Selection of Spectral-Spatial Channels in SDM Flexgrid Optical Networks

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***Abstract*—Space division multiplexing (SDM) is a promising solution with the scaling potential to overcome the possible capacity crunch problem in optical backbone networks. The key idea behind SDM is to exploit the spatial dimension to provide a significant increase in the transmission system capacity. In SDM, optical signals are transmitted in parallel through spatial resources (fibers, cores or modes), thus co-propagating in the same optical fiber structure. The goal of this paper is twofold. First, we propose and evaluate several versions of a greedy algorithm for optimization of flexible-grid SDM optical networks, including comparison with optimization results yielded by the CPLEX solver. Second, using best found algorithm settings, we complement our study with an analysis of SDM network performance in terms of the spectrum usage. We report and discuss results of numerical experiments run on a representative network topology with realistic physical assumptions. The key observation is the low scalability of the CPLEX solver, while the greedy algorithm is capable of generating solutions for larger network scenarios. However, even the relatively simple heuristic experiences quite large execution times.**

***Index Terms*—space division multiplexing; optical networks; network optimization; routing, space, and spectrum allocation**

I. INTRODUCTION

Due to continuously increasing popularity of various network services the overall Internet traffic grows quickly. According to the recent Visual Networking Index report published by Cisco, the IP traffic will grow at a compound annual growth rate (CAGR) of 22 percent from 2015 to 2020. These trends lead to incremental exhaustion of available spectral resources in currently deployed fixed-grid optical networks [1]. Various time division and wavelength division multiplexing technologies, including flexible-grid (flexgrid) elastic optical networking (EON) [2], are used to increase transmission capacity in single-mode optical fibers (SMFs) that are currently deployed in backbone networks. However, they are reaching its upper bound, due to the nonlinear Shannon limit [3].

Space division multiplexing (SDM) architectures appear as an up-and-coming solution for overcoming bandwidth limitations [3]. SDM utilizes a spatial dimension with the aim to increase network capacity and reduce its cost, which is achieved by integration of network elements realizing transmission through spatial resources (SpRcs). The SpRcs correspond either to a bundle of SMFs, a multi-core fiber (MCF) that involves many fiber cores embedded in a single fiber cladding, or a multi-mode fiber (MMF) as well as a few-mode fiber (FMF), where optical signals are transmitted through many transvers optical modes. The SDM technology allows a high-capacity super-channel (SCh) [4], consisting of a number of optical carriers (OCs)—which are generated/terminated using transceiver devices, each making use of a certain modulation format and carrying a fraction of aggregated traffic—to be transmitted using both spectral and spatial resources [5].

A basic concern in the design and operation of flexgrid SDM networks is the problem of routing, space (i.e., fiber/core/mode), and spectrum allocation (RSSA) [6], [7]. RSSA consists in finding optical paths (lightpaths), tailored to the actual width of the transmitted signal and routed through SpRcs available in network links, for a set of end-to-end demands that compete for spectral and spatial resources. The application of SDM increases network capabilities since OCs forming SChs are not carried just on adjacent frequencies in the frequency domain (as in flexgrid EONs), but they can also be distributed over different modes, cores or fibers [5] – in the most flexible scenario, mixed ”spectral-spatial” SChs can be created [8]. This results in a large set of decision variables in network optimization, which makes RSSA more complex than the routing and spectrum allocation (RSA) problem in EONs. Consequently, new algorithms are required for solving RSSA.

In a flexible SDM scenario allowing for transmission and switching of ”spectral-spatial” SChs, a SCh may consist of a number of sub-channels (SubChs), where each SubCh is carried over different SpRc and comprises a subset of OCs of the SCh. Since each SubCh requires some guardbands to separate it (in the frequency domain) from adjacent SubChs belonging to other lightpath connections, the use of SChs that are allocated on several SpRcs may lead to wastage of spectral resources. Moreover, in SDM scenarios in which regular (rectangular) spectral-spatial blocks are assigned to SChs, another wastage may occur. Indeed, the allocated blocks of resources may not precisely fit the size of SChs, i.e., they are over-provisioned, and thus some spectrum is wasted due to ”rounding” (i.e., the difference between the allocated block and actual SCh shape). If we consider the use of tunable transceivers capable of forming arbitrary spectral-spatial SChs, there may exist a number of possible candidate SCh configurations supporting given traffic demand, each characterized by a certain number of SubChs and the number of OCs in each SubCh. Assuming such flexibility, an important research question is to examine how these two factors, i.e., guardbands and rounding, influence network performance.

In this paper, we focus on optimization of SDM flexgrid

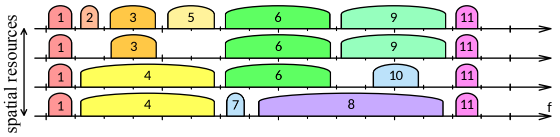

Fig. 1: Allocation of spatial and spectral resources.

optical networks. Namely, we address the RSSA problem in an SDM network implementing the independent switching (Ind-Sw) paradigm [9], which provides full space–wavelength switching granularity. In Ind-Sw, all frequency slices (i.e., spectral resources) and spatial modes can be independently directed to any output port. The contribution of the paper is twofold. First, we propose and analyze several versions of a heuristic algorithm applying a greedy approach for solving the RSSA problem. Second, we examine performance of the SDM network with Ind-Sw architecture in terms of the spectrum usage with a special focus on issues related to potential spectrum wastage due to guardbands and rounding.

The rest of the paper is organized as following. In Section II, we provide more details on SDM and discuss related works. In Section III, we describe the considered SDM network scenario and present an Integer Linear Programming (ILP) formulation of our resource allocation problem. In Section IV, we develop several versions of a greedy algorithm for optimization of flexgrid SDM networks. In Section V, we perform numerical experiments that aim at evaluating the algorithm and examining the network performance, as well as we discuss the obtained results. Finally, in Section VI, we conclude this work.

II. SDM and Related Works

SDM enables parallel transmission of optical signals propagating through spatial channels realized in fiber optic media. Several fiber approaches have been proposed for SDM, among others: single-mode fiber bundle (SMFB), multi-core fiber (MCF), few-mode fiber (FMF), and few-mode multi-core fiber (FM-MCF). In FMFs, strong coupling of spatial modes occurs, which limits the transmission distance. Also, weakly-coupled MCFs are prone to signal impairments due to inter-core crosstalk (XT). On the contrary, intermodal XT impairments are not present in SMFBs. For more details refer to [5], [10].

In [5] and [9], several levels of spectral and spatial switching flexibility in flexgrid SDM optical networks are defined, including independent switching (Ind-Sw) and joint switching (full or fractional, J-Sw/FrJ-Sw) options. Most of previous works concerning resource allocation in SDM optical networks have focused on ”spectral” SChs, which use single SpRcs (e.g. one fiber core) and operate with the Ind-Sw paradigm, or ”spatial” SChs, which occupy either all (in case of J-Sw) or a subgroup (in FrJ-Sw) of SpRcs within a particular spectrum range. In this paper, we address a less frequently studied scenario, in which ”spectral-spatial” SChs can be formed flexibly using both domains (i.e., spectral and spatial) and have allocated an arbitrary, regular (rectangular) block of spectral-spatial resources, as shown in Fig. 1.

The problem of modeling and optimization of RSSA has been a subject of several papers. In [6], [11], [12], ILP formulations of RSSA for an SDM network with MCFs and inter-core XT are proposed. Besides, in [6] and [13] some heuristics for XT-aware SDM network planning are developed. The authors of [14] use a simple k-shortest path and first-fit allocation algorithm to analyze different SDM switching strategies in an off-line network planning scenario. Similarly, a comparison of SCh allocation schemes in a dynamic SDM network is a subject of [15]. Moreover, some heuristic algorithms for dynamic lightpath setup are studied in [15], [16], [17], [18]. Finally, in our previous work [7], generic ILP models for flexgrid SDM optical networks with different spectral and spatial flexibility are presented. This paper is a continuation of [7], i.e., we implement the flexible ILP model, propose greedy algorithms and discuss the results of numerical experiments.

Moreover, to the best of our knowledge, there are no works concerning a detailed analysis of issues related to potential spectrum wastage due to guardbands and rounding in SDM networks. In addition, there are no papers that provide a detailed investigation of network performance under various spectral-spatial channel allocation policies in the context of static optimization and accounting for the fact that candidate spectral-spatial SChs can utilize a various number of SpRcs.

III. Network Model and RSSA Problem

The SDM network is modeled as a graph $G = (V, E)$, where V is a set of network nodes and E is a set of directed fiber links that connect pairs of network nodes. Each network link comprises a set of SpRcs. Although in this paper we neglect the impact of crosstalk on transmission quality, similarly as in [14], [15], [19], still the optimization framework presented here can be easily modified to account for XT constraints. We assume that the network operates within a flexible ITU-T grid [20]. In particular, on each SpRc of each network link, the available spectral resources are divided into frequency *slices* of 12.5 GHz width, which are included in set S. By grouping a number of adjacent frequency slices, optical channels of different width can be created.

Traffic demands are included in set D. For each demand $d \in D$, a lightpath has to be established in the network such that it could carry given bit-rate h_d. To model the routing of lightpaths, we apply the link-path notation [1], i.e., a set of *candidate paths* $P(d)$ is given for each $d \in D$. Let n_{dp} denote the number of slices required to carry bit-rate h_d of demand d on candidate path p. The value of n_{dp} depends on the modulation format (MF) selected to realize demand d on path p. In this paper, we apply a *distance-adaptive transmission* (DAT) rule, which selects MFs according to the transmission distance (path length) [1].

The optimization of RSSA in a flexgrid SDM network, besides addressing the routing problem, needs to solve the spectrum assignment problem in both spectral and spatial domains. To model the fact that demand d on path p can have allocated spectral resources on more than one SpRc, we use a concept of *spectral-spatial channel* (SSCh) [7]. A SSCh is a two dimensional structure representing resource allocation in both spectral and spatial domains. Let $C(d, p)$ denote set of candidate SSChs for demand d using path p and including at least n_{dp} slices plus required guardbands (for separating adjacent connections) on a subset of SpRcs.

The candidate SSChs approach allows us to model easily various SDM scenarios without the need to modify ILP formulations of RSSA (see [7]). Indeed, by generating different sets of SSChs, we can represent different scenarios, including Ind-Sw, J-Sw, and FrJ-Sw. However, the key disadvantage of this approach is a growing complexity of the number of possible SSChs when the most flexible resource allocation models are accounted for. In this paper, we consider an Ind-Sw scenario, where each SSCh in $C(d,p)$ can utilize a subset of SpRcs within the allocated spectrum channel.

The overall spectrum (slices) allocated on all SpRcs can be divided into three types: (i) demand volume (n_{dp}), (ii) guardbands, (iii) spectrum wasted for rounding the size of SSCh according to the required demand volume (i.e., slices included in the SSChs minus demand volume and guardbands).

Having for each demand d both candidate paths $P(d)$ and candidate SSChs $C(d,p)$, the RSSA optimization consists in selecting candidate path p from $P(d)$ and SSCh c from $C(d,p)$ for each $d \in D$. The objective function is to minimize the *maximum spectrum* usage, defined as the index of the maximum allocated slice in the network required to provision all demands in the network, considering all links and SpRcs. Below, we formulate an ILP model of the considered optimization problem. The key assumption is that the formulation accounts for a detailed modeling of all SpRcs and uses SSChs.

sets

E	links composed of multiple SpRcs
$K(e)$	SpRcs available on link e
S	slices
D	demands
$P(d)$	candidate routing paths for demand d
$C(d,p)$	candidate SSChs for demand d on path p

constants

δ_{edp}	=1, if link e belongs to path p realizing demand d; 0, otherwise
γ_{dpcsk}	=1, if SSCh c associated with demand d allocated on path p uses slice s on SpRc k; 0, otherwise

variables

x_{dpc}	=1, if SSCh c on candidate path p is used to realize demand d; 0, otherwise (binary)
y_{esk}	=1, if slice s is occupied on SpRc k of link e; 0, otherwise (binary)
y_{es}	=1, if slice s is occupied on any SpRc of link e; 0, otherwise (binary)
y_s	=1, if slice s is occupied in any SpRc of any network link; 0, otherwise (binary)

objective

$$\min \sum_{s \in S} y_s \tag{1}$$

constraints

$$\sum_{p \in P(d)} \sum_{c \in C(d,p)} x_{dpc} = 1, \quad d \in D \tag{2}$$

$$\sum_{d \in D} \sum_{p \in P(d)} \sum_{c \in C(d,p)} \gamma_{dpcsk} \delta_{edp} x_{dpc} \le y_{esk}, \quad e \in E, k \in K(e), s \in S \tag{3}$$

$$\sum_{k \in K(e)} y_{esk} \le \mid K(e) \mid y_{es}, \quad e \in E, s \in S. \tag{4}$$

$$\sum_{e \in E} y_{es} \le \mid E \mid y_s, \quad s \in S \tag{5}$$

The objective (1) is to minimize the spectrum usage defined as the maximum number of slices allocated in the network, accounting for all links and SpRcs. Constraint (2) guarantees that for each demand exactly one routing path and one SSCh is selected. The usage of spectral and spatial resources is controlled by inequality (3). Constraint (4) ensures that if at least one SpRc on link e uses slice s, then variable y_{es} must be switched on. Similarly, inequality (5) defines variable y_s. For more details on the ILP model refer to [7].

IV. OPTIMIZATION ALGORITHM

In this section, we propose a greedy algorithm designed to solve the RSSA problem. Several versions of the algorithm are presented. The method is applicable to SDM scenarios of different spectral and spatial flexibility. We introduce the following notation to represent particular properties of an SSCh: 1) $begin(SSCh)$ returns an index of the lowest slice used by $SSCh$; 2) $end(SSCh)$ returns an index of the highest slice used by $SSCh$; 3) $demand(SSCh)$ returns the amount of slices used for carrying the demand; 4) $rounding(SSCh)$ returns the amount of slices wasted for rounding (as explained in Sec. III); 5) $guardband(SSCh)$ returns the amount of slices used for guardbands. Besides, we define functions: 1) $findSSCh(p, comp)$, which finds the best SSCh, among the SSChs allowable in a given SDM scenario, on path p according to SSCh comparison strategy *comp*; 2) $allocate(p, ssch)$ that allocates channel SSCh on path p.

The greedy algorithm processes demands in a certain order and analyses allowable path and SSCh candidates for each demand. It makes locally optimal choices with a hope of a good final result. A pseudocode is presented in Algorithm 1. At first step, it sorts demands in descending order according to provided metric *sort* (line 2). Next, it iterates over all demands, and for each demand it selects the best path and SSCh by using auxiliary procedure $FPCSpectrum$ (line 5).

Algorithm 1: Greedy Algorithm

```
Require: set of demands $D$, sets $P(d)$ with candidate
         paths for each demand $d \in D$, SSCh
         comparator strategy $comp$, sorting type $sort$
Ensure : routing, spectrum and space allocation for each
         demand $d \in D$
1 function Greedy(D, P, comp, sort)
2     $D$ := sortDemands($D$, $sort$)
3     for $i := 0$ to $|D|$ do
4         $d := D[i]$
5         [$p$, $ssch$] := FPCSpectrum($P(d)$, $comp$)
6         allocate($p$, $ssch$)
```

As *sort*, we consider one of the following metrics:

Algorithm 2: FPCSpectrum (Find Path and SSCh for Spectrum Objective)

```
Require: set of candidate paths $P$ for demand $d$, SSCh comparator strategy $comp$
Ensure : selected path and SSCh with the lowest index of allocated spectrum slice
1 function FPCSpectrum(P, comp)
2     $p^*$ := null
3     $ssch^*$ := null        // begin(null) returns $\infty$
4     for $i := 0$ to $|P|$ do
5         $p$ := $P[i]$
6         $ssch$ := findSSCh($p$, $comp$)
7         if begin($ssch$) $\leq$ begin($ssch^*$) then
8             $ssch^*$ := $ssch$, $p^*$ := $p$
```

- Distance – the length (in *km*) of the demand's shortest path;
- Slices – the required number of slices on the shortest path;
- Hop count – the number of links on the shortest path.

The $FPCSpectrum$ procedure is presented in Algorithm 2. It selects a path and an SSCh that guarantee the best result in terms of spectrum usage. There are two variables p^* and $ssch^*$ responsible for storing the best path and SSCh, respectively. The procedure iterates over all possible paths for demand d (line 4). For each path, it obtains best SSCh according to provided $comp$ parameter (line 6). In each iteration, the obtained SSCh is checked if it is better than the current best solution (line 7), and if so, it is stored as the best one (line 8).

Candidate SSChs may differ both in the number of utilized SpRcs and in the number of slices used for guardband and rounding purposes. As a result, selection of different SSChs may lead to different spectral and spatial allocation in the network. Therefore, when running procedure $findSSCh(p, comp)$ in Algorithm 2, we determine which SSCh c^* is the best candidate for allocation of demand d on path p. We consider 4 different strategies for that purpose:

- Lowest Start (LS) — the SSCh of the lowest starting slice index is selected:
  $$begin(c^*) = \min_{c \in C(d,p)} begin(c).$$
  If there are more SSChs meeting the above criteria, the one of the lowest value of $guardband(SSCh)$ is considered.
- Lowest End (LE) — the SSCh of the lowest ending slice index is selected:
  $$end(c^*) = \min_{c \in C(d,p)} end(c).$$
- Penalty (PEN) — the SSCh with the lowest penalty Θ_1 value is selected:
  $$\Theta_1(c) = \alpha \cdot (guardband(c) + rounding(c)) + end(c),$$
  where $\alpha \in \langle 0, 1 \rangle$ is a parameter. Notice, if α equals 0, it is equivalent to the LE strategy.

- Demands-Varying Penalty (DVP) — the SSCh with the lowest penalty Θ_2 value is selected:
  $$\begin{aligned}\Theta_2(c) =&\alpha \cdot (1 - \tau) \cdot (guardband(c) + rounding(c)) + \\ &+ (1 - \alpha) \cdot \tau \cdot end(c),\end{aligned}$$

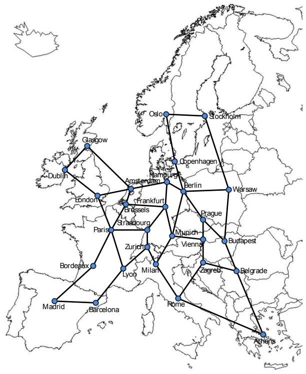

Fig. 2: Euro28 network topology.

  where $\alpha \in \langle 0, 1 \rangle$ is a parameter, $\tau \in \langle 0, 1 \rangle$ is equal to the ratio of currently allocated demands to all demands. Again, if α equals 0, it is equivalent to the LE strategy.

In each above case, if more SSChs are found, the one with the lowest sum of guardband and rounding is selected.

V. NUMERICAL EXPERIMENTS

The goal of numerical experiments is twofold. First, we focus on the greedy algorithm, i.e., we tune the algorithm to find the best configuration parameters and next we compare the results of the heuristic with results yielded by CPLEX when solving the ILP model. Second, using the best found algorithm settings, we examine the SDM network performance in terms of the spectrum usage. For the experiments, we use a representative European network of 28 nodes and 82 links with average link length 625 km (Fig. 2).

We assume that the transceivers operate at fixed baud rate of 28 GBaud and each transceiver transmits/receives an optical channel (optical carrier) that occupies 3 slices of 12.5 GHz [21]. A fixed guardband defined as 1 slice of 12.5 GHz is assumed to separate neighbor SSChs in the spectral domain. Similar to [15], we consider four modulation formats: BPSK, QPSK, 8-QAM, and 16-QAM. The bit-rates supported by a transceiver depend on the spectral efficiency of the modulation format in use and are presented in Table I. Moreover, the assumed transmission reaches of considered modulation formats are based on [15] and shown in Table I. We do not consider crosstalk constraints analogously as in similar papers focused on resource allocation in SDM networks (e.g., [14], [15], [19]). However, we want to point out that the transmission reaches we use here (Table I) are smaller than the transmission reaches applied in papers that account for the crosstalk such as [12], [13]. Thus, the presented results would not change much if we include the crosstalk in our experiments. But we would like to stress that in our future works we plan to address the crosstalk between different SpRcs such as cores or modes.

In most of the experiments, the overall traffic volume is equal to 1 Pbps and we evaluate 10 randomly generated demand sets. Each demand has the bit-rate selected at random from range 50 Gbps to 1 Tbps with 50 Gbps granularity. The number of candidate paths for each demand is 30.

First, we evaluate the heuristic algorithm with the aim to find the best combination of demand sorting and SSCh

TABLE I: Transmission reach and supported bit-rate per one transceiver for various modulation formats.

	BPSK	QPSK	8-QAM	16-QAM
Reach [km]	6300	3500	1200	600
Bit-rate [Gbps]	50	100	150	200

selection strategies. We assume that each network link contains 5 SpRcs. Both PEN and DVP are tested with three different values of the α parameter. The results reported in Table II show that the best algorithm performance is obtained for the Slices sorting and the LS SSCh selection strategy. Consequently, in the following parts of this section, the results of the greedy method are generated using this tuning configuration. A deeper analysis of obtained results shows that the LS strategy tends to select the SSCh that utilize just a single SpRc. It follows from the fact that this strategy first looks for a SSCh having the lowest starting slice index and in a case of a tie, it checks the guardband overhead. Therefore, the best performance achieved by the LS strategy may be caused by the fact that this method indirectly reduces the amount of slices used for guardband and rounding. The other evaluated strategies more frequently select the SSChs that use many SpRcs and thus they lead to a higher overhead in spectrum due to guardbands and rounding.

TABLE II: Maximum spectrum usage (number of slices) for different sorting strategies for Euro28 network.

Flexible Strategy	Sorting		
	Slices	Distance	Hop Count
LS	**1066.1**	1125.8	1079.5
LE	1300.8	1367.3	1331.3
PEN (α = 0.2)	1300.1	1366.7	1335.5
PEN (α = 0.5)	1301.4	1365.3	1332.6
PEN (α = 0.8)	1264.1	1323	1288.1
DVP (α = 0.2)	1236.7	1319	1278.6
DVP (α = 0.5)	1202.3	1274.1	1230.6
DVP (α = 0.8)	1159.0	1217.5	1157.7

The next goal of numerical experiments is to compare two optimization approaches, i.e., CPLEX used to solve the ILP model (1)-(5) and the greedy algorithm. We use CPLEX v.12.5.1 [22] with a 1-hour run-time limit, run on a PC with 32 GB of RAM. Due to low scalability observed in preliminary experiments, we use traffic with only 20, 30, 40 and 50 demands. Moreover, 2 and 4 candidate paths for each node pair are applied. Again, each network link contains 5 SpRcs. Table III presents the comparison in terms of the objective function (number of used slices) and execution time. CPLEX is able to find an optimal solution in 1-hour run-time limit only for 20 demands. For 30 and 40 demands, CPLEX returns a feasible result, but without the optimality guarantee. Finally, for 50 demands CPLEX cannot find any solution and returns out of memory (OoM) error. The results of the greedy algorithm are the same as CPLEX in 7 of 8 cases. But, the greedy method always needs less than $1ms$ and is able to find a solution for all cases. Concluding this part of experiments, CPLEX has very low scalability and even for small traffic is not able to yield results. In turn, the greedy method runs very fast and provides results almost the same as CPLEX.

TABLE III: Comparison of CPLEX and greedy algorithm for Euro28 network.

$\|P(d)\|$	$\|D\|$	Number of slices		Execution time	
		CPLEX	Greedy	CPLEX	Greedy
4	20	28	28	$260s$	$< 1ms$
4	30	31	31	$1h$	$< 1ms$
4	40	34	34	$1h$	$< 1ms$
4	50	OoM	58	-	$< 1ms$
2	20	28	28	$60s$	$< 1ms$
2	30	25	31	$1h$	$< 1ms$
2	40	34	34	$1h$	$< 1ms$
2	50	OoM	58	-	$< 1ms$

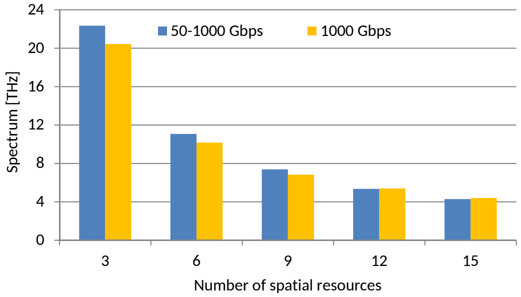

Fig. 3: Spectrum usage for various types of demands.

The next goal of experiments is to present an analysis of SDM network performance in terms of the spectrum usage. Five values of the SpRcs available on each network link are examined: $3, 6, 9, 12, 15$. The overall traffic volume is equal to 1 Pbps and we evaluate 10 randomly generated demand sets. Here, we consider two types of demands: bit-rate selected at random in range 50 Gbps - 1 Tbps and fixed bit-rate of 1 Tbps. The main performance metric is the maximum spectrum usage. Moreover, we present results of *overall spectrum* defined as the sum of all allocated slices in the network.

Fig. 3 reports the maximum spectrum usage as a function of the number of SpRcs. Moreover, Fig. 4 shows the percentage usage of the overall allocated spectrum divided into three categories: demand volume, guardbands, and rounding. The first observation is that the maximum spectrum usage decrease almost proportionally with the increase of SpRcs. Furthermore, we can see that for 3-9 SpRcs the traffic pattern with only 1 Tbps demands consumes less spectrum, while for 12 and 15 SpRcs both traffic patterns need similar amount of spectrum. These differences follow mostly from: wastage of spectrum and spectrum fragmentation. In particular, as shown in Fig 4 about 5% and 3% of spectrum is wasted for guardbands in for 50-1000 Gbps and 1000 Gbps demand types, respectively. The difference between both types of demands is a consequence of the fact that in the case of large demands (1000 Gbps), bigger SSChs (in terms of number of slices) are allocated and thus proportionally smaller amount of the spectrum accounts for the guardbands. However, when only larger demands of 1 Tbps are to be allocated in the network, the spectrum fragmentation can cause that it is more difficult to find a spectrum window for a new demand. Since, the fragmentation is intensified with increasing the number of SpRcs, for 12 and 15 SpRcs the results for both types of demands are similar.

In addition, we can observe in Fig. 4 that very small amount of spectrum is used for rounding, what suggests that

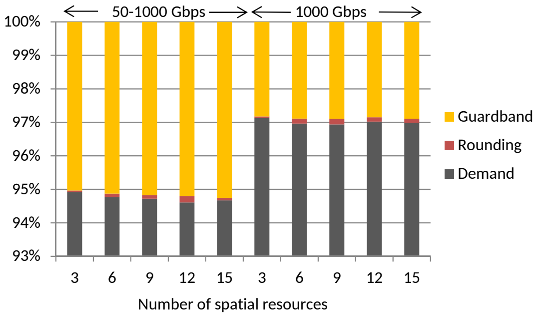

Fig. 4: Spectrum usage for various types of demands.

in majority of cases the greedy method allocates SSChs on a single SpRc. In future work, we plan to investigate this issue in more detail and compare the considered flexible scenario with a possibility to allocate SSCh on many SpRcs with a scenario when a SSCh can use only one SpRc.

TABLE IV: Average execution time of the greedy heuristic method (in seconds) as a function of the number of SpRcs.

Number of SpRcs	3	6	9	12	15
Execution time [s]	2	11	63	325	1691

The last goal of experiments concerns the greedy algorithm execution times. In Table IV, we report average execution times in seconds as a function of the number of SpRcs. We can easily notice that the execution time drastically grows with the number of SpRcs what is a direct consequence of the number of available candidate SSChs (as described in Sec. III). These results confirm our intuition that the RSSA problem in the considered SDM scenario is much more complex than RSA optimization in EONs. Thus, optimization methods such as ILP modeling can be used here for very small problem instances, while for larger and more realistic cases, we need very fast and relatively simple heuristic or metaheuristic methods.

Due to limited space, we present results for only one network topology (Euro28). However, we also made experiments for a German national topology with 14 nodes and the obtained results present very similar trends as those reported above.

VI. CONCLUDING REMARKS

In this paper, we focused on the optimization of flexible-grid SDM optical networks considering flexibility of using many spatial resources for allocation of SSChs. We proposed and evaluated several versions of a greedy algorithm based on different strategies for sorting of demands and allocation of spectral-spatial channels. Due to very large complexity of the considered RSSA problem, a relatively simple heuristic algorithm—such as the proposed greedy method—seems to be a good option for SDM optimization, since even this method needs more than 1000 seconds to solve the most complex among analyzed cases. We performed experiments to compare the proposed versions of the greedy algorithm and selected the best option. Next, we presented an analysis of SDM network performance showing spectrum usage as a function of the number of spatial resources. In the future work, we plan to develop more sophisticated optimization methods based on metaheuristic approaches such as Simulated Annealing or Tabu Search. Moreover, we plan to analyze other SDM scenarios accounting for crosstalk.

VII. ACKNOWLEDGMENTS

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