On the Complexity of RSSA of Anycast Demands in Spectrally-Spatially Flexible Optical Networks

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ABSTRACT

Spectrally-spatially flexible optical networks (SS-FONs) are proposed as a solution to overcome the expected capacity crunch caused by the rapidly growing overall Internet traffic. SS-FONs combine two network technologies, namely, flex-grid optical networks and spatial division multiplexing yielding a significant capacity increase. Moreover, network services applying anycast transmission are gaining popularity. In anycasting, the same content is provided in several geographically spread data centers (DCs), and the requested content is delivered to the network client from the most convenient DC, e.g., minimizing the network traffic and delay. The main optimization challenge in SS-FONs is routing, spectrum and space allocation (RSSA) problem, which can be solved using integer linear programming (ILP). The main goal of this paper is to compare the complexity of various ILP models for routing static anycast traffic in SS-FONs over single-mode fiber bundles (SMFBs). The proposed ILP models apply different modeling techniques, i.e., slice-based and lightpath-based. Moreover, proposed models differ with the core switching (lane changes) capability and consideration of DCs location problem. In order to test the complexity and scalability of models, we run simulations assuming a different number of demands, fibers in SMFBs, candidate paths and DCs.

1 INTRODUCTION

The rapid increase of overall Internet traffic results with the intensive effort concentrated on preventing the future capacity crunch. Spectrally-spatially flexible optical networks (SS-FONs) are proposed as a possible solution to overcome the limitations of currently deployed wavelength division multiplexing (WDM) backbone optical networks. SS-FONs combine two network technologies, namely, flexgrid optical networks and spatial division multiplexing (SDM) providing a massive capacity increase. Due to the additional spatial dimension, SS-FONs enable parallel transmission of several co-propagating optical channels in properly designed optical fibers. As the main advantages, SS-FONs allow for multi-carrier (super-channel, SCh) transmission, adaptive modulation formats selection, better spectral utilization with additional flexibility in the spatial resources management and potential cost savings due to the integrated devices. One of the possible fiber technologies supporting SS-FONs is single-mode fibers bundles (SMFBs), i.e., several single-core single-mode fibers aggregated in a single bundle [4]. The key network devices, such as reconfigurable optical add/drop multiplexers (ROADMs), are yet expected, thus, different assumptions are taken about their switching capabilities. In particular, if core switching (lane changes) is considered, the spatial switching between input and output ports is allowed in network nodes, i.e., the lightpaths may have assigned differently indexed fibers in the SMFB links belonging to the routing path. Otherwise, each lightpath has assigned fibers with the same index (resulting in lower devices complexity). The fundamental optimization challenge in SS-FONs is routing, spectrum and space allocation (RSSA). It aims to select a routing path, optical channel and spatial resources for each of the traffic requests [3]. The most common approach for solving static optimization problems is the integer linear programming (ILP). Two common ILP techniques are applied in the modeling of optical networks, namely, slice-based and lightpath-based. In the former, the starting and ending slice of each request is considered as a decision variable, while in the latter, a set of precomputed lightpaths is used, where each lightpath defines valid optical channel [10].

Concurrently, many network services, such as content delivery networks (CDNs) or cloud computing, apply anycast transmission in order to minimize the traffic load and delay in the network. According to Cisco forecast, the CDNs will cover almost 71% of total traffic in 2021 [1] making optimization of anycast traffic an important issue. In more detail, anycast is the one-to-one-of-many transmission technique, where one of the request end nodes is fixed, i.e., a client node, and the second node is selected from the set of possible nodes where the data centers (DCs) are located. DCs are spread geographically and each one provides the same content, hence, the request may be handled with any of the available DCs (e.g., the closest one) [14]. Besides improvement of the network performance, the anycast traffic makes related optimization problems more complex and challenging.

In this paper, we focus on the modeling and complexity analysis of RSSA of anycast demands. We consider scenarios with and without core switching possibility. Moreover, we study cases with given DC locations and cases that incorporate DC placement into the optimization task. Overall, we focus on four RSSA versions and each version we define using two ILP models (slice-based and lightpath-based) proposing eight ILP models. Then, we compare them in terms of complexity (measured in number of included variables and constraints), processing time and scalability.

2 RELATED WORKS

Recently, the topic of SS-FONs has been extensively studied (e.g., see [3, 5, 13]). Different ILP models have been used to define RSSA problem variations using link-path slice-based [3, 7, 8, 16], link-path lightpath-based [3, 9, 11], or node-link [3, 6] formulations. In particular, in [8], the authors propose ILP model for routing, spectrum and core allocation (RSCA) problem for SS-FONs over multi-core fibers (MCFs) minimizing the highest allocated slice index, with worst-case inter-core crosstalk (XT) awareness assuming realistic physical fiber parameters. In turn, in [6], ILP model is proposed for routing, wavelength and core allocation problem, maximizing the number of accepted traffic while minimizing the total number of used network resources in MCF-based SDM networks applying multi-input multi-output XT suppression. In [7], RSCA ILP model is given that minimizes the overall

ISBN 978-3-89318-079-0 on OpenProceedings, ISSN 2510-7437

DOI: 10.5441/002/inoc.2019.03

network cost due to the number of switching modules required for different cores assuming programmable ROADMs. In [11], ILP model of extended RSSA problem is presented, namely, routing, modulation format, baud-rate and spectrum allocation which jointly minimizes the cost of installed transceivers and spectrum occupation utilizing few-mode transmission. In [15], different lightpath-based ILP models are proposed for the RSSA considering various spatial allocation flexibility. In [9], lane changes are allowed and the lightpath-based model makes use of the relaxation of the space continuity constraint resulting with the lower number of constraints and decision variables. ILP model assuming anycast traffic in SS-FONs is only considered in [16].

To the best of our knowledge, there has been no work that compares the complexity of various ILP models formulations for the allocation of anycast demands in SS-FONs. To fill the literature gap, in this paper, we define eight ILP models assuming two modeling techniques, i.e., link-path slice-based and link-path lightpath-based. The models differ with the core switching capability and additional DCs placement problem.

3 NETWORK MODEL

The network is modeled as a directed graph $G = (V, E)$ where V is the set of network nodes and E is the set of directed optical links that connect the nodes. Each link $e \in E$ comprises a number of single-mode fibers that are aggregated in the bundle and are included in set K. Spectrum resources of each fiber $k \in K$ are divided into narrow frequency slices (slots) of 12.5 GHz width and are included in set S. Signals are transmitted using optical corridor within spectral super-channel (SCh) by grouping several adjacent slices. Each SCh has to be separated from the adjacent one using fixed-size guardband of 12.5 Ghz width. We assume that there are R DCs available in the network and each one provides the same content. Depending on the problem, either DCs are located at some nodes or the DCs location problem is considered.

A set of anycast traffic requests (D) to be served in the network is given. Each demand is defined with the client node and bit-rate. To simplify the problem, we assume only downstream (from DCs to client nodes) transmission. Let P_d denote the set of candidate routing paths for each demand $d \in D$. Each routing path $p \in P_d$ originates in one of the DCs and terminates in the client node. The number of required slices for given demand depends on the requested bit-rate and length of the applied routing path and is denoted with n_{dp}. Each demand is realized using one routing path within selected spectral SCh in such a way that each slice of each fiber of each link is used at most by one demand. Finally, if in the considered scenario core switching ability is not assumed, each SCh has to be realized using the same indexed fibers. Otherwise, it can be freely switched between fibers among the routing path.

The aim of the optimization task is to allocate all demands and minimize index of the highest allocated slice [3]. We study four problem versions which differ with the core switching possibility (with core switching — WCS, without core switching — WOCS) and DC location scenario. For DC location scenario, we analyze two cases: (*i*) the location of DCs is given in advance, (*ii*) the problem of DCs placement is a part of the optimization task. Below, we present ILP models of the four problem versions using slice-based (Sec. IV) and lightpath-based (Sec. V) approaches. All presented models are based on link-path modelling technique. Details about considered models, number of decision variables and constraints are presented in Table 1.

4 SLICE-BASED (SB) MODELS

In this section, link-path slice-based models are proposed. According to Table 1, the models complexity depends mostly on the number of demands to be realized.

sets and indices

$v \in V$	network nodes
$e \in E$	network physical links
$s \in S$	frequency slices
$k \in K$	link fibers
$d \in D$	traffic anycast (DC to client direction) demands
$p \in P_d$	candidates paths for demand d

constants

R	number of DCs (to be) placed in the network
$\|K\|$	number of fibers available on each physical link
δ_{edp}	= 1, if link e belongs to routing path p associated with demand d; 0, otherwise
n_{dp}	number of slices required to realize demand d on candidate path $p \in P_d$
$o(d, p)$	origin node of path $p \in P_d$ defined for demand $d \in D$

variables

x_{dp}	=1, if demand d is realized using candidate path $p \in P_d$; 0, otherwise (binary)
y_{dk}	=1, if demand d uses fiber k; 0, otherwise (binary)
y_{dke}	=1, if demand d uses fiber k on physical link e; 0, otherwise (binary)
w_d/z_d	index of starting/ending slice for demand d (integer ≥1)
z	index of the highest allocated slice in the network (integer ≥ 1)
a_{di}	= 1, if ending slot of demand d is greater or equal to starting slice of demand i (binary)
c_{di}	=1, if demands d and i have some common fibers and links; 0, otherwise (binary)
r_v	=1, if DC is placed in node $v \in V$; 0, otherwise (binary)

4.1 Without core-switching + given DCs (SB_WOCS)

Objective (1) and constraints (2)–(8).

objective

$$\min z. \tag{1}$$

subject to

$$\sum_{p \in P_d} x_{dp} = 1, d \in D \tag{2}$$

$$\sum_{k \in K} y_{dk} = 1, d \in D \tag{3}$$

$$z_d - w_d + 1 = \sum_{p \in P_d} x_{dp} n_{dp}, d \in D. \tag{4}$$

$$z \geq z_d, d \in D \tag{5}$$

$$|S| a_{di} \geq z_d - w_i + 1, d, i \in D : d \neq i \tag{6}$$

$$c_{di} \geq \sum_{p \in P_d} x_{dp} \delta_{edp} + y_{dk} + \sum_{p \in P_i} x_{ip} \delta_{eip} + y_{ik} - 3,$$
$$e \in E, k \in K, d, i \in D, d \neq i \tag{7}$$

$$a_{di} + a_{id} + c_{di} \leq 2, d, i \in D : d < i \tag{8}$$

The objective 1 is to minimize the overall spectrum usage defined as the width of spectrum (i.e., number of slices) required to allocate the demands. Constraint 2 ensures that exactly one routing path is selected for each demand. The selection of only one fiber for request is controlled with the equation 3. Constraint 4 defines starting and ending slice index of each demand. The value of objective is controlled by the inequality 5. Inequality 6 denotes the relation between starting slice of one demand with ending

Table 1: Modeling technique, core switching capability and DC placement location selection for considered ILP models

	ILP model	core switching	DC placement	Number of variables	Number of constraints
slice based	SB_WOCS	no	no	$\|D\|\,(\|P\|+\|K\|+2+2\|D\|)+1$	$\|D\|(4+\frac{3}{2}\|D\|+\|E\|\|K\|\|D\|)$
	SB_WCS	yes	no	$\|D\|\,(\|P\|+\|K\|\|E\|+2+2\|D\|)+1$	$\|D\|(3+\|E\|+\frac{3}{2}\|D\|+\|E\|\|K\|\|D\|)$
	SB_WOCS_DC	no	yes	$\|D\|\,(\|P\|+\|K\|+2+2\|D\|)+\|V\|+1$	$\|D\|(4+\frac{3}{2}\|D\|+\|E\|\|K\|\|D\|+\|P\|)+1$
	SB_WCS_DC	yes	yes	$\|D\|\,(\|P\|+\|K\|\|E\|+2+2\|D\|)+\|V\|+1$	$\|D\|(3+\|E\|+\frac{3}{2}\|D\|+\|E\|\|K\|\|D\|+\|P\|)+1$
lightpath based	LB_WOCS	no	no	$\|S\|+\|D\|\|L\|+\|E\|\|K\|\|S\|+\|E\|\|S\|$	$\|D\|+\|E\|\|K\|\|S\|+\|E\|\|S\|+\|S\|$
	LB_WCS	yes	no	$\|S\|+\|D\|\|L\|+\|E\|\|S\|$	$\|D\|+\|E\|\|S\|+\|S\|$
	LB_WOCS_DC	no	yes	$\|S\|+\|D\|\|L\|+\|E\|\|K\|\|S\|+\|E\|\|S\|+\|V\|$	$\|D\|+\|E\|\|K\|\|S\|+\|E\|\|S\|+\|S\|+1+\|D\|\|L\|$
	LB_WCS_DC	yes	yes	$\|S\|+\|D\|\|L\|+\|E\|\|S\|+V$	$\|D\|+\|E\|\|S\|+\|S\|+1+\|D\|\|L\|$

slice of another one while 7 switches c_{di} on if demands d and i have some common fibers and links. Finally, the spectrum not overlapping is controlled with the inequality 8, which is a contradiction if two demands utilize slices within the same frequency region and contain common fiber.

4.2 With core-switching + given DCs (SB_WCS)

Objective (1) and constraints (2), (9), (4)–(6), (10), (8).
subject to

$$\sum_{k\in K} y_{dke} = \sum_{p\in P_d} x_{dp}\delta_{edp}, d\in D, e\in E \tag{9}$$

$$c_{di} \geq \sum_{p\in P_d} x_{dp}\delta_{edp} + y_{dke} + \sum_{p\in P_i} x_{ip}\delta_{eip} + y_{ike} - 3,$$
$$e\in E, k\in K, d, i\in D, d\neq i \tag{10}$$

Equation 9 assures selection of exactly one fiber on each link of the selected routing path for each demand. Additionally, inequality 10 instead of 7 does account for the core switching ability.

4.3 Without core-switching + DC placement (SB_WOCS_DC)

Objective (1) and constraints (2)–(8), (11), (12).

$$\sum_{v\in V} r_v = R \tag{11}$$

$$x_{dp} \leq r_{o(d,p)}, d\in D, p\in P_d \tag{12}$$

Equality 11 ensures that exactly R nodes are chosen to host DCs, while the inequality 12 controls that each selected routing path originates in the node selected for DC location.

4.4 With core-switching + DC placement (SB_WCS_DC)

Objective (1) and constraints (2), (9), (4)–(6), (10), (8), (11), (12).

5 LIGHTPATH-BASED (LB) MODELS

In this section, link-path lightpath-based ILP models are proposed. Let L_d denote the set of precomputed available lightpaths for demand $d\in D$, where each lightpath $l\in L_d$ is associated with one routing path. Moreover, each lighpath defines utilized starting and ending slice index of the SCh and, in the case of WOCS models, fiber on each link among the routing path. Note, the size of the lightpath corresponds to the n_{dp} constant. According to Table 1, the models complexity depends mostly on the number of candidate lightpath for each demand, which in turn is determined by the number of candidate paths and available spectrum width.

sets and indices (additional)
$l\in L_d$ candidates lightpaths for demand d
constants (additional)
β_{dls} = 1, if lightpath l for demand d uses slice s; 0, otherwise
ξ_{dle} = 1, if link e belongs to lightpath l for demand d; 0, otherwise
γ_{dlk} = 1, if lightpath l for d uses core k; 0, otherwise
$o(d,l)$ origin node of lightpath $l\in L_d$ for demand d
variables (binary)
u_{dl} =1, if demand d uses lightpath $l\in L_d$; 0, otherwise
v_{eks} =1, if slice s is used on fiber k on link e; 0, otherwise
v_{es} =1, if slice s is used on any fiber of link e; 0, otherwise
v_s =1, if slice s is used on any fiber on any link; 0, otherwise

5.1 Without core-swithing + given DCs (LB_WOCS)

Objective (13) and constraints (14)–(17).
objective

$$\min \sum_{s\in S} v_s \tag{13}$$

subject to

$$\sum_{l\in L_d} u_{dl} = 1, d\in D \tag{14}$$

$$\sum_{d\in D}\sum_{l\in L_d} u_{dl}\xi_{dle}\gamma_{dlk}\beta_{dls} \leq v_{eks}, e\in E, s\in S, k\in K \tag{15}$$

$$\sum_{k\in K} v_{eks} \leq |K| v_{es}, e\in E, s\in S \tag{16}$$

$$\sum_{e\in E} v_{es} \leq |E| v_s, s\in S \tag{17}$$

The objective 13 is to minimize the overall spectrum usage. Equality 14 assures selection of exactly one lightpath for each demand. In 15, v_{esk} is switched on if slice s is used on fiber k on physical link e. Inequalities 16 and 17 control whether slice s is used on any fiber of link e and on any link, respectively.

5.2 With core-switching + given DCs (LB_WCS)

Objective (13) and constraints (14), (18), (17).

$$\sum_{d\in D}\sum_{l\in L_d} u_{dl}\xi_{dle}\beta_{dls} \leq |K| v_{es}, e\in E, s\in S. \tag{18}$$

Constraint 18 assures that the slice s on link e is used at most $|K|$ times. This constraint makes use of the relaxation of the space continuity constraint.

Table 2: Supported bit-rate and transmission reach for modulation formats.

Modulation format	BPSK	QPSK	8-QAM	16-QAM
Supported bit-rate [Gbps]	200	150	100	50
Transmission reach [km]	6300	3500	1200	600

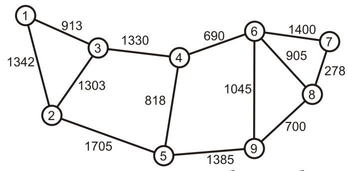

Figure 1: Int9 network topology.

5.3 Without core-swithing + DC placement (LB_WOCS_DC)

Objective (13) and constraints (14)–(17), (11), (19).

$$u_{dl} \leq r_{o(d,l)}, d \in D, l \in L_d. \tag{19}$$

Inequality 19 controls whether each selected lightpath associated with the demand d originates in a DC node.

5.4 With core-swithing + DC placement (LB_WCS_DC)

Objective (13) and constraints (14), (18), (17), (11), (19).

6 NUMERICAL EXPERIMENTS

In this section, we evaluate performance of various ILP models for the RSSA problem in SS-FONs, considering anycast demands. We run experiments on Int9 network topology (Fig. 1) composed of 9 nodes and 13 links, with an average link length of 1063 km. We assume SS-FON composed of SMFBs, where each fiber provides a 4 THz bandwidth (spectrum) divided into 320 frequency slices, each of 12.5 GHz width. As in [12], we assume that the transceiver operates at the fixed baud rate and each transceiver transmits/receives optical channel (optical carrier, OC) of 37.5 GHz width (3 slices). We consider 4 available modulation formats, namely, BPSK, QPSK, 8-QAM and 16-QAM. Supported bit-rate and transmission reach depend on the selected modulation format and are presented in Table 2 [2]. If the requested bit-rate exceeds a single transceiver capacity for the applied MF, the request is transmitted using several OCs within one SCh using a set of adjacent slices (i.e., a spectral SCh). Each request is transmitted using the most efficient MF supporting the required transmission reach, i.e., a distance adaptive transmission is used. In most of the experiments, we assume that the number of fibers per SMFB is $|K| = 2$, the number of candidate shortest paths is $|P| = 2$ (number of candidate paths between client node and one of the DCs) and number of available DCs is $R = 2$. The number of demands is equal to $|D| = \{10, 20, 30, 40, 50, 60, 80, 100\}$. For each value, we evaluate 5 randomly generated sets of demands. Each demand has randomly selected source and destination nodes and a bit-rate uniformly selected within the range from 50 Gbps to 1 Tbps, with 50 Gbps granularity. All experiments were run on a virtual machine with available 2 cores of Intel Xeon E5 series CPU at 2.90 GHz and 32 GB RAM using CPLEX v12.5 solver, executed through Java interface, with a 1-hour run-time limit.

In Table 3, average spectrum usage and time are presented for various ILP models. Normally, spectrum usage should be the same for all models considering given DCs and DC placement problem, respectively. However, for larger demands set, the results start to vary, as it is only possible to obtain feasible (not optimal) solution within given 1-hour run-time limit. Note, the corresponding time may be lower than 1 hour, as this is the average value. In particular, only part of the results may be feasible, while the rest of them may be optimal obtained in shorter time. The lack of results reflects the situation when out of memory error has occurred for all studied cases. As it can be observed, the required computational time increases rapidly even for small sizes of demands sets. In terms of models with given DCs, the SB_WOCD and LB_WCS are able to yield results for the largest demand sets due to the lower number of variables and constraints. Moreover, for 30 to 60 demands sets, LB_WCS ILP model provides worse results than SB_WOCS, despite that the required time is lower. It is possible due to the presence of far from optimal feasible results, while other instances were solved in shorter time. It can be justified with the Table 4, which presents the number of optimal, feasible and out of memory results for each tested case (the numbers are separated with the slash). In terms of models with DC placement, SB_WOCS_DC performs the best.

Next, we compare the models scalability. We study different number of candidate paths $|P| = \{2, 4\}$, fibers per SMFB $|K| = \{2, 4\}$ and number of DCs $R = \{2, 4\}$. In the presented results, let $S(X = \alpha)$ and $t(X = \alpha)$ denote the spectrum usage and time in seconds, respectively, when given parameter X has value α (e.g., $S(|P| = 2)$ denotes spectrum usage for 2 candidate paths). It is worth noting, the missing of results in the charts indicates that the run out of memory was obtained for all 5 tested cases.

Fig. 2 presents spectrum usage and time for models for candidate paths $|P| = \{2, 4\}$ and 20 demands. As it can be observed the increase of number of candidate paths yields slightly lower spectrum usage, however, required time for LB models grows quickly. In turn, number of candidate paths has the low impact on the required time of SB models. Fig 3 reports spectrum usage and time as a function of number of demands for SB_WOCS_DC for various number of candidate paths. The first conclusion is that for small instances with the larger number of candidate paths it is possible to find a lower optimal solution. However, in the presence of run-time limits, the feasible results are worse and the out of memory error is obtained for smaller instances (100 and 80 demands for 2 and 4 candidate paths, respectively). The results for models with given DCs are similar.

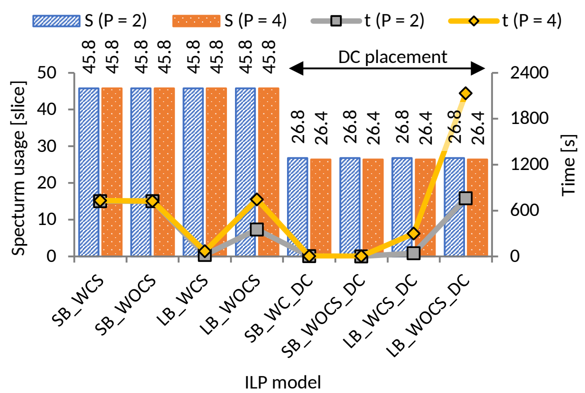

Figure 2: Spectrum usage and time as a function of ILP models for 2 and 4 candidate paths for 20 demands.

Fig 4 shows the spectrum usage as a function of ILP models for number of fibers per SMFBs $|K| = \{2, 4\}$ for 30 demands. Firstly, the increase of number of fibers allows reducing the spectrum

Table 3: Spectrum usage and time for ILP models for various number of demands.

ILP model	Spectrum usage: 10	20	30	40	50	60	80	100	Time [s]: 10	20	30	40	50	60	80	100
SB_WCS	35.0	45.8	70.3	86.5	—	—	—	—	0.4	721.8	3600.0	3600.0	—	—	—	—
SB_WOCS	35.0	45.8	70.3	91.0	99.0	142.3	201.0	233.0	0.3	721.7	3600.0	3600.0	3600.0	3600.7	3600.7	3600.7
LB_WCS	35.0	45.8	72.6	103.0	120.2	154.2	196.8	185.5	2.8	20.7	2005.1	2156.8	2309.0	2411.6	2602.0	2714.8
LB_WOCS	35.0	45.8	72.6	103.2	120.6	128.5	—	—	10.3	352.6	2892.1	2614.4	3236.4	3283.6	—	—
SB_WCS_DC	19.0	26.8	29.0	33.2	69.3	86.0	118.0	—	0.1	2.8	1682.7	3600.0	3600.0	3600.0	3600.1	—
SB_WOCS_DC	19.0	26.8	29.0	33.2	47.8	80.5	96.0	—	0.1	2.1	853.9	3600.0	3600.0	3600.0	3600.0	—
LB_WCS_DC	19.0	26.8	29.0	34.7	49.0	—	—	—	7.9	43.0	2378.1	3600.1	3600.0	—	—	—
LB_WOCS_DC	19.0	26.8	35.0	—	—	—	—	—	69.9	759.4	3600.1	—	—	—	—	—

Table 4: Number of optimal/feasible/out-of-memory results for ILP models for various number of demands.

ILP model type	10	20	30	40	50	60	80	100
SB_WCS	5/0/0	4/1/0	0/3/2	0/2/3	0/0/5	0/0/5	0/0/5	0/0/5
SB_WOCS	5/0/0	4/1/0	0/3/2	0/3/2	0/2/3	0/3/2	0/2/3	0/1/4
LB_WCS	5/0/0	5/0/0	3/2/0	4/1/0	2/3/0	4/1/0	4/1/0	1/1/3
LB_WOCS	5/0/0	5/0/0	1/4/0	4/1/0	1/4/0	2/0/3	0/0/5	0/0/5
SB_WCS_DC	5/0/0	5/0/0	3/2/0	0/5/0	0/4/1	0/2/3	0/5/0	0/0/5
SB_WOCS_DC	5/0/0	5/0/0	4/1/0	0/5/0	0/4/1	0/4/1	0/3/2	0/0/5
LB_WCS_DC	5/0/0	5/0/0	3/2/0	0/3/2	0/2/3	0/0/5	0/0/5	0/0/5
LB_WOCS_DC	5/0/0	5/0/0	0/4/1	0/0/5	0/0/5	0/0/5	0/0/5	0/0/5

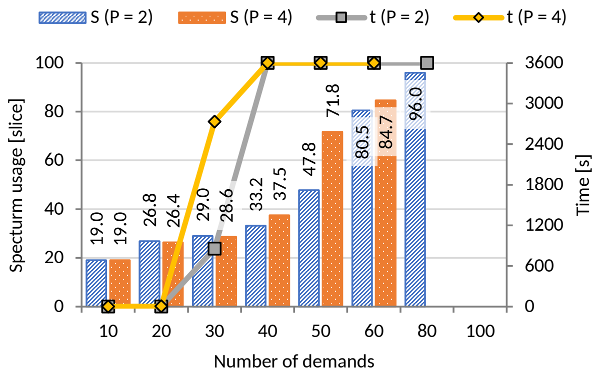

Figure 3: Spectrum usage and time as a function of number of demands for SB_WOCS_DC for 2 and 4 candidate paths.

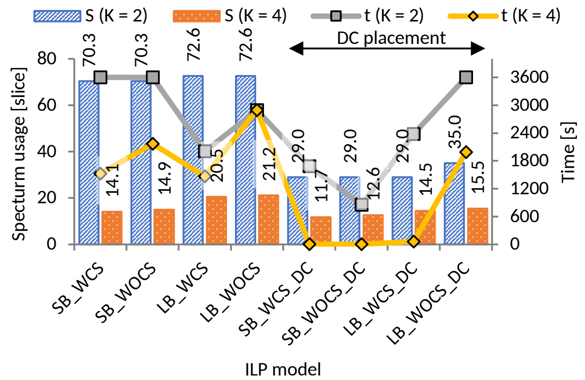

Figure 4: Spectrum usage and time as a function of ILP models for 2 and 4 fibers per SMFB for 20 demands.

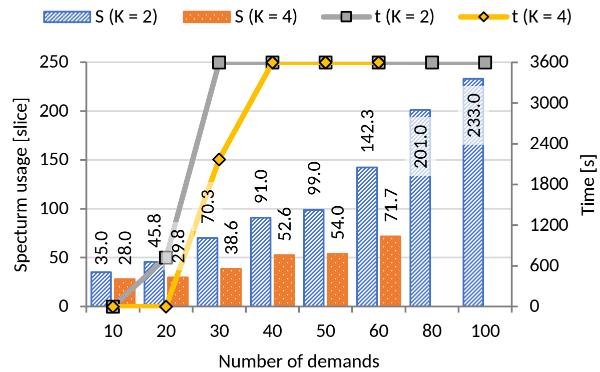

Figure 5: Spectrum usage and time as a function of number of demands for SB_WOCS for 2 and 4 fibers per SMFB.

usage around 46% and 11% for given DCs and DC placement, respectively. Surprisingly, the computational time is also lower. It may follow from the fact, that for a higher number of fibers, it is easier to allocate traffic and find a feasible good quality solution and quicker discard other worse solutions. Next, Figs 5 and 6 present spectrum usage and time as a function of number of demands for SB_WOCS and SB_WOCS_DC ILP models, respectively, for number of fibers per SMFB $|K| = \{2, 4\}$. We can easily observe that the run out of memory occurs for smaller demands sets when the number of fiber is higher, because the number of decision variables and constraints in ILP model is higher.

Fig 7 reports the spectrum usage and time as a function of ILP models for number of DCs $R = \{2, 4\}$ and 20 demands. The increase of number of DCs from 2 to 4 allows reducing required spectrum usage around 41% and 45% for given DCs and DC placement problems, respectively. Note, that for higher number of DCs, the lower time is required to solve the model. Figs 8 and 9 present spectrum usage and time as a function of number of demands for SB_WOCS and SB_WOCS_DC ILP models, respectively, for number of DCs $R = \{2, 4\}$. Despite that for higher number of DCs the spectrum utilization and required computational time is lower, again the run out of memory error occurs for smaller demands set sizes due to the higher number of variables and constraints in ILP instances.

7 CONCLUSIONS

In this paper, we study RSSA of anycast demands in SS-FONs. We analyze four problem versions which differ with the core switching possibility (WCS and WOCS) and DC location scenario (given DCs and DC placement involved into optimization task). Then, we define all RSSA versions using two modeling techniques

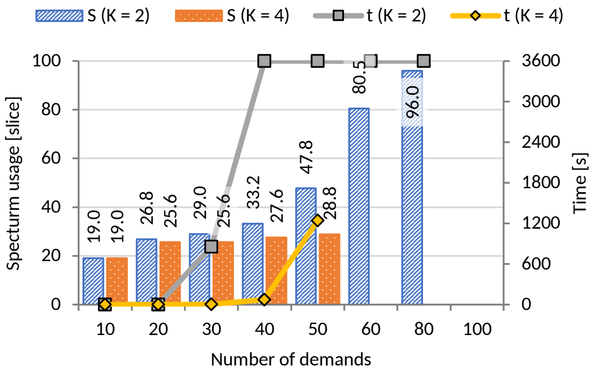

Figure 6: Spectrum usage and time as a function of number of demands for SB_WOCS_DC for 2 and 4 fibers per SMFB.

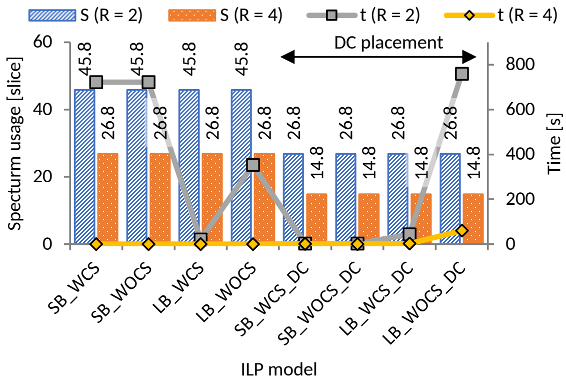

Figure 7: Spectrum usage and time as a function of ILP models for 2 and 4 DCs for 20 demands.

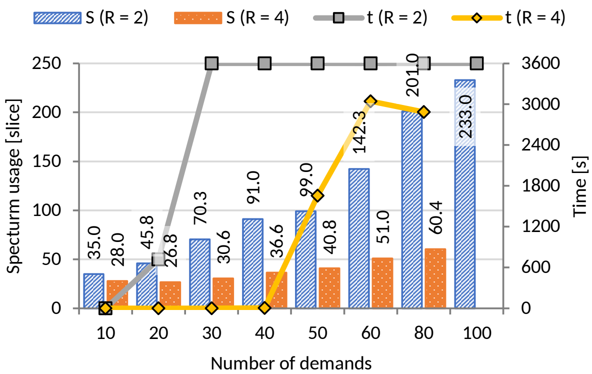

Figure 8: Spectrum usage and time as a function of number of demands for SB_WOCS for 2 and 4 DCs

(slice-based (SB) and lightpath-based (LB)) proposing eight ILP models. Next, we compare models in terms of complexity (measured in the number of variables and constraints), processing time and scalability. The analysis reveals that the complexity of SB models strongly depends on the number of demands while the complexity of LB models on the number of candidate paths and available spectrum width. The core switching possibility increases complexity of SB models while decreases complexity of LB models. The incorporation of DC placement into optimization task makes problem more complex considering both — SB and LB models. Concluding simulations, LB_WCS and SB_WOCS_DC provide the best performance for RSSA with given DC location and DC location selection problem, respectively.

In the future work, we plan to further study RSSA complexity considering different traffic types and network survivability.

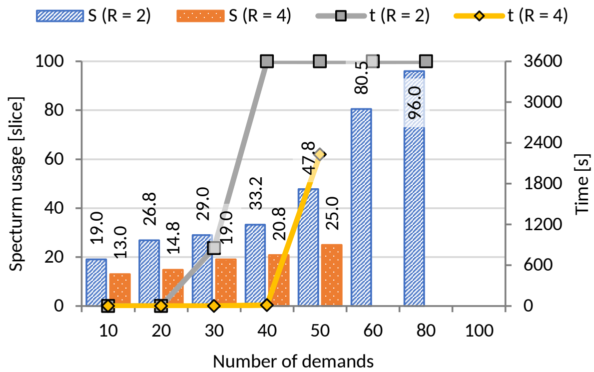

Figure 9: Spectrum usage and time as a function of number of demands for SB_WOCS_DC for 2 and 4 DCs

ACKNOWLEDGMENTS

The work was supported by National Science Centre, Poland under Grant 2015/19/B/ST7/02490 and statutory funds of the Department of Systems and Computer Networks, Wroclaw University of Science and Technology under Grant 0402/0112/18.

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