" and "LP Blocking Avoidance", aiming to dynamically reconfigure existing lightpaths to optimize network performance and postponing the higher investment required by Space Division Multiplexing (SDM) solutions. Evaluation in different network topologies demonstrates the effectiveness of the proposed methods, showcasing increased throughput, reduced underprovisioning, and improved spectrum utilization. This research contributes valuable insights into ongoing efforts to enhance network efficiency within existing capacity constraints.**

I. Introduction

With the perpetual expansion of the Internet and bandwidth-intensive services, it is an ongoing challenge to accommodate these services within the limited capacity of the current age of optical transport networks [1]. Network operators are actively seeking solutions that increase network utilization without necessitating substantial alterations to the existing infrastructure. Elastic Optical Networks (EON) emerged as a viable solution by introducing flexgrid channels, thereby enhancing spectrum efficiency in contrast to the rigid spectrum allocation of Wavelength Division Multiplexing (WDM) optical networks. EON based methods, such as Dense wavelength division multiplexing (DWDM), orthogonal frequency division multiplexing, and digital subcarrier multiplexing (DSCM), have also helped to increase the network utilization of optical networks, providing high flexibility and scalability by generating frequency slots with a precision of 12.5 GHz to align with the nuanced bandwidth requirements of specific demands [2]. The integration of Bandwidth Variable Transceivers (BVTs) facilitates adaptive resource allocation and flexibility in data transmission formats. Given these tools, there is a need for optimization of routing and spectrum allocation (RSA) algorithms to maximize throughput while concurrently optimizing spectrum utilization. The adaptability of BVTs extends the NP-hard RSA problem to the usage of different datarate and modulation formats (referred to *configurations* in this paper) and is named the routing, configuration selection, and spectrum allocation problem (RCSA).

Commercial optical transport networks currently use coherent transmission in the C-band [3]. Recent research has shown that the capacity of current systems is saturating [4] [5], thus increasing the need for newer SDM technologies, such as multiband [6] [7], multicore [8] solutions or lighting of dark fibers [9], etc. The biggest limitation in introducing these technologies in commercial optical networks is the massive migration of optical equipment, which requires substantial investments. For example, transmission of the C + L band in the network will require the deployment of new components such as transceivers, amplifiers, and switches over the network. Furthermore, along with the high CAPEX requirement, the current shortage of chips [10] also introduces a hurdle to the deployment of these components. As it currently stands, increasing network utilization efficiency within current capacity is the key to improving network performance. One of the solutions to increase the spectral efficiency and postpone the high CAPEX required in SDM solutions is the use of regenerators [11]. Given the variability of demands and their routing paths, different configurations can have different optical reach, i.e., maximum transparently transmittable distance. Regeneration aids in increasing this reach by performing optical-electric-optical (OEO) conversions and transmission of a replenished signal [2]. The OEO conversion also means that the LP will be divided into more than two path segments, rather than a completely transparent LP. Using regenerators allows the deployment of LPs with higher datarates and bandwidth efficient configurations, thereby increasing the spectral efficiency. Furthermore, using regeneration at intermediate nodes allows the relaxation of the spectrum continuity constraints, as the path segments can be allocated to different spectrum slots over each segment.

In scenarios involving multiperiod planning, each demand is routed and assigned a designated spectrum segment for every planning period. In this context, the RCSA algorithms do not take into account the progressive surge in yearly traffic demands. Furthermore, the annual increase in the LP density in the network increases the chances of blocking existing LPs due to nonlinear interference (NLI), increased ASE noise, and fiber impairments [12]. In this paper, we consider the RCSA for a multiperiod planning study, with incremental annual traffic to

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represent the realistic real world scenario.

In this paper, we propose different heuristic solutions aiming to increase the efficiency of the existing RCSA solutions with regeneration by adaptively reconfiguring the placed LPs with regeneration based on the spectrum usage of the LPs, the increasing yearly traffic, and NLI. In the course of this study, we endeavor to address the following inquiries:

- To what extent can the deployment of regenerators defer the investments in SDM solutions, e.g.,multiband, multi-core amidst the growing network traffic?
- Does the reconfiguration of existing LPs hold the potential to extend the lifespan of current optical transport networks?
- Can reconfiguring existing LPs offer a quicker solution in comparison to blocking LPs?

The presented work reconfigures existing LPs to add regenerators and increase their throughput. We also consider the case of avoiding LP blocking by downgrading LPs. The aforementioned schemes work in conjunction with the existing planning methods to maximize the usage of the C-band before exploring the spatial division multiplexing (SDM) solutions. We evaluate our heuristics with existing solutions on three different topologies: Nobel-Germany, DTNet, and Polska.

The remainder of the paper is organized as follows. Section II covers the related work and state-of-art, Section III provides a detailed overview of the network model and heuristics. The observations and results are discussed in Section IV, followed by concluding remarks in Section V.

II. Related Work

Recent works [13] [14] highlight the saturation of the C-band and the requirement of spectrum efficient solutions before moving to multiband solutions. The RSA problem has been extensively investigated over the years [15] [16]. The authors of [16] provided a dynamic solution for selecting modulation format along with routing and spectrum assignment. The paper [17] also provides a configuration selection heuristic and the RCSA method for different networks with dynamically increasing traffic.

Yildiz *et al.* [18] presented a regenerator placement and a routing, modulation format, and spectrum allocation (RP-RMLSA) method using a branch-and-price algorithm with path segment formulation. An overview of the available regeneration placement and assignment problem is presented in [19]. They consider a definite traffic demand and propose heuristics for assigning regenerator locations, based on its optical reach or spectrum usage. The authors in [20] present a joint RSA and regenerator placement problem to minimize the number of regenerator enabled nodes for given static demands. The study investigates the cost of installing and maintaining regenerator locations. Halder *et al.* [2] use a genetic sorting algorithm to optimize spectrum assignment and energy consumption for a regeneration-aware RSA problem. In this study, the authors did not take into account the number of regenerators and the impact of modulation format conversion. Finochietto *et al.* [21] analyze provisioning methods for demands with incremental load of a fixed granularity, considering the trade-off between regeneration devices and spectrum availability. The study takes a rigid approach in terms of the types of demands, and does not account for higher diversity in modulation format selection.

In most of these works, the regenerators are placed and assigned for static traffic using an ILP solution, where re-optimization is required for any increase in the traffic. The heuristics can provide a faster solution that can be adapted with any traffic changes. Moreover, the aforementioned studies do not consider reconfiguration from a regeneration perspective.

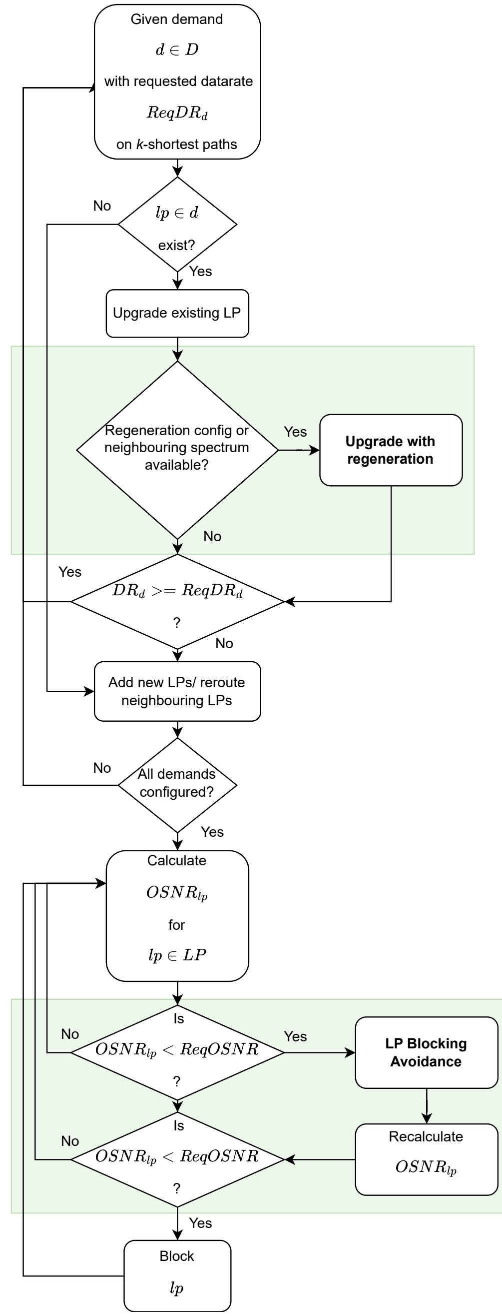


Fig. 1: Flowchart showing the proposed algorithms and their location in the RCSA method.

Our presented work presents the adaptability of existing LPs with regeneration, and investigates if regeneration can defer the investment of other SDM methods.

III. Problem Formulation

This section provides a detailed overview of the proposed solutions for reconfiguration of existing LPs placed within the C-band by using regenerators in multiperiod planning scenarios. Before we discuss the proposed methods, we present the network model used for our simulations.

A. Network Model

The network is represented as a graph $G(V, E)$ with $|V|$ nodes and $|E|$ links for a given network topology. Every node is designed to house multiple BVTs for transmission over single-mode fiber links with fixed length spans. The set of demands is represented by $D = \{d\}$ with the aggregated requested traffic DR_d, which is updated at the end of each planning period t. Each demand can be routed through the k shortest paths, which are calculated using Yen's shortest path [22] method. The demands are sorted according to path lengths from the calculated shortest paths, with a higher priority for longer demands, as shorter demands can block the spectrum, leading to lower network performance. A set of configurations $\Gamma = \{\gamma\}$ is available to configure lightpaths (LP) for each demand. Different configurations are enabled with the use of BVTs in terms of their data rate, modulation format, bandwidth and minimum OSNR requirements, and FEC. The regenerators are considered as 2 BVTs in a back-to-back (B2B) configuration, thereby contributing to the overall number of BVTs used in the network. The requested aggregate traffic is provided for every demand, which increases with every planning period to represent the dynamic ever increasing traffic in the network,

B. RCSA Model

Figure 1 shows the complete process of the network planning simulation, with the parts in white representing the underlying RCSA model per planning period. At the start of every planning period, LPs for each demand are individually mapped per demand given the requested aggregate traffic. The spectrum allocation is performed using the first-fit (FF) spectrum allocation method. Our previous work with the RCSA provides a set of provisioned LPs for all demands using MILP, which are placed subject to available spectrum [17] [23]. Once the LP provisioning and spectrum allocation is completed for all demands, all the LPs are validated with OSNR calculation based on its configuration, ASE noise, and existing neighbouring LPs, which contribute in the NLI [24]. All placed and existing LPs with OSNR lower than required OSNR are blocked and the spectrum is made available for the next planning period.

In our previous works, the regeneration enabled LPs are only provisioned when new LPs are added to the network. The proposed work reconfigures existing LPs for adaptable use of regeneration based on network performance and available capacity. The adaptable regeneration enabled reconfiguration can be divided into two heuristics: **Upgrade LP with Regeneration** and **LP Blocking Avoidance**. The heuristics work in conjunction with our RCSA solution, with the Upgrade LP with regeneration intending to upgrade existing LPs, prior to provisioning of additional LPs if the requested traffic is not met. The LP blocking avoidance is used when all LPs have been provisioned and attempted for placement on the spectrum, and the overall OSNR of all LPs is calculated. Their usage and position in the existing RCSA are represented by

Algorithm 1 Upgrade LP with Regeneration

Input: Network $G(V, E)$, Lightpath $lp_{upgrade}$ mapped to Demand $d \in D$ (source src_d, destination dst_d nodes) on path $k \in KSpath_{dk}$, current configuration $\gamma \in \Gamma$, Datarate DR_γ required OSNR $reqOSNR_{\gamma,lp}$, required BW BW_γ for configuration γ

Output: new configuration $\tilde{\gamma} \in \Gamma$ using regeneration for $lp_{upgrade}$

```
for Configuration γ̃ ∈ Γ for path do
  if DR_γ̃ > DR_γ & BW_γ̃ == BW_γ then
    Step 1 Calculate OSNR OSNR_γ̃,lp for lp_upgrade
    if OSNR_γ̃,lp < reqOSNR_γ,lp then
      Step 2 Upgrade lp_upgrade to configuration γ̃
      if γ̃ uses regeneration on path k then
        Step 3 Reconfigure lp_upgrade to configuration γ̃
        Step 4 Update lp_upgrade with sublps with given
        regeneration nodes
        Step 5 Update total datarate for d
  else if DR_γ̃ > DR_γ & BW_γ̃ >= BW_γ then
    Check for neighbouring spectrum slots
    if Slots available then
      Repeat steps 1-5
```

Algorithm 2 LP Blocking Avoidance

Input: Network $G(V, E)$, Lightpath lp mapped to Demand $d \in D$ (source src_d, destination dst_d nodes) on path $k \in KSpath_{dk}$, current OSNR $OSNR_{lp}$, current configuration $\gamma \in \Gamma$, Datarate DR_γ required OSNR $reqOSNR_{\gamma,lp}$, required BW BW_γ for configuration γ,

Output: new configuration $\gamma‘ \in \Gamma$ without regeneration for lp

```
if OSNR_γ,lp < reqOSNR_γ,lp then
  for Configuration γ‘ ∈ Γ for path do
    if reqOSNR_γ‘,lp < OSNR_γ,lp & BW_γ‘ <= BW_γ
    then
      Validate OSNR OSNR_γ‘,lp
      if lp uses regeneration then
        if spectrum slots for sublp are continuous then
          Remove regenerator points from lp
      Reconfigure lp with configuration γ‘
      Update total datarate for d
      Clear spectrum slots if BW_γ‘ < BW_γ
```

the green blocks in Figure 1.

C. Upgrade LP with Regeneration

This module is applied when there are pre-existing LPs mapped to a specific demand that can be upgraded to meet the requested traffic. The pseudocode for the heuristic is shown in Algorithm 1. In the upgrade phase, the heuristic looks for a subset of configurations that have a higher datarate with a similar BW requirement. The configurations' subset size can be increased with the use of configurations with regenerator nodes. Regeneration aims to provide higher DR with lower spectrum usage, thereby increasing the spectral efficiency in the network. In case of lack of configurations with the stringent bandwidth and datarate requirements, the neighbouring slots of the LP can be employed in upgrading the LP.

D. LP Blocking Avoidance

Another roadblock in efficiently using the current available spectrum is blocking of LPs that fails transmission due to lower received OSNR, caused by ASE noise over the spans, and due to the NLI contributed by the neighbouring LPs. In case the LP is blocked, the now empty spectrum slots cannot be used until the next planning period. Furthermore, the free slots can be used for new LPs only if there are substantial neighbouring slots available to deploy an LP with higher datarate and BW constraints. A simple solution is to reconfigure the LP with a configuration with lower requirements, at the cost of lowering the datarate of the LP. The pseudocode for LP blocking avoidance is shown in Algorithm 2.

In addition to downgrading the transparent LPs, downgrading LPs with regeneration is also considered. In such cases, the spectrum continuity of the path segments (called $sublp$ in Algorithm 1 and 2) needs to be taken into account. Each $sublp$ needs to use the same slot indices to be reconfigured into a transparent LP. This reconfiguration allows for lower number of BVTs used, along with preventing drastic reduction in throughput in case of blocking.

IV. Results

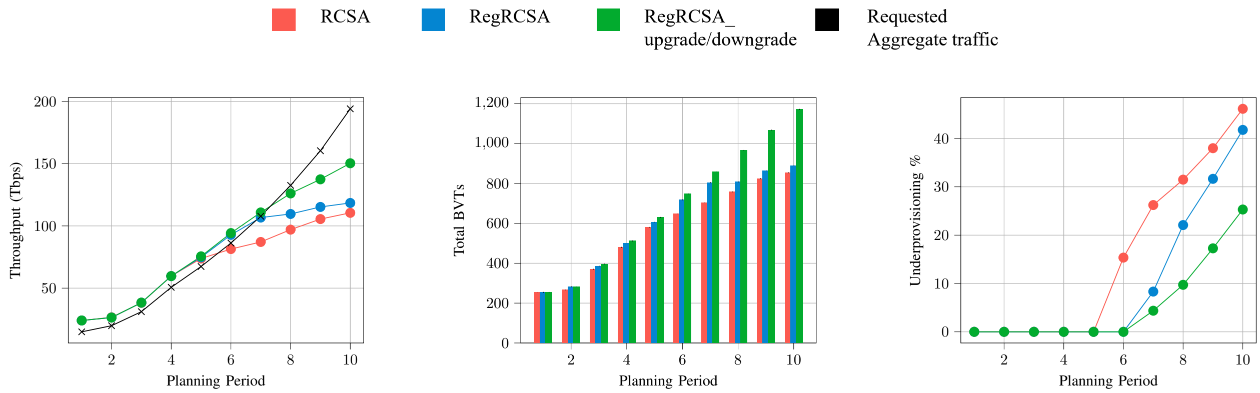
The proposed heuristics are evaluated on three topologies: Nobel-Germany ($|V| = 17, |E| = 26$ and $|D| = 123$, $diameter = 992.2\ km$), Deutsche Telekom Germany DTNet ($|V| = 14, |E| = 23$ and $|D| = 91$, $diameter = 874.0\ km$) [25] and Polska ($|V| = 12, |E| = 18$ and $|D| = 66$, $diameter = 382.3\ km$) topologies. The finite time horizon is set to $T = 10$ years, with $k = 5$ shortest paths per demand. Each link is traversed with uniform length spans of 80 km each. The heuristics (mentioned in the Figures as **RegRCSA_upgrade/downgrade**) are compared with the existing RCSA solutions(**RCSA** in the plots) and the state-of-the-art RCSA with regeneration (**RegRCSA** in the plots). 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 traffic increment for each demand is modeled as a Gaussian model with variable increase per year for a realistic network scenario. As previously mentioned, this work presents to increase the usage of the existing C-band technologies before migrating to new infrastructure-laden multiband solutions.

We use 4 metrics for evaluating the performance of the proposed methods: throughput (Figures 2a, 3a, and 4a) underprovisioning for all demands (Figures 2c, 3c, and 4c), number of BVTs deployed (Figures 2b, 3b, and 4b), and configuration distribution in terms of relative difference in the number of LPs per datarate in the final planning year (see Figure 5).

In Nobel-Germany topology, the throughput is overall higher than the RCSA counterpart, with a significant increase of 37 Tbps in the final planning year. In smaller topologies such as DTNet and Polska, the improvements are visible from year 7 onwards, with an improvement of 43 Tbps and 38 Tbps respectively in the final year. This is due to the mesh nature and high betweenness centrality of the topologies, which allow for diverse path selection and enabling more regeneration locations. The inclusion of upgrading previous LPs with regeneration during the planning phase helps in increasing the throughput by 27 Tbps in the final planning year compared to just using regeneration for new LPs. It also helps in meeting the requested traffic for later years for all topologies, and the proposed method meets the requested traffic completely till year 8.

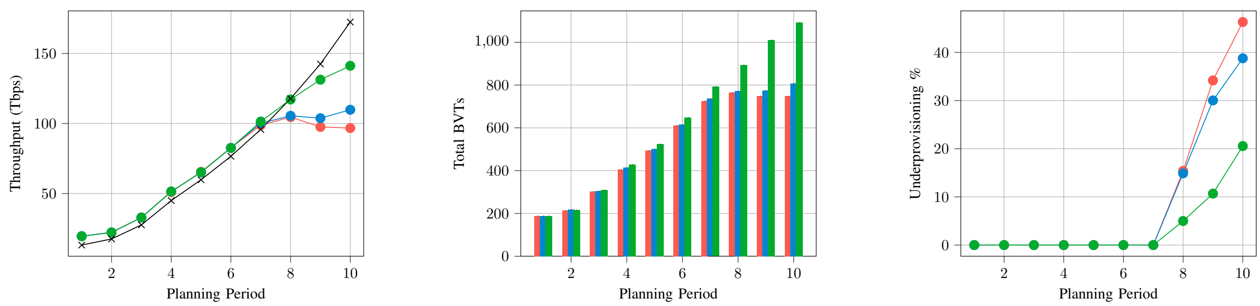
A direct consequence of using multiple regenerator nodes in the solution is the increase in number of BVTs required. We can observe a direct correlation between the throughput and number of BVTs in all topologies. With the current shortage of semiconductors, manufacturing, procurement, and deployment of new technologies for multiband solutions is difficult. The additional BVTs can be deployed using existing technologies within the limited capacity to meet traffic as a cost-effective solution, as these BVTs can be redeployed if dark fibers are lighted as an SDM solution [9]. In terms of the effectiveness of increase in number of BVTs, we calculate the increase in throughput per 2 BVTs (for source and destination, assuming no regeneration). In year 10, the average is 331.23 Gbps for Nobel-Germany, 259.67 Gbps for DTNet, and 256.1 Gbps for Polska topologies. Given the limited capacity, the RCSA is not able to place new LPs. This throughput measure can be considered as the placement of 159, 172, and 161 additional LPs in the respective topologies using RCSA, by adding regenerators in existing LPs, thereby using the same capacity to get higher throughput.

In terms of the underprovisioning, the proposed solution provides more than 20% lower underprovisioning than the RCSA solution, with the minimum improvement of 23% in Polska topology and the maximum improvement of 26% in DTNet topology in the final planning year. The results confirm that our solution can delay the underprovisioning by upto 2 years in all topologies, with only a small underprovisioning in the final planning year in case of Polska topology. Compared to the RCSA with regeneration, the proposed method adds value with lower underprovisioning from year 6 onwards in Nobel-Germany, and year 7 onwards in DTNet and Polska topology. The increasing traffic in the further planning years



(a) Throughput (b) Number of BVTs (c) Underprovisioning

Fig. 2: Comparison of the proposed solution with existing works for Nobel-Germany topology.



(a) Throughput (b) Number of BVTs (c) Underprovisioning

Fig. 3: Comparison of the proposed solution with existing works for DTNet topology.

would require expansion in the SDM scenario.

The previous parameters depict a holistic view of the network, and does not account for the improvement seen with using regeneration and upgrading existing LPs with regeneration. Therefore, we show the relative difference in number of LPs (Figure 5) between the RCSA and the proposed method per configuration for the final planning year. Observing 26 different configurations can make the plot convoluted, and since throughput is one of the major metrics to evaluate the performance of the planning schemes, we group the configurations in terms of datarate only. Furthermore, we only consider the final planning year as it shows the worst-case scenario in terms of the requested traffic. It is observed that in case of Nobel-Germany and DTNet, we see an increased use of 450-550 Gbps configurations by upto 30 LPs, which is enabled with the use of regeneration. We also observe that configurations with lower datarates of 150-200 Gbps are the ones reduced, which is made possible by upgrading the existing LPs to use regenerators.

V. Conclusion

The presented work dynamically adapting the existing LPs with regenerators to improve the network performance by increasing the network throughput and spectrum efficiency. It also considers avoiding LP blocking by downgrading the existing LPs with high NLI and accumulated noise to be functional and aid in preventing drastic decrease in network throughput. The heuristics are evaluated over three topologies, and results show that regenerators increase the network throughput by a maximum of 43 Tbps, and lower the underprovisioning by more than 20% in the final planning year. We also observe an increase in number of LPs using configurations with higher datarates, improving the spectrum utilization. Increasing the number of regenerators further increases the number of BVTs deployed in the network. The cost of BVTs can be compensated with the resultant increase in network throughput. The presented solution delays the investment in the infrastructure required for migrating to C+L band methods, with the investment in BVTs being a cheaper option that can be easily deployed in the network to meet the increasing traffic. Furthermore, the additional BVTs can be reutilized in case of dark fiber activation, making this a cost-effective solution with consideration for future traffic.

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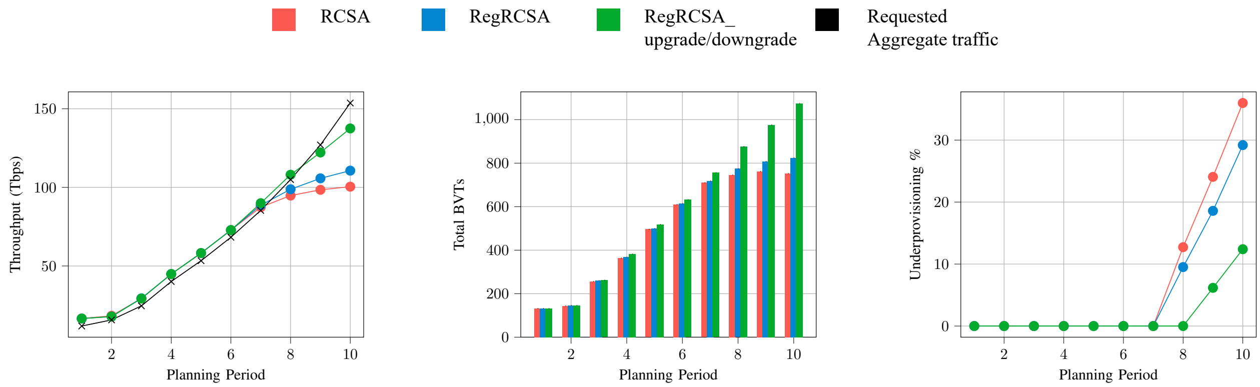

(a) Throughput (b) Number of BVTs (c) Underprovisioning

Fig. 4: Comparison of the proposed solution with existing works for Polska topology.

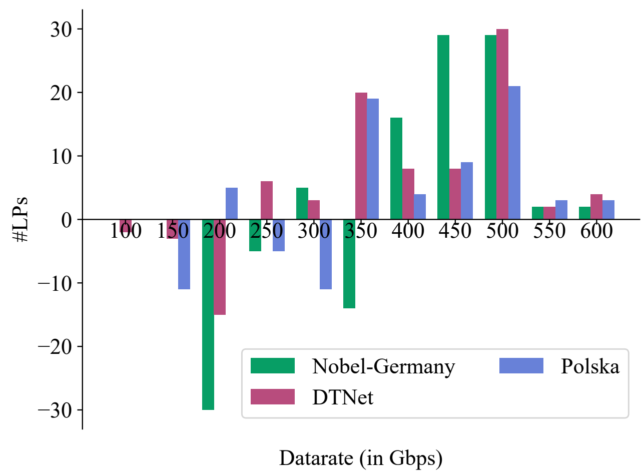

Fig. 5: Relative difference of number of LPs per configuration in terms of datarate between the proposed methods and RCSA for the final planning year.

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