Evaluation of Lightpath Deployment Strategies in Flexible-Grid Optical Networks

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***Abstract*—With the recent advances in elastic optical networks, a significant increase in throughput is promised with the use of bandwidth variable transponders. These transponders support different lightpath configurations, in terms of data rate, modulation format, and bandwidth. Considering the ever-increasing traffic in the core optical networks, routing, configuration, and spectrum assignment (RCSA) algorithms are crucial to increase the network throughput over the planning periods. To do this, lightpaths should be configured with enough data rate, while guaranteeing the signal quality at the receiver.**

In this work, we present a detailed evaluation of different lightpath deployment strategies in the context of multi-period elastic optical network planning. We show that in our RCSA algorithm, a multi-objective optimization can cope with the increasing traffic by deploying up to 31% fewer lightpaths while reducing the over-provisioning by 9% compared with the greedy approaches. Further, our simulation results indicate that our proposed approach can lead up to 16% higher power-efficiency.

***Index Terms*—Flexible-Grid Optical Networks, Local Optimization, Power consumption, software tunable bandwidth variable transponders, Reconfiguration, Adaptation.**

I. Introduction and Background

Recent advances in coherent optics, digital signal processing (DSP), and photonic integrated circuits have led to a paradigm shift in the design and operations of long-haul Dense Wavelength Division Multiplexing (DWDM) optical networks. These include, but are not limited to, *i)* evolution from ITU-T fixed grid DWDM channels (each of 50 GHz) to ITU-T flex-grid channels [1], *ii)* market availability of software tunable bandwidth variable transponders (BVTs) and optical terminals, and *iii)* Software-Defined-Networking (SDN)-enabled disaggregated optical transport networks [2]. In particular, these developments have helped operators achieve up to 1.2 Tbps of data rate per optical channel [3]. Also, they can undertake complex network operations using open source interfaces, while driving down the effective operational cost per bit.

However, this increased flexibility leads to an increased complexity in planning flexible grid networks. Specifically, a fixed grid optical transponder capable of achieving only 100 Gbps is replaced by a software tunable optical transponder. These transponders can achieve data rates between $100-$

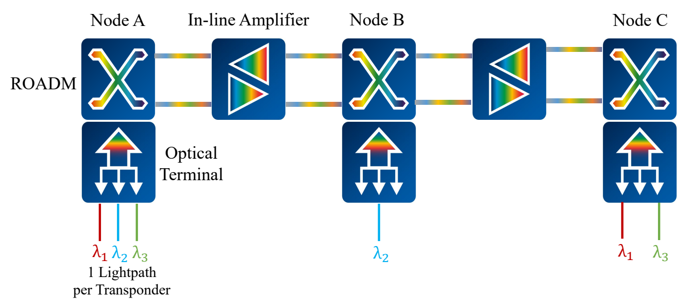

Fig. 1: Architecture of a long-haul optical transmission. Each optical terminal contains multiple software tunable BVTs. Every BVT is configured with one lightpath.

600 Gbps on a $37.5-100$ GHz channel using any dual-polarized modulation formats between QPSK to 64QAM. This additional degree of freedom requires network planners to determine BVT configurations in addition to the conventional routing and spectrum assignment (RSA).

Particularly, a planning algorithm that determines routing, configuration, and spectrum assignment (RCSA) of BVTs, first finds the path (e.g., Dijkstra's shortest-path) for source-destination pairs (demands) in the network. Thereafter, for each of these demands, it finds the set of channel configurations for BVTs, which can satisfy the physical transmission constraints (e.g., Optical Signal to Noise Ratio (OSNR)). Then, using spectrum assignment, empty channel slots which can fit the configurations are found on all links of the chosen path to obtain a central channel frequency. Finally, the software tunable BVTs at both the source and destination are tuned to this frequency and a lightpath (LP) is established.

In our work, we define an LP as a channel configuration assigned to a BVT pair between each source-destination demand. As seen in Fig. 1, two BVT pairs at source Node A and destination Node C are assigned LPs λ_1 and λ_3, whereas one transponder pair between Node A and Node B is assigned λ_2. A channel configuration can be assigned to an LP as long as *(i)* the calculated generalized OSNR (GSNR) is higher than the minimum receiver sensitivity OSNR of the configuration (see

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Data rate R_c (Gbps)	Modulation Format Q_c	Bandwidth B_c (GHz)	min. receiver sensitivity OSNR SNR_c (dB)
100	QPSK	50	11
200	8 QAM	62.5	16
400	32 QAM	62.5	24
500	32 QAM	75	27

TABLE I: Channel configuration examples of a software tunable BVT [5].

examples in Table I), and *(ii)* there are enough free contiguous channel slots in the links to accommodate the configuration. Applying this to the example shown in Fig. 1, LPs λ_1, λ_2, and λ_3 are assigned to different central channel frequencies and may operate on different channel configurations. We note that to calculate the GSNR of each LP, both linear and non-linear noise are taken into account. The linear noise comes from the in-line amplifiers, and the non-linear noise (NLIN) from the cross channel interference of neighboring channels. The NLIN is calculated using a closed form equation of the Enhanced Gaussian Noise (EGN) model [4].

In our previous work [5], we have introduced a configuration selection algorithm considering NLIN. Also, an RCSA optimization for a multi-period network planning scenario has been presented in [6]. We have observed that in this optimization problem, in addition to meeting the increased yearly traffic, it is important for network operators to reduce the total number of deployed LPs, which is proportional to the power consumption of the networks and plays a role in making strategic decisions for effectively planning optical networks [7]. However, deploying a low number of LPs can lead to under-provisioning in the future, which can lead to the need for more LPs later on. Therefore, considering the channel configuration of the LPs (data rate) can play a big role in the efficiency of the RCSA algorithms. In this work, we present an algorithm for optimized RCSA using different objective functions and determine the number of LPs and their channel configurations in a multi-period planning scenario. Moreover, we provide an evaluation of the power consumption of our algorithm with different objective functions.

The rest of the paper is organized as follows: In Section II, we formulate our problem mathematically and introduce four different LP deployment strategies. In Section III, we discuss the planning scenario and subsequent results on two core networks. Section IV deals with related work and state-of-the-art. Finally, the paper is concluded in Section V.

II. Mathematical Formulation

A. System Model

We start by defining a core network as a graph $G = (N, L)$ with N nodes and L links. Each node is an optical ROADM with add/drop capabilities. Also, each link consists of single-mode fiber pairs with heterogeneous span lengths [8]. Considering T planning years, the set of demands per year is defined as $D_t, \forall t \in T$. We define each yearly demand set $d \in D_t$ as $d_{i,j,t} = (i_d, j_d, r_{d,t})$, where $i, j \in N$ are source and destination nodes respectively, and $r_{d,t}$ is the requested data rate at year t. The value of $r_{d,t}$ is calculated based on $r_{d,t-1}$ and the expected yearly increase of $\Delta_{d,t}$, i.e., $r_{d,t} = r_{d,t-1} + \Delta_{d,t}$. The data rate requested by a demand should be fulfilled by deploying one or more LPs in the network. The set of deployed LPs for demand d in year t is defined as $L_{d,t}$. Each of these LPs $l_c \in L_{d,t}$ is associated with an LP configuration $c \in C_d$, where C_d is the set of feasible configurations. This set of feasible configurations per demand is determined based on our previous work [5]. Each configuration c is defined as (R_c, Q_c, B_c, SNR_c), where R_c is the data rate, Q_c is the modulation format, B_c is the channel bandwidth, and SNR_c is the minimum receiver sensitivity OSNR. The LPs in the network can be assigned to a path $p \in KSP_d$, where KSP_d is the set of paths (e.g., k-shortest-path) for demand d. The notations have been summarized in Table II.

In this work, we answer three questions for each demand at every planning period:

1) How many LPs and on which path each LP for the demand should be deployed?
2) How to reconfigure the LPs to meet the required demands data rate?
3) How to answer the above questions with low over-provisioning and power consumption?

In addition to meeting the yearly requested data rate, an objective of this work is to study the power-consumption of the variations of our RCSA algorithm. We consider the power consumption of a flexible optical network from the deployed LPs (using transponders) and their configured data rate [9]. When an LP is configured, a static amount of power P_s is consumed. Additionally, there is a dynamic power consumption P_d which depends on the data rate R_c (in Gbps) for the configuration c. Thus, the total power consumption P_T of the network in each year is considered as:

$$P_T = \sum_{d \in D_t} \sum_{l_c \in L_{d,t}} \big(P_s + P_d \times R_c\big), \forall t \in T. \quad (1)$$

We note that $P_s \gg P_d$ [9].

In the following, we explain how we deal with the above questions and objectives, by utilizing an RCSA with different objective functions. Particularly, we extend the proposed approach in our previous work (i.e., the *LP Addition* method) [10] to evaluate the performance of different objective functions.

B. The RCSA Algorithm

At the beginning of the planning (i.e., $t = 0$), the LPs, their configurations, and the path to deploy them are pre-selected by using the approach from our previous work, HeCSON [5]. For every source-destination demand pair routed on any of the k-shortest paths in the network, HeCSON provides a list of feasible BVT configurations, taking into account the GSNR as well as the minimum receiver sensitivity OSNR.

From the first year onward ($t \geq 1$), the algorithm is triggered yearly, in a demand-by-demand manner. For each

Notation	Definition
$G = (N, L)$	The physical network graph with N nodes and L links
T	The set of planning years ($T = \{t_1, t_2, ...\}$)
D_t	The set of demands in year t
$d_{i,j,t}$	The demand with src/dst node i/j at year t
$r_{d,t}$	The requested data rate of demand d at year t
$\Delta_{d,t}$	The increased data rate for demand d at year t
$L_{d,t}$	The set of deployed LPs for demand d at year t
$c \in C_d$	The LP configuration
l_c	An LP with configuration c
R_c	The data rate of LP configuration c
Q_c	The modulation format of LP configuration c
B_c	The channel bandwidth of LP configuration c
SNR_c	The minimum receiver SNR of LP configuration c
KSP_d	The set of k-shortest-paths for demand d
δ	The maximum over-provisioning bound
$x_{c,p} \geq 0$	Integer decision variable, indicating the number of deployed LPs with configuration c on path p

TABLE II: Notation definition

demand, the algorithm is triggered if the sum of the data rate of the deployed LP(s) is lower than the total increased traffic:

$$\sum_{l_c \in L_{d,t-1}} l_c \times R_c \leq r_{d,t}, \forall t \in T, \forall d \in D_t(t > 0) \quad (2)$$

In this case, to cope with the increased data rate, the RCSA algorithm performs a three-step approach:

1) Step 1: The algorithm first tries to upgrade each LP in $L_{d,t-1}$ to a configuration with a higher data rate. These LPs might have been deployed on any path in KSP_d. If neither enough frequency slots are available, nor the required GSNR can be guaranteed, the algorithm moves to Step 2. For more detailed information on this method, we refer the readers to our previous work HeCSON [5].

2) Step 2: At this stage, the algorithm deploys new LPs on one of the available paths from KSP_d. In particular, it uses an Integer Linear Program (ILP) which is formulated based on the Bounded Knapsack Problem. This formulation uses an integer decision variable $x_{c,p} \geq 0$ where its value determines the number of LPs of configuration c to be deployed on path p. Further, this ILP model must satisfy a set of constraints, which is described below. Firstly, the sum of data rate of the newly deployed LPs must be greater than the requested data rate by the demand:

$$\sum_{c \in C_d} \sum_{p \in KSP_d} x_{c,p} \times R_c \geq \Delta_{d,t} \quad (3)$$

Secondly, the allocated data rate should be bounded by a value of δ:

$$\sum_{c \in C_d} \sum_{p \in KSP_d} x_{c,p} \times R_c \leq \Delta_{d,t} + \delta \quad (4)$$

We note that we use δ to balance the over-provisioning and the need for future LP deployments. Further, we consider four objective functions to formulate the optimization problem:

Objective 1: Min LP. The first objective is to minimize the number of newly deployed LPs for the demand to reduce the power consumption incurred by deploying new LPs. Hence, the ILP formulation is:

$$\begin{aligned} &\text{Minimize} \sum_{c \in C_d} \sum_{p \in KSP_d} x_{c,p}, \quad (5)\\ &\text{s.t. Constraints } (3), (4),\\ &\text{vars. } x_{c,p} \geq 0, \forall c \in C_d, \forall p \in KSP_d. \end{aligned}$$

Objective 2: Max DR. The second formulation has the objective of maximizing the configured data rate. The idea behind this formulation is to deploy LPs with large data rates so that the need of deploying new LPs in subsequent planning years is decreased:

$$\begin{aligned} &\text{Maximize} \sum_{c \in C_d} \sum_{p \in KSP_d} \big(x_{c,p} \times R_c\big), \quad (6)\\ &\text{s.t. Constraints } (3), (4),\\ &\text{vars. } x_{c,p} \geq 0, \forall c \in C_d, \forall p \in KSP_d. \end{aligned}$$

Objective 3: Max DR, Min LP. This formulation is developed as a multi-objective case with hierarchical objectives (i.e., optimizing the first objective, and then the second one while keeping the first one as a constraint). In this case, the first objective (with higher priority) is to maximize the data rate, and the second one (with lower priority) is to minimize the number of deployed LPs. The goal behind this formulation is to prevent future need for new LPs, while using the minimum number of LPs in the current year. Thus, we have:

$$\begin{aligned} &\text{Maximize} \sum_{c \in C_d} \sum_{p \in KSP_d} \big(x_{c,p} \times R_c\big), \quad (7)\\ &\text{Minimize} \sum_{c \in C_d} \sum_{p \in KSP_d} x_{c,p},\\ &\text{s.t. Constraints } (3), (4),\\ &\text{vars. } x_{c,p} \geq 0, \forall c \in C_d, \forall p \in KSP_d. \end{aligned}$$

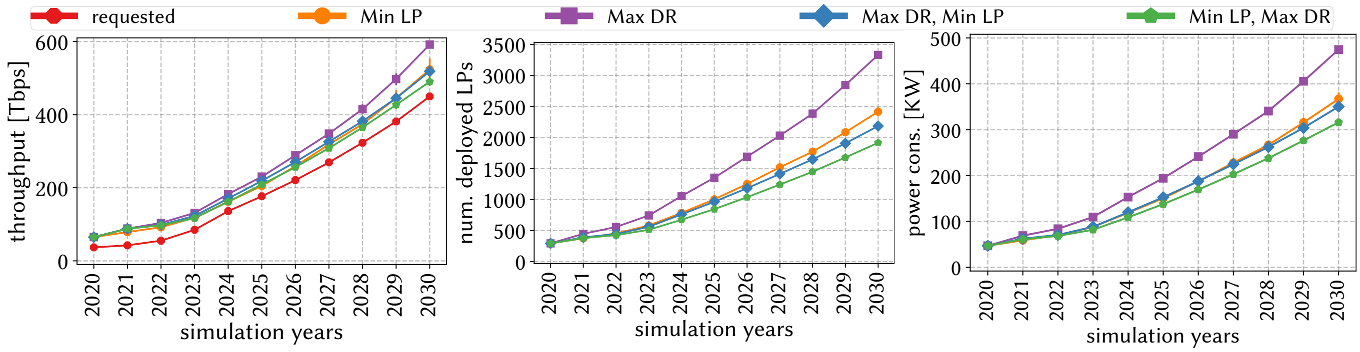
Objective 4: Min LP, Max DR. The last formulation is to deploy a minimum number of LPs, and maximize the data rate. Thus, We have:

$$\begin{aligned} &\text{Minimize} \sum_{c \in C_d} \sum_{p \in KSP_d} x_{c,p}, \quad (8)\\ &\text{Maximize} \sum_{c \in C_d} \sum_{p \in KSP_d} \big(x_{c,p} \times R_c\big),\\ &\text{s.t. Constraints } (3), (4),\\ &\text{vars. } x_{c,p} \geq 0, \forall c \in C_d, \forall p \in KSP_d. \end{aligned}$$

In the evaluation section, we extensively compare the performance of these four different objective functions.

After determining the required number of LPs, their configurations, and respective paths, in case the required data rate cannot still be met, the algorithm considers using Step 3.

3) Step 3: In this step, the algorithm tries to cope with the requested data rate by rerouting the neighboring LPs of each demand, such that the released spectrum can be used to upgrade the existing LPs to a higher data rate (i.e., Step 1). The details of the rerouting algorithm can be found in our



(a) Total throughput (b) Number of deployed LPs (c) Power consumption

Fig. 2: Nobel-EU topology.

previous work [10]. Note that, the rerouting method does not have a significant effect on the power consumption, since it only enables possible upgrade of existing LPs to a higher data rate (i.e., an increase in P_d).

III. Performance Evaluation

In this section, we evaluate the performance of the introduced objective functions. We start by presenting the simulation setup. Thereafter, we discuss the results of the performance evaluation in different topologies and settings.

A. Simulation Setup

We evaluate our planning algorithm with different objective functions for $T = 10$ years. We consider two topologies, Nobel-EU ($|N| = 28$, $|L| = 41$, and $|D| = 378$) and Nobel-Germany ($|N| = 17$, $|L| = 26$, and $|D| = 136$) networks [11]. Each link consists of a single fiber pair and the transponders are equipped to handle 26 different configurations for the C-Band [5]. The data rate request model for the first year is taken from our previous work [6]. In addition to different numbers of links, nodes, and demands, the volume of yearly traffic in Nobel-EU is higher than Nobel-Germany, up to 3x [6]. To include the uncertainty of the traffic increase, we extend [6] by considering a $\pm 15\%$ of random deviation in traffic request onward from the second planning year. The paths for routing the demands can be chosen from the set of k-shortest-paths with $k = 3$. Also, the static and dynamic power consumption values are taken from [9]: $P_s = 120$ Watts, and $P_d = 0.18$ Watts per Gbps. Finally, the value of δ is considered as 150 Gbps. This value is the minimum possible data rate to be over-provisioned, such that the model can deploy at least one LP (i.e., to make the ILP formulation feasible to be solved). The planning tool has been implemented in Java and the optimization has been solved using Gurobi [12]. The evaluations have been performed on a machine equipped with Intel Core i7-6700HQ @2.60 GHz, 16 GB of RAM, running Ubuntu 18.04. Finally, to generate reliable results, each scenario is run for 100 random traffic request cases.

B. Simulations Results

In this section, we explain and compare the evaluation results per topology in terms of total throughput, total number of deployed LPs, and power consumption. Afterward, we present the comparison of the power-efficiency of different approaches.

Let us start with the achieved network throughput in the Nobel-EU topology. As it can be seen in Fig. 2a, the *Max DR* approach results in the maximum over-provisioning in the network, while *Min LP, Max DR* achieves the minimum. A similar behavior can be seen for the number of deployed LPs in the network (Fig. 2b). The reason for this behavior is *Max DR* greedily increases the data rate, with no constraints on the number of deployed LPs. Meanwhile, in *Min LP, Max DR*, a lower number of LPs is provisioned with a higher data rate configuration.

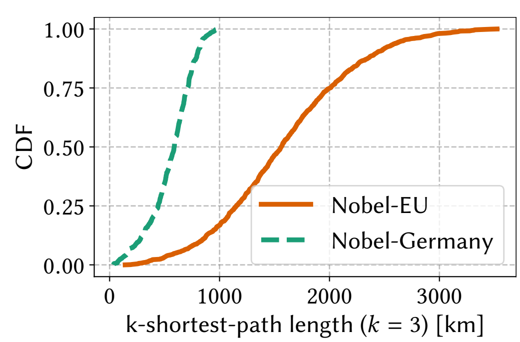
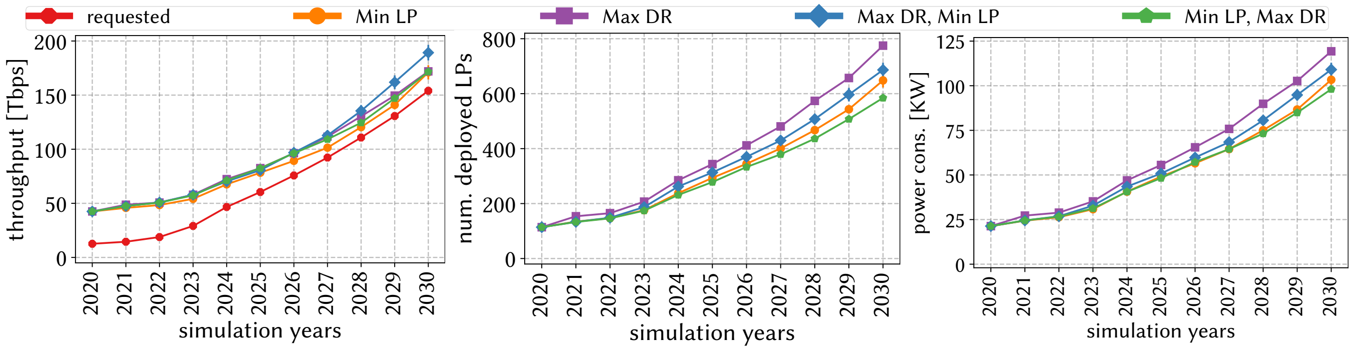


Fig. 4: The comparison of the length of the demands k-shortest-paths ($k = 3$) for Nobel-EU and Nobel-Germany topologies.

Surprisingly, Fig. 2b shows that *Min LP* results in deploying more LPs than *Max DR, Min LP*. The main reason is, as shown in Fig. 4, the path lengths in the Nobel-EU are up to 3x longer compared to the Nobel-Germany topology. This can prevent LPs from using high data rate configurations, due to a decrease in the GSNR in longer distances. Applying the same reasoning, *Max DR* meets the requested traffic by deploying many low-data-rate LPs.



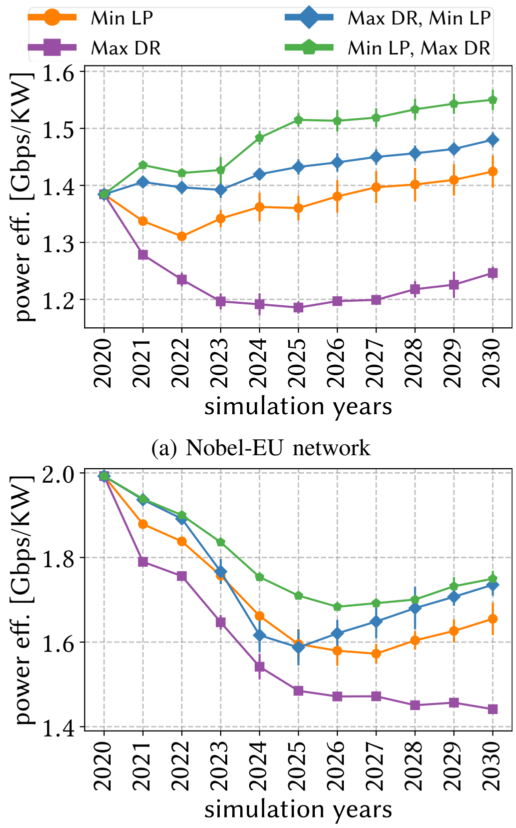
(a) Total throughput (b) Number of deployed LPs (c) Power consumption

Fig. 3: Nobel-Germany topology.

Moreover, by deploying a low number of high data rate LPs, *Min LP, Max DR* can support the future requested traffic with a lower number of LPs as compared to the other approaches. Further, Fig. 2c shows that the power consumption of the network follows the same trend as the number of deployed LPs. It shows that the static power due to the LP deployment is the dominant factor in the power consumption of the network.

Moving to the Nobel-Germany topology, Fig. 3 shows that the behavior of different objective functions is similar to the Nobel-EU; however, with some differences. These differences are due to the characteristics of the topologies, specifically in terms of path length (see Fig. 4). That is, the *Max DR, Min LP* objective leads to the maximum throughput, while in the Nobel-EU topology, *Max DR* results in the maximum. In other words, since the average path length is lower in Nobel-Germany than Nobel-EU, *Max DR* can provision more throughput compared to the other three objective functions. This is because the capability of deploying LPs with a higher data rate is higher in Nobel-Germany. Another difference is shown in Fig. 3a, where it can be observed that *Min LP, Max DR* over-provisions the network more than *Min LP* while deploying less LPs (see Fig. 3b). Further, as opposed to Nobel-EU, the different path length leads to *Min LP* deploying a lower number of LPs than *Max DR, Min LP*.

Finally, we present the results for the power-efficiency, which is defined as the consumed power per Gbps of traffic. Interestingly, by combining the throughput and power consumption, we can see similar behavior in both topologies in terms of power-efficiency (see Fig. 5). In particular, Fig. 5 shows that the single-objective approaches perform poorly compared to multi-objective approaches. For example, it can be seen that during the planning years, deploying with *Min LP* becomes insufficient over time, leading to deploying more LPs in later years (i.e., lower power-efficiency). However, when we consider the multi-objective approaches (considering both the static and dynamic power consumption), the power-efficiency significantly improves. That is, the *Min LP, Max DR* approach achieves the best power-efficiency compared to the other approaches.



(a) Nobel-EU network

(b) Nobel-Germany network

Fig. 5: Comparison of power-efficiency.

IV. Related Work

Prior studies for RCSA algorithms have used ILP and/or heuristics to dynamically provision new LPs in a flex-grid optical network. Recently, for a multi-period planning scenario, Moniz et. al [13] have proposed two separate ILPs for provisioning 32 and 64 GBaud channels, respectively. For upgrading in-operation LPs to a configuration with a higher data rate, a push-pull technique has been introduced by [14]. In their method, they have a dynamic reconfiguration to allocate additional frequency slots for the future upgrade of the LP. However, they do not consider re-routing and also the different paths to route the traffic. Also, they have only tested their approach for 10 and 100 Gbps LPs. However, since many modern software tunable BVTs can achieve variable symbol rates with the same number of frequency slots, their approach does not consider these requirements.

Further, Rottondi et. al [15] have provided a comprehensive solution for routing, modulation format, baud rate, and spectrum assignment using few-mode transmission in metro-ring networks. Although the goal of their study is to compare few-mode fibers with single-mode fibers, they have shown that they can improve the overall savings on the spectrum usage using an ILP. However, they have not considered higher symbol rates, which could potentially reduce the cost per bit even in single-mode fibers. Also, the network architecture in their study was an eight-node ring network with varying network radius. Therefore, it is not clear how their approach performs on long-haul optical networks with a high number of nodes and links.

Additionally, Ahmed et. al [16] have presented a novel RCSA heuristic for LP provisioning. However, the effect of NLIN on LPs is not considered, which may lead to inaccurate configuration selection. Moreover, the assumption of semi-static traffic profiles with fixed distribution and a Poisson arrival of traffic demands may not hold true when catering for unexpected traffic growth in the network.

On the other hand, several works have studied energy-efficient RCSA algorithms which try to minimize the total power consumption of transponders while meeting the simulated traffic demands [17]–[19]. For example, El-Mirghani et. al [19] have presented a comprehensive power consumption analysis for different optical transponders based on their data-rates. However, the assumption of approximately 1 W/Gbps power consumption for 100 Gbps, 400 Gbps and 1 Tbps transponders does not hold true for software tunable BVTs [9]. However, in this work, we consider a base and dynamic power consumption for a BVT. In particular, the base power is required for operating the tunable laser and the dynamic one is consumed for different data rates [9].

V. Conclusions

We formulated and compared four different variations of our proposed RCSA algorithm, mainly in terms of network throughput, deployed lightpaths (LPs), and power-efficiency. It has been shown that the multi-objective approach, *Min LP, Max DR*, performs the best by achieving the highest power-efficiency while reducing the number of required LPs and a lower over-provisioned throughput.

In particular, for Nobel-EU (Nobel-Germany), *Min LP, Max DR* approach deploys up to 31% (17%) less LPs, while reducing the over-provisioning up to 8% (4%) compared to the other approaches. Also, *Min LP, Max DR* leads to a higher power efficiency up to 16% and 11% for Nobel-EU and Nobel-Germany, respectively, as compared to the other approaches. These differences can be translated into a higher profit for the network operators, without the need of adding additional physical resources during the planning period.

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