A Routing and Spectrum Assignment Problem in Optical OFDM Networks

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***Abstract*— Optical Orthogonal Frequency Division Multiplexing (O-OFDM) is a novel and attractive modulation technology enabling flexible sub-wavelength and super-channel transmission in optical networks. In an OFDM-based optical network with elastic bandwidth provisioning, the problem of Routing and Spectrum Assignment (RSA) emerges. RSA is $\mathcal{NP}$-hard and it can be computationally exhaustive even for small network scenarios. In this paper, we both formulate RSA as an Integer Linear Programming (ILP) problem and propose an heuristic method to find a sub-optimal solution. Numerical results show the heuristic performs efficiently even for larger problem instances.**

I. Introduction

O-OFDM has recently emerged as a very promising modulation technology to cope with the 100 Gb/s and beyond data transmission in optical networks [1][2]. This enabling technology allows for flexible bandwidth allocation and, in particular, it can provide, at the same time, sub-wavelength granularity for low-rate transmission and the super-channel provisioning for accommodating ultra-high capacity client signals. In this context, a spectrum-efficient and scalable elastic optical path (SLICE) network architecture has been proposed [3].

As an analogy to the Routing and Wavelength Assignment (RWA) problem in Dense Wavelength Division Multiplexing (DWDM) optical networks [4], the Routing and Spectrum Assignment/Allocation (RSA) problem emerges in the O-OFDM-based SLICE network [5]. RSA concerns assigning a contiguous fraction of spectrum to each connection request subject to the constraint of no frequency overlapping in network links. An heuristic approach initially proposed to solve the problem makes use of the Fixed-Alternate routing and First-Fit frequency assignment (FA-FF) algorithm [5]. As the authors of [5] noticed, FA-FF is not very efficient because it tends to produce unstaffed spectrum occupancy. Indeed, although the FA-FF strategy results in low overall frequency resources usage since it favors shorter routing paths, still the spectrum of frequencies that are used in different network links is wide.

The RSA problem is novel and, to the best of our knowledge, there is little work that addresses this problem in the literature. In the very recent work by Christodoulopoulos et al. [6], the RSA is formulated as an Integer Linear Programming (ILP) problem. Heuristic solutions are obtained by means of a decomposition method that breaks RSA into the routing and spectrum allocation subproblems and with the assistance of a sequential algorithm.

In this paper, we address the RSA problem by means of an alternative, to the one presented in [6], ILP formulation. The problem objective is to minimize the set of different frequency slots, which represent the frequency sub-carriers, in the frequency spectrum that are occupied in the network. RSA is $\mathcal{NP}$-hard and, as the results show, it is computationally difficult even for small network scenarios. Anticipating large problem instances in real networks due to the high number of frequency slots supported in O-OFDM, we propose an ILP-based heuristic method to improve FA-FF. The main idea behind the heuristic is to release certain (low-occupied) frequencies in the network and rearrange the frequency assignment with the assistance of the RSA problem formulation. Numerical experiments show such strategy can effectively reduce the required frequency spectrum and still maintain the low overall frequency usage in the network.

The reminder of this paper is organized as follows. In Section II we present our assumptions regarding the network scenario and the optical switching node architecture. In Section III we define the RSA problem and in Section IV we formulate it as an ILP problem. In Section V we describe the heuristic algorithm and in Section VI we present numerical results that allow us to evaluate its performance. Finally, in Section VII we conclude obtained results.

II. Network and Node Architecture

The application of OFDM as a modulation technique in optical networks has been proposed recently [1]. In an O-OFDM-based transmission system, a high-rate data stream is split into a number of low-rate streams that are transmitted simultaneously over a number of frequency sub-carriers through the optical fiber link. The high number of frequency sub-carriers that are maintained in O-OFDM ensures finer connection granularity when compared to DWDM. At the same time, the connection capacity can be provisioned elastically by allocating a required number of subcarriers, in accordance to connection demands.

In this paper, we consider the O-OFDM-based network implements the SLICE architecture [3][5]. The concept of SLICE is to allocate flexibly appropriate-sized optical bandwidth, by means of contiguous concatenation of optical spectrum, to an end-to-end optical path and according to the offered traffic volume. In this approach, the requested spectral resources on a given route are sliced off and allocated to the end-to-end optical path. Figure 1 shows an illustrative example.

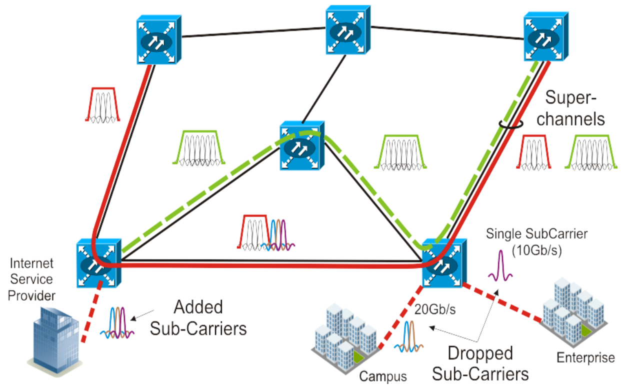

Fig. 1. The O-OFDM-based bandwidth elastic optical network.

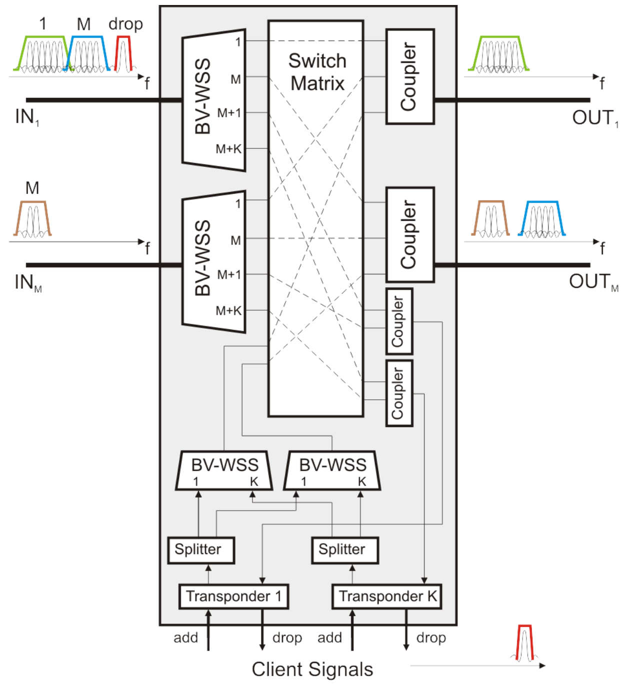

Fig. 2. An architecture of the elastic optical switching node.

The red (continuous) and green (dotted) super-channel paths are established in the network with two different allocated bandwidths (i.e. different number of contiguous frequency subcarriers). The Internet Service Provider on the bottom, left hand side of the figure is able to add two allocations in the frequency spectrum, next to the red path allocation, one of them transporting optical signal to the Campus client and the other to the Enterprise client. Each of these paths may allocate different number of sub-carriers, e.g. to transport 20 Gb/s and 10 Gb/s bandwidth, as presented in the figure.

To provide these features the network should be equipped with the bandwidth-variable transponders at the network edge and the bandwidth variable wavelength cross-connects (WXCs) in the network core as discussed in [3]. The role of the bandwidth-variable transponder is to introduce the add/drop functionality able to adapt the client data signal to be sent to/received from the optical network using the required number of subcarriers. Concurrently, the bandwidth variable WXC allows to create an optical routing path by switching the subcarriers to an appropriate switch output port.

In Figure 2 we present an exemplary architecture of the optical cross-connect with the add-drop functionality. Such network element can be built with the already existing technology such as the WaveShaper programmable optical processor [7] acting as a bandwidth variable wavelength-selective switch (BV-WSS). The WaveShaper makes use of the Liquid Crystal on Silicon (LCoS) spatial phase modulator to perform flexible narrow-band filtering of the optical signal. Accordingly, by means of filtering only the frequency spectrum corresponding to the data signal is transferred to the proper switch output port.

Alternative switching node architectures can be also considered. For instance, a broadcast-and-select configuration is discussed in [3]. In such architecture, the optical signal is first split and forwarded to all output interfaces where BV-WSSs provide grooming, routing and filtering functions.

III. Problem Definition

In order to represent spectral resources, the concept of *frequency slot* (FS) has been proposed in [5] as an extension to the current ITU-T DWDM rigid frequency grid specified in the G.694.1 recommendation [8]. In the proposal, the ITU-T frequency grid is further divided into a number of narrow spectrum segments (i.e., the FSs). Each FS represents an optical channel and, accordingly, an optical path can be established by assigning the required number of contiguous FSs according to the user signal spectrum width. The authors of [5] consider each ITU-T-defined 100 GHz-spaced wavelength channel corresponds to up to 8 FSs and, as a consequence, 72 DWDM channels might result in 576 FSs. Such fine granularity improves the network flexibility and resource utilization but, on the other hand, it puts additional requirements on the network equipment and connection provisioning mechanisms.

In this paper, we assume a static (off-line) RSA problem, where traffic demands (i.e., the set of connection requests) are known in advance. We assume, the volume of traffic can be translated into a number of requested FSs (as discussed in [5]). The RSA problem objective is to find, for a given set of demands, the end-to-end optical paths and assign the requested FSs in a contiguous way with a constraint to avoid FS overlapping in network links. In the version of problem addressed, we consider the network has capacity sufficient to serve all offered demands, i.e., there is no connection blocking.

IV. RSA Problem Formulation

We formulate RSA as an ILP problem. For the sake of simplicity, we make use of the so-called *path-link* approach [4] for the network flow representation of RSA. In such formulation, a set of paths is predefined between network nodes, where each path is identified by a subset of network links.

A. Notation

We use $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ to denote the graph of an O-OFDM network; the set of nodes is denoted as $\mathcal{V}$, and the set of unidirectional links is denoted as $\mathcal{E}$. In each link an ordered set $\mathcal{F} = \{f_1, f_2, \ldots, f_{|\mathcal{F}|}\}$ of frequency slots is given.

Let $\mathcal{D}$ denote the set of demands, where each demand corresponds to a connection request. Demand d is determined by a triple (s_d, t_d, n_d), where s_d and t_d are source and termination nodes, and $n_d \in \mathbb{Z}_+$ is the number of FSs requested by the connection. Let $\mathcal{P}_d$ denote the (non-empty) set of predefined candidate paths for demand $d \in \mathcal{D}$. Each set $\mathcal{P}_d$ comprises a number of paths, e.g., k shortest paths, which have the origin in s_d and the termination in t_d. Let $\mathcal{P}$ denote the set of all paths, i.e., $\mathcal{P} = \bigcup_{d\in\mathcal{D}} \mathcal{P}_d$. Each path $p \in \mathcal{P}$ is identified with a subset $p \subseteq \mathcal{E}$. Adequately, subset $\mathcal{P}_e \subseteq \mathcal{P}$ identifies all paths that go through link e.

Remark: For the sake of simplicity, we consider n_d to be independent on the path length. As discussed in [5], the path-length dependency starts to play a role when $|p| \geq 10$.

B. ILP formulation

We introduce a set of problem variables:
$x_{pf} \in \{0, 1\}$ - equal to 1 if FS $f \in \mathcal{F}$ on path $p \in \mathcal{P}$ is selected to be the lowest indexed slot that is assigned to a demand, and equal to 0 otherwise,
$y_{pf} \in \{0, 1\}$ - equal to 1 if FS $f \in \mathcal{F}$ on path $p \in \mathcal{P}$ is assigned to a demand, and equal to 0 otherwise,
$x_{ef} \in \{0, 1\}$ - equal to 1 if FS $f \in \mathcal{F}$ is occupied in link $e \in \mathcal{E}$, and equal to 0 otherwise,
$x_f \in \{0, 1\}$ - equal to 1 if FS $f \in \mathcal{F}$ is assigned to at least one demand in the network, and equal to 0 otherwise,
$F \in \mathbb{Z}^+$ - number of FSs in the frequency spectrum that are assigned to at least one demand in the network.

We formulate RSA as an ILP optimization problem:

$$minimize \qquad F \qquad \text{(ILP1)}$$

$$subject\ to$$

$$\sum_{p\in\mathcal{P}_d}\sum_{f\in\mathcal{F}} x_{pf} = 1, \qquad \forall d \in \mathcal{D}, \qquad \text{(1a)}$$

$$x_{pf_i} - y_{pf_j} \leq 0, \qquad \begin{array}{l}\forall d \in \mathcal{D}, \forall p \in \mathcal{P}_d, \forall f_i, f_j \in \mathcal{F}, \\ \text{where } i = 1, \ldots, |\mathcal{F}| - n_d + 1, \\ \text{and } j = i, \ldots, i + n_d - 1,\end{array} \qquad \text{(1b)}$$

$$x_{pf_i} = 0, \qquad \begin{array}{l}\forall d \in D, \forall p \in \mathcal{P}_d, \forall f_i \in \mathcal{F}, \\ \text{where } i = |\mathcal{F}| - n_d + 2, \ldots, |\mathcal{F}|,\end{array} \qquad \text{(1c)}$$

$$\sum_{p\in\mathcal{P}_e} y_{pf} - x_{ef} = 0, \qquad \forall e \in \mathcal{E}, \forall f \in \mathcal{F}, \qquad \text{(1d)}$$

$$\sum_{e\in\mathcal{E}} x_{ef} - |\mathcal{E}|\, x_f \leq 0, \qquad \forall f \in \mathcal{F}, \qquad \text{(1e)}$$

$$\sum_{f\in\mathcal{F}} x_f - F = 0, \qquad \text{(1f)}$$

$$x_{pf}, y_{pf}, x_{ef}, x_f \in \{0, 1\}, F \in \mathbb{Z}^+, \quad \begin{array}{l}\forall p \in \mathcal{P}, \forall f \in \mathcal{F}, \\ \forall e \in \mathcal{E}.\end{array} \qquad \text{(1g)}$$

The problem objective is to minimize the number of FSs in the frequency spectrum that are assigned to at least one demand in the network. Constraints (1a) are the path and FS selection constraints. For each demand a path is selected from the set of candidate paths and, concurrently, a FS is selected on this path as the lowest indexed slot assigned to this demand. Constraints (1b) are the contiguous FS assignment constraints. Indeed, whenever there is a FS f_i selected as the lowest indexed slot for demand d, the consecutive slots f_j, where $j = i, \ldots, i + n_d - 1$, should be assigned to this demand. Note, that the spectrum continuity constraint along a route is imposed implicitly since the assignment of a FS concerns the entire path and, therefore, each link on the path. Constraints (1c) aim to exclude such FS selection options for which there is no enough space for the FS assignment in the frequency spectrum. Constraints (1d) are the capacity constraints and they say that each FS in each network link can be assigned to at most one demand, what is guaranteed by the binarity of x_{ef}. Constraints (1e) state that a FS is used if it is used in at least one network link. Consequently, constraint (1f) counts the total number of such FSs. Finally, (1g) are the variable range constraints.

Remark: The main difficulty of formulation ILP1 comes from the large number of FSs (equal to $|\mathcal{F}|$) in some O-OFDM network scenarios. As a result, there is a huge number of constraints (1b), which is of the order of $O(|\mathcal{P}|\,|\mathcal{F}|\,X_n)$, where $X_n = |\mathcal{D}|^{-1}\sum_{d\in\mathcal{D}} n_d$ is the mean number of slots requested by demands. Indeed, the presence of the contiguous FS assignment constraints (1b) is the main difference between RSA and RWA. In fact, the special case of RSA, in which $n_d = 1, \forall d \in \mathcal{D}$, is equivalent with the RWA problem. As a consequence, the RSA optimization problem is $\mathcal{NP}$-hard in general.

V. Heuristics

Although, the optimal RSA solution may be unattainable even for small networks with large number of FSs and demands, still ILP1 may be employed to improve the solution provided by FA-FF. According to [5], FA-FF searches (iteratively for all demands) for the requested number of unoccupied and contiguous FSs starting from the lowest indexed FS in $\mathcal{F}$, first on the primary and, if not found, on alternative paths. Having the solution of FA-FF, the proposed heuristic method: 1) selects a subset of $\mathcal{D}$, denoted as $\mathcal{D}'$, 2) maintains all the FS assignments for $d \in \mathcal{D} \setminus \mathcal{D}'$, and 3) optimizes RSA for $\mathcal{D}'$.

Let F^*, U^*, $\boldsymbol{x}^*_{pf}$, $\boldsymbol{y}^*_{pf}$, and $\boldsymbol{x}^*_{ef}$ be the solution of FA-FF representing, respectively, the overall number of diverse FSs that are assigned, the overall usage of FSs in all network links, and the solution vectors corresponding to the vectors of variables $\boldsymbol{x}_{pf}$, $\boldsymbol{y}_{pf}$, and $\boldsymbol{x}_{ef}$ in ILP1. According to the first-fit strategy, only first F^* FSs are assigned in the network. Therefore, we can reduce set $\mathcal{F}$ to $\mathcal{F}^* = \{f_1, f_2, \ldots, f_{F^*}\} \subseteq \mathcal{F}$ without impact on the problem solution.

We consider two strategies to form $\mathcal{D}'$, namely:

1) include demands that have assigned the FSs which are used in L network links at most, i.e., $\mathcal{D}' =$

Scenario						*ILP1*				*FA-FF*			*Heur*			*FA-FF vs. Heur*	U_{LB}
No	**Network**	$\lvert\mathcal{D}\rvert$	$\lvert\mathcal{F}\rvert$	L	K	F	U	T	G	F	U	T	F	U	T	ΔF	
1	SIMPLE	30	21	10	–	16	142	7	0%	21	134	0.01	16	134	1.7	24%	134
2		30	21	–	15	16	142	7	0%	21	134	0.01	16	134	1	24%	134
3		60	38	10	–	30	283	95	0%	38	259	0.01	31	259	15	18%	259
4		60	38	–	20	30	283	95	0%	38	259	0.01	32	259	8	16%	259
5		90	45	10	–	35	454	171	0%	45	391	0.02	35	391	20	22%	391
6		90	45	–	20	35	454	171	0%	45	391	0.02	35	391	3	22%	391
7		120	87	10	–	54	688	13525	0%	87	545	0.02	60	545	568	31%	545
8		120	87	–	70	54	688	13525	0%	87	545	0.02	60	545	386	31%	545
9		150	108	10	–	85	832	36000	21%	108	679	0.03	74	679	720	31%	679
10		150	108	–	70	85	832	36000	21%	108	679	0.03	83	679	35	23%	679
11	NSFNET	210	88	17	–	85	1631	36000	31%	88	1502	0.02	76	1502	292	14%	1502
12		210	88	20	–	85	1631	36000	31%	88	1502	0.02	73	1502	2059	17%	1502
13		210	88	–	30	85	1631	36000	31%	88	1502	0.02	76	1502	15	14%	1502
14		210	88	–	50	85	1631	36000	31%	88	1502	0.02	76	1502	567	14%	1502
15		420	141	15	–	*no solution found after 10h*				141	2875	0.02	134	2875	37	5%	2875
16		420	141	16	–	*no solution found after 10h*				141	2875	0.02	134	2875	201	5%	2875
17		420	141	–	30	*no solution found after 10h*				141	2875	0.02	139	2875	963	1%	2875
18		420	141	–	50	*no solution found after 10h*				141	2875	0.02	134	2875	100	5%	2875
19		420	141	–	70	*no solution found after 10h*				141	2875	0.02	134	2875	2040	5%	2875
20	UBN24	138	47	30	–	36	1376	26245	0%	47	1294	0.03	39	1294	3219	17%	1294
21		138	47	–	30	36	1376	26245	0%	47	1294	0.03	40	1294	2723	15%	1294
22		552	170	20	–	*out of memory*				170	5204	0.03	142	5204	1767	16%	5204
23		552	170	–	50	*out of memory*				170	5204	0.03	145	5204	637	15%	5204

TABLE I

PERFORMANCE OF RSA ALGORITHMS.

$$\left\{d : d \in \mathcal{D}, y_{pf} = 1, p \in \mathcal{P}_d, f \in \mathcal{F}^*, \sum_{e\in\mathcal{E}} x^*_{ef} \leq L\right\},$$

2) include demands that have assigned any of the K most indexed FSs, i.e., $\mathcal{D}' = \{d : d \in \mathcal{D}, y_{pf} = 1, p \in \mathcal{P}_d, f \in \{f_{F^*-K+1}, \ldots, f_{F^*}\}\}$.

Our choice of $\mathcal{D}'$ is based on the low occupation of the corresponding FSs and a relatively low number of demands, together with the expectation both these FSs can be released and the demands reallocated more easily.

Now we solve ILP1 subject to the constraints:

$$\sum_{p\in\mathcal{P}_d}\sum_{f\in\mathcal{F}} x_{pf} = 1, \qquad \forall d \in \mathcal{D}', \tag{1h}$$

$$x_{pf} = x^*_{pf}, \qquad \forall d \in \mathcal{D}\setminus\mathcal{D}', \forall p \in \mathcal{P}_d, \forall f \in \mathcal{F}^*, \tag{1i}$$

$$\sum_{e\in\mathcal{E}}\sum_{f\in\mathcal{F}} x_{ef} \leq U^*, \tag{1j}$$

and constraints (1b), (1c), (1d), (1e), (1f), and (1g), where we substitute $\mathcal{F}$ with $\mathcal{F}^*$. Constraints (1h) and (1i) are used instead of (1a) so that to release the assignment of FSs for the demands in $\mathcal{D}'$ and keep it unchanged for the rest of demands. Constraint (1j) guarantees that the overall FS usage is not worse than that in FA-FF.

The above method reduces the complexity of ILP1 since we keep partially unchanged the FS assignment. Obviously, the solution is sub-optimal but, on the other hand, we guarantee that it is at least as good as the one provided by FA-FF with respect to both the overall FS usage and the diversity of the FSs assigned. Eventually, in the obtained solution the occupied frequency spectrum can be compressed by shifting the assignment of frequencies over the FSs that are not used anymore in the network.

VI. NUMERICAL RESULTS

In Table I, we present RSA performance results, expressed in terms of FS diversification (F), the overall FS usage (U), and the computation time (T, in seconds). Additionally, we provide the duality gap (G) for *ILP1* and the percentage of improvement of F when performing *Heur* and with respect to *FA-F* (denoted as ΔF). The results are obtained for SIMPLE (6 nodes, 16 links), NSFNET (15 nodes, 46 links), and UBN (24 nodes, 86 links) mesh network topologies [9]. We use IBM ILOG CPLEX v.12.2 [10] on an Intel i3 2.27GHz 2GB computer to solve optimization problems. The demand pairs (s_d, t_d) are generated randomly and the number of FSs requested n_d is uniformly distributed on $\{1, \ldots, 5\}$. We assume $|\mathcal{P}_d| = 3, \forall d \in \mathcal{D}$ and the paths are shortest paths. Parameters L and K are selected arbitrarily so that to observe their impact on the algorithm performance.

ILP1 has difficulties even for a small network (SIMPLE) with large number of demands and FSs. Indeed, in Scenario 9 the optimality gap is still equal to 21% after ten hours of calculation. In moderate size networks the gap is even higher and equal to 31% after ten hours of performance (Scenario 11), whereas with large number of demands and FSs either a feasible solution is not found (Scenario 15) or there is the out-of-memory problem (Scenario 22).

On the other hand, *Heur* improves always the solution (F) of *FA-FF* (up to 30%) and it maintains U, which for both *FA-FF* and *Heur* attains the lower bound $U_{LB} = \sum_{d\in\mathcal{D}} n_d \cdot \min\{|p| : p \in \mathcal{P}_d\}$. Both parameters L and K have impact on the *Heur* performance and there is a trade-off between F and T. Both versions of *Heur* offer similar performance.

Comparing *Heur* and *ILP1*, we can see that in most of the scenarios the optimality was attained (Scenarios $1-8$ and $20-21$) the results obtained with *Heur* are satisfying and do not differ significantly. Some difference may result from the constraints (1j) introduced in *Heur*, which limit the solution space. On the other hand, thanks to these constraints the overall FS usage (U) is much better in *Heur* than in *ILP1*.

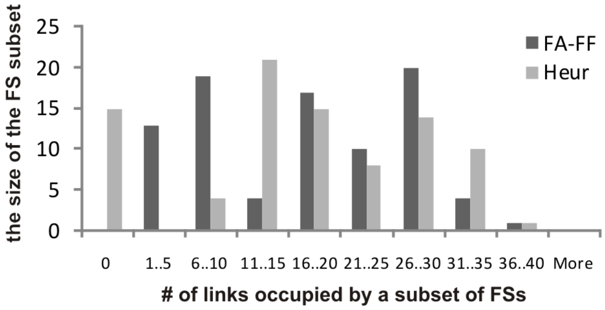

Fig. 3. FS occupancy in network links (for Scenario 12 in Table I).

Concurrently, in larger scenarios, when *ILP1* is computationally expensive, *Heur* can provide improved solutions, with respect to *FA-FF*, in reasonable time of several hundreds of seconds.

In Figure 3 we can see a histogram of the FS occupancy in network links for both *FA-FF* and *Heur*. In particular, the x-axis represents the number of links which are occupied by a subset of FSs, where the cardinality of the FS subset is represented in the y-axis. For instance, for *FA-FF*, there are 15 FSs that do not occupy any link and, for *Heur*, there are 13 FSs that occupy between 1 to 5 links. As we can observe, some FSs are released and, consequently, the remaining FSs are utilized more frequently in network links in order to support reallocated connection demands after *Heur* is performed.

VII. Concluding Remarks

Although the proposed heuristic method improves the efficiency of RSA, when compared to *FA-FF*, still the assignment of individual FSs is not completely balanced in the network and, therefore, some further savings might be possible. Also, the memory requirements of the solver are high when solving the heuristic for very large problem instances (of some hundreds of FSs and demands). Development of more effective RSA solutions is left for future work.

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