Evaluation of Core-Continuity-Constrained ROADMs for Flex-Grid/MCF Optical Networks

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Abstract—In order to effectively keep pace with the global IP traffic growth forecasted in the years to come, Flex-Grid over Multi-Core Fiber (MCF) networks can bring superior spectrum utilization flexibility, as well as bandwidth scalability far beyond the non-linear Shannon's limit. In such a network scenario, however, full node switching re-configurability will require an enormous node complexity, pushing the limits of current optical device technologies at expenses of prohibitive capital expenditures. Therefore, cost-effective node solutions will most probably be the key enablers of Flex-Grid/MCF networks, at least in the short- and mid-term future. In this context, this paper proposes a cost-effective Reconfigurable Optical Add/Drop Multiplexer (ROADM) architecture for Flex-Grid/MCF networks, called CCC-ROADM, which reduces technological requirements (and associated costs) in exchange of demanding core continuity along the end-to-end communication. To assess the performance of the proposed CCC-ROADM in comparison with a fully-flexible ROADM (i.e., a Fully Non-Blocking ROADM, called FNB-ROADM in this work) in large-scale network scenarios, a novel lightweight heuristic to solve the route, modulation, core and spectrum assignment (RMCSA) problem in Flex-Grid/MCF networks is presented in this work, whose goodness is successfully validated against optimal ILP formulations previously proposed for the same goal. The obtained numerical results in a significant number of representative network topologies with different MCF configurations of 7, 12 and 19 cores show almost identical network performance in terms of maximum network throughput when deploying CCC-ROADMs vs. FNB-ROADMs, while decreasing network capital expenditures to a large extent.

Index Terms—**Core-Continuity, Flex-Grid Networks, Multi-Core Fiber, Space Division Multiplexing, RMCSA.**

I. INTRODUCTION

The constant growth of the Internet traffic has motivated the study of new technologies able to optimize the spectrum usage of traditional Wavelength Division Multiplexing (WDM) networks, while also upgrading the network capacity of single-mode fibers (SMFs) bounded by the so-called non-linear Shannon's limit.

On one hand, Flex-Grid [1] proposes to discretize the optical spectrum into 12.5GHz width Frequency Slots (FSs), according to the ITU-T recommendation [2]. This technology enables transmissions at ultra-high bit-rates by concatenating multiple adjacent flexible sub-channels, thus forming a super-channel. The spectral elasticity introduced by Flex-Grid has to be supported by different network elements like Bandwidth Variable Transponders (BVTs), which adapt the required bit-rates of the traffic demands using different degrees of flexibility, namely, modulation format, baud-rate and number of sub-channels. Other key elements in Flex-Grid are the Bandwidth Variable Optical Cross Connects (BV-OXCs), which have both switching and filtering functionalities. Both operations, sometimes simply referred in the literature as optical express or pass-through operation (i.e., transparent switching of the lightpaths at intermediate nodes) with additional adding and dropping capabilities are implemented in the so-called Reconfigurable Optical Add/Drop Multiplexer (ROADM) nodes based on Spectrum Selective Switches (SSSs) [3].

On the other hand, Space Division Multiplexing (SDM) technology is currently under development to scale up the capacity of current optical fiber systems [4]. Different alternatives have been proposed to realize it. The straightforward solution consists in extending currently deployed telecom operators' networks to convert them into Multi-Fiber (MF) infrastructures, where every link bundles several SMFs. However, as in WDM, parallelization is a must for SDM to become economically attractive and, hence, novel fiber designs are required [5]. A possible solution relies on a single core, large enough to transmit multiple guided modes, thus having a Multi-Mode Fiber (MMF). If the number of modes is limited to only a few, they are known as Few-Mode Fibers (FMFs). Another alternative is to incorporate several single-mode cores in the same fiber, that is, a Multi-Core Fiber (MCF). If these cores carry few modes each, the solution is referred to as a Few-Mode Multi-Core Fiber (FM-MCF). To come up with the best SDM solution, coupling among cores or modes becomes a relevant

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parameter. Weakly-coupled MCFs [6]-[8], which exhibit an extremely low inter-core crosstalk (ICXT) are very attractive, since multiple-input multiple-output (MIMO) equalization may be unnecessary. Although heterogeneous MCFs (cores with slightly different parameters) show the lowest ICXT [9], homogeneous MCFs (i.e., cores describing exactly the same parameters) provide similar propagation characteristics (e.g., delay) for all cores, which may simplify transmitter/receiver design and switching [10].

Several ROADM architectures have been proposed to offer switching flexibility to next generation Flex-Grid optical networks [3]. The two main concepts behind them are the so-called *Broadcast-and-Select* (B&S) and *Route-and-Select* (R&S). The B&S architecture offers cost, power consumption and optical/electronic complexity reductions, as well as low overall system penalties. On the other hand, the R&S practically doubles the number of SSSs to provide superior isolation on the blocking ports and a low insertion loss regardless of the port count [11]. According to [11], the B&S architecture seems the best choice for ROADMs with nodal degree (*F*) lower or equal than 9, while for *F*>9, R&S benefits compensate its extra cost.

Colorless, Directionless and Contentionless (CDC) ROADMs, namely, nodes that are able to switch any wavelength from any add port to any output fiber port, as well as any wavelength from any input fiber port to any drop port (i.e., fully non-blocking –FNB– ROADMs) may require an enormous node complexity. In this regard, multiple studies exist in the literature evaluating the performance penalty of ROADM architectures where some internal blocking is allowed. For example, the internal blocking for Flex-Grid optical networks is evaluated in [12]. In a MCF-enabled network, extending the CDC property to any core index implies a largely increased ROADM complexity, being necessary to introduce new performance vs. cost trade-offs. Initial works in the literature present allocation schemes for MCF networks assuming FNB-ROADMs (e.g., see [13], [14]). However, as stated before, the complexity and cost of such SDM-ROADM architectures is enormous. In particular, when directly applying B&S or R&S concepts, if each input/output fiber supports S spatial channels: (i) the number of required SSS devices at ROADMs must be multiplied by S, and (ii) its individual size is also multiplied by S, resulting in an S^2 complexity increase.

To simplify these architectures, alternative ROADM designs have been proposed in [15] and [16], called *Architecture on Demand* (*AoD*) and *Joint-switching* (*JoS*), respectively. The first one, *AoD* [15], can avoid underutilized hardware modules by sharing them on demand via node programmability capabilities. All input/output ports, add/drop ports, as well as hardware components, like SSSs, splitters/combiners, amplifiers, mux/demux, etc., are connected to a backplane and interconnected in a customized manner according to the network traffic requirements. With this ROADM architecture, different super-channel allocation policies can be configured, namely, spatial super-channel, spectral super-channel, and some hybrid spatial-spectral super-channel thanks to flexibility of the node programmability. However, processing complexity and resilience mechanisms of the backplane are important aspects to be considered. The second one (i.e., *JoS* [16]), allows reducing the number of SSS devices by switching a spectral slice in all cores at once, in exchange for increasing the port count of these SSS devices. *JoS* utilization is mandatory in strongly-coupled SDM fibers (i.e., some types of MCFs, FMFs/MMFs and FM-MCFs), so as to properly apply the required MIMO to make end-to-end communications feasible. This switching technique requires using spatial super-channels, where each sub-channel must be assigned with individual spectral guard-bands (GBs) to guaranty the integrity of optical signals through the multiple SSSs filters. As a consequence, the spectral overhead of the spatial super-channel increases, compared to that required in spectral super-channels that can potentially eliminate the inter-subchannel GB (e.g., Nyquist-WDM is employed). This latter aspect, together with the fact that every spectral slice across all spatial channels is reserved to lightpaths that have common source-destination node pairs, results in a reduced spectral efficiency of *JoS* compared to FNB-ROADM (also referred to as *Independent-switching* in [17][18]). On the positive side, *JoS* strategy relaxes the hardware requirements and cost [18]. An intermediate ROADM architecture is possible if the spatial channels are grouped and *JoS* is applied to each group. The lower the group size, the higher the flexibility in the space domain. This technique is called *fractional JoS* [17]. Node complexity and cost of all aforementioned switching architectures is analyzed in a recent work [19].

The goal of this paper is to evaluate the network-wide performance of an alternative ROADM architecture for Flex-Grid/MCF networks that trades core switching flexibility for superior cost-efficiency. In addition to the spectrum continuity and contiguity constraints traditionally imposed by Flex-Grid, the proposed ROADM architecture requires that the core continuity constraint (CCC) is enforced along the end-to-end path, similarly as in the "space-wavelength switching granularity without SDM lane change" solution analyzed (only node-wide) in [19]. In a previous publication [20], we presented two Integer Linear Programming (ILP) formulations for optimally allocating demands in a Flex-Grid/MCF network, assuming that FNB or cost-effective ROADMs enforcing the CCC are deployed in the network. Such ILP formulations, however, were only valid for solving small problem instances. In the present study, we extend this work proposing a very lightweight heuristic for allocating optical connections in Flex-Grid/MCF networks with either FNB or CCC-based ROADMs (hereafter referred to as CCC-ROADM). Then, we exhaustively investigate on the performance vs. cost trade-off involved in enforcing the CCC in the Flex-Grid/MCF networks. Results suggest that CCC hardware complexity reduction come at a cost of a very limited performance reduction, and thus that CCC-ROADMs are a promising architecture for building Flex-Grid/MCF networks.

The remainder of this paper is structured as follows. Section II elaborates on the analysis of the internal blocking in the Flex-Grid/SDM ROADMs. Section III describes the transmission reach estimation model for MCF-enabled optical networks used later on in the numerical evaluation.

Section IV presents the ILP formulations and heuristic for the resource allocation problem in Flex-Grid/MCF optical networks employing FNB-ROADM and CCC-ROADM architectures. Section V presents the obtained numerical results. Finally, section VI draws up the main conclusions of this paper and envisions future research lines.

II. FLEX-GRID/SDM ROADM INTERNAL BLOCKING ANALYSIS

One of the most attractive ROADM architectures follows the so-called B&S scheme. In B&S ROADMs, optical signals entering the node are broadcasted by a passive splitter device to all the available output/drop ports. All the signals reaching the same output are switched using a SSS, a Flex-Grid version of the Wavelength Selective Switch (WSS). The SSS is the key element in the process providing the ROADM the capability of switching any frequency slice from an input port to any of the output ports. The number and size of the SSS devices need to be optimized due their high cost, compared with the rest of the ROADM components.

R&S architectures are a variation of B&S ones, where the splitter at the input side is replaced by an SSS. The key benefit is the elimination of the splitting losses, which could require extra amplification for a large number of ports. The drawback of such alternative is obviously the much higher cost [21].

Flex-Grid/MCF networks are still under research and new ROADM designs are required to deal with the additional space dimension. In this paper, we compare two B&S ROADM proposals for Flex-Grid/MCF networks. The first one is the FNB-ROADM, which is able to manage all the traffic within the ROADM with flexibility to choose the output core of each connection, whatever its input core is. The second proposal is our cost-effective CCC-ROADM proposal, where lightpaths must remain at the same core. It is worth to note that these architectures are also valid for MF networks.

Fig. 1 depicts the FNB-ROADM architecture with B&S scheme and F input/output fibers (two degrees are shown for simplicity), each one carrying C cores. We assume that the architecture is CDC, this means that any wavelength can be directed from/to any input/output fiber port and without contention at the add/drop module. The CDC operation can be implemented by using multicast switching (MCS) handled by CDC MUX/DEMUX devices [3]. Remarkable features have been extracted from Fig. 1 and summarized as follows:

- The number of passive splitters and SSSs is FxC, which grows linearly with the number of cores and fibers.
- The number of SSS ports is $(F-1)C+1$, which grows linearly with the number of cores and fibers.
- Splitting losses are $10 \cdot log\{(F-1)C+1\}$. They grow logarithmically with the number of cores and fibers.
- The number of 1xF CDC MUX/DEMUX in the Add/Drop module is C.

The architecture proposed for a Flex-Grid/MCF B&S CCC-ROADM node of degree F with C cores per fiber including the add/drop module is shown in Fig. 2. Observing the architecture, we see that:

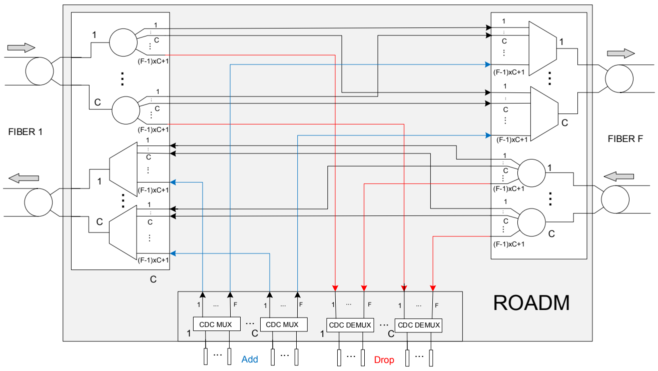

Fig. 1. B&S FNB node architecture

- The architecture can be built as a parallel deployment of C (one per core) regular ROADMs for SMFs with node degree F.
- The total number of splitters and SSSs per ROADM is F, which grows linearly with the node degree regardless of the number of cores.
- The number of SSS ports is F, which grows linearly with the node degree regardless of the number of cores.
- Splitting losses are $10 \cdot \log\{F\}$. They grow logarithmically with the node degree regardless of the number of cores.
- One PxF CDC MUX/DEMUX in each regular ROADM implements the adding and dropping operation where P is number of transceivers needed to avoid add/drop contention.

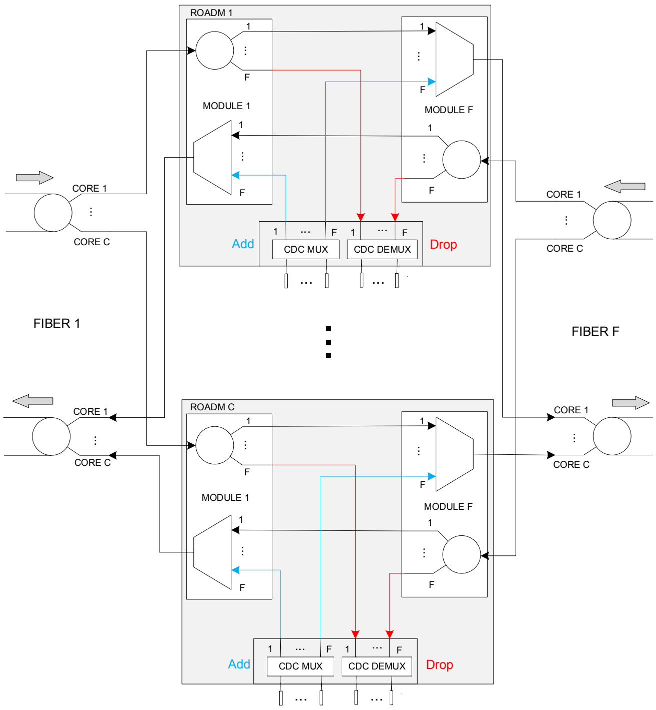

Fig. 2. B&S CCC node architecture

The pros and cons of the proposed MCF-ROADM designs can be quantified using the intrinsic attenuation introduced by the splitters and the number of input ports per SSS. Table I and II compare these metrics for each architecture, respectively. Results are compiled for nodes with degree $F = \{2,4,8\}$ and the number of cores per fiber $C = \{7,12,19\}$.

TABLE I

SPLITTING LOSSES [DB]

C	$F = 2$		$F = 4$		$F = 8$	
	FNB	CCC	FNB	CCC	FNB	CCC
7	9.03	3.01	13.42	6.02	16.99	9.03
12	11.14	3.01	15.68	6.02	19.29	9.03
19	13.01	3.01	17.63	6.02	21.27	9.03

As expected we can see in Table I how splitting losses in FNB-ROADMs are much larger than in CCC-ROADMs. The differences are obviously higher as the number of cores increases. The higher the losses, the higher the required amplification and so the ASE noise introduced. Assuming a maximum gain of 20 dB, a 12-core FNB-ROADM would be limited to 8 fibers, while a CCC-ROADM could handle up to 100 fibers. Considering the interferences introduced by the splitters, the maximum splitting ratio may be limited to a factor of 9 [11], requiring the replacement by SSSs for higher values. The scalability of FNB-ROADMs would be much compromised.

Table II shows the number of input ports required in the SSS devices for the proposed MCF-ROADMs with the same number of cores nodal-degrees, as in Table I. In order to contextualize, the largest size of state-of-the-art SSSs is 1x32 [22]. The shadowed cells in Table II are those that exceed 32 ports. As we can observe, several settings for FNB overcome this limitation, while in CCC the number of ports is way below it.

TABLE II

NUMBER OF REQUIRED INPUT PORTS PER SSS

C	$F = 2$		$F = 4$		$F = 8$	
	FNB	CCC	FNB	CCC	FNB	CCC
7	8	2	22	4	50	8
12	13	2	37	4	85	8
19	20	2	58	4	134	8

The analysis in this section reveals that the complexity of FNB-ROADMs might be unfeasible or its cost unaffordable (according to the analysis conducted in [19]). Conversely, the CCC-ROADM scheme rises as an option with excellent scalability.

III. TRANSMISSION REACH ESTIMATION

Maximum transmission distance limitation is key when a connection is to be established because the quality of service is strongly dependent on it. However, modelling the fiber channel is a difficult task given the high complexity of variables which makes every scenario a particular case. Thanks to the advent of coherent detection, chromatic dispersion can be electronically equalized avoiding the need of dispersion compensating fibers (DFC) even for long-haul links. In such scenario, fiber nonlinearities can be treated as an optical noise source that reduces the optical signal to noise ratio (OSNR). The Gaussian noise (GN) model [23] has become a de facto standard given its simplicity and reliability in most cases of interest. In any case, the GN model can always be taken as an upper bound of the nonlinear interference (NLI) calculation, which provides slightly pessimistic reach estimations. In this work it is assumed a type of links defined in [23]:

- 85-km spans of standard single-mode fiber (SSMF).
- Erbium-doped fiber amplifiers (EDFA) with noise factor NF=5 dB.
- Polarization-multiplexed (PM) quadrature amplitude modulation (PM-QAM).
- Ideal Nyquist WDM (i.e., channel spacing equal to the symbol rate).
- Full Digital Signal Processing (DSP)-based chromatic dispersion compensation.
- No fiber nonlinearities compensation.
- No Polarization-Mode Dispersion (PMD).
- State-of-the-art soft Forward Error Correction (FEC) with 20% overhead at pre-FEC BER of $2.7\cdot10^{-2}$.
- 3-dB Signal-to-Noise Ratio (SNR) margin from ideal performance and 1.5-dB penalty of soft FEC with respect to infinite-length codes ideal performance.

The resulting transmission reach for the considered modulation formats is summarized in Table III. This is a pessimistic estimation for several reasons: (1) the GN-model is intrinsically pessimistic, (2) the channel spacing is set to its theoretical minimum, while in our simulations guard-bands (GBs) are included, (3) no fiber nonlinearities compensation is considered, and (4) no Raman amplification is employed.

Note that the OSNR degradation introduced by the ROADM amplifiers has not been considered in the TR estimation. The impact would have been higher in the FNB case provided the larger splitting ratios.

TABLE III

TR IN KM GIVEN BY THE GN-MODEL [23]

BPSK	QPSK	16-QAM	64-QAM
>20,000	9,000	2,000	600

TABLE IV

ICXT-LIMITED TR IN KM FOR DIFFERENT MCF

XT [dB/km]	C	BPSK	QPSK	16-QAM	64-QAM
-84.7 [6]	**7**	$4.7\cdot10^{6}$	$2.3\cdot10^{6}$	$5.9\cdot10^{5}$	$1.5\cdot10^{5}$
-61.9 [7]	**12**	24,322	12,190	3,062	769
-54.8 [8]	**19**	4,755	2,383	599	150

In a MCF link, ICXT can also limit the maximum reach and needs to be considered. Given its random nature some sophisticated models based on outage probabilities are under development [24]. These preliminary studies have shown that estimations based on average ICXT may be way too optimistic. In the present study the worst aggregate ICXT is taken as a deterministic in-band XT that accumulates coherently through propagation. The maximum tolerated in-band XT for a 1-dB OSNR penalty [25] is then used to determine the maximum reach. The values obtained for the 3 types of MCF considered (7, 12, and 19 cores) are summarized in Table IV. The measured worst aggregate ICXT (normalized to 1550 nm) for state-of-the-art prototypes [6]-[8] are also shown. Similarly to the nonlinear propagation case, a 4-dB OSNR margin has been included. The grey cells in Table IV correspond to the cases where the maximum reach is lower than the one introduced by NLI (19-core MCF for all modulation formats). In this simplified approach the most limiting TR values are considered assuming that either NLI or ICXT is the dominating impairment.

IV. ILP AND HEURISTIC ALGORITHMS

In this section, we present two different approaches to solve the route, modulation, core and spectrum assignment (RMCSA) problem in Flex-Grid/MCF networks deploying the aforementioned FNB-ROADM or CCC-ROADM. The first strategy relies on optimal ILP formulations, while the second one relies on a lightweight heuristic.

A. ILP Formulations

The ILP formulations aims to minimize the total spectrum occupation, in other words, minimize the total number of FSs used in the network, while optimizing the total carried traffic. The spectrum assignment of the lightpaths with FNB-ROADMs has absolute freedom to select any available core in any MCF. Conversely, with CCC-ROADMs lightpaths have to accomplish the additional CCC. Either assuming FNB-ROADMs or CCC-ROADMs, the offered traffic for each IP demand must be fulfilled by summing the operational line rates of the transponders assigned to the underlying lightpath carrying it, which has to be at least the offered IP traffic volume. Finally, the ILP is aware of the slot-clashing constraint with FNB-ROADMs, regardless the core, and also is extended to enforce the CCC with CCC-ROADMs. The interested reader can find further details of such ILP formulations in our previous work [20].

B. Heuristic Algorithm

This subsection presents a heuristic algorithm for solving the RMCSA problem in large Flex-Grid/MCF network scenarios, either employing FNB- and CCC-ROADMs. Its pseudo-code is shown in Fig. 3.

The algorithm target is maximizing the carried traffic attempting to fully satisfy the traffic demand. This algorithm is based on the local search technique, in which a performance metric is used to evaluate the goodness of a solution within a main loop. Before entering the loop, it is necessary to calculate the *k*-shortest candidate paths for all available traffic demands (i.e., between their source and destination) and transponder modulation formats. During this calculation, some modulation formats may have no available path for a node pair that falls within its transmission reach, and will not be included as valid options for that node pair.

Secondly, the algorithm enters into the main loop. This loop ends when all demands have enough lightpaths to satisfy the offered traffic. In other words, when eventually the rejected traffic volume becomes zero. Every time when the execution returns to the start of the loop, unserved demands are sorted in descending order according to the percentage of remaining traffic to be carried, and stored in D_{notSat}. As a result, the demand with the highest unserved traffic proportion will be the first one for which the RMCSA will be tried. Later, for each demand *d* in D_{notSat}, the algorithm calculates how to allocate a lightpath for each path *p* of the demand *d* taking into account the First-Fit spectrum assignment. With CCC-ROADMs, it is mandatory to know the core index *c* where the lightpath is placed to fulfil the CCC. Given their core assignment extra degree of freedom, this step is not necessary with FNB-ROADMs. Each accepted path is represented by a performance metric consisting in its spectral efficiency. In this way, the algorithm is aware of the optimization of spectrum resources available in the network. For a demand *d,* the path with highest performance metric is chosen. Notice that in this step the allocated core index is taken into account for the CCC. This process is repeated for the next demand in D_{notSat}. After that, if all demands have one lightpath allocated, the algorithm goes back to the top of the main loop. This step will be repeated until all the demands are satisfied or all the feasible possibilities had been analyzed.

```
Initialization;
   Set $\mathcal{CPL}$   comment: Compute k candidate path list of possible paths;
   Set $\mathcal{FPL}$   comment: List of feasible paths ordered by length;
do
    atLeastOneLpAdded = false ;
    $\mathcal{D}_{notSat}$: demands ordered in descending the relative blocked traffic;
    foreach $d \in \mathcal{D}_{notSat}$ do
        bestMetric = 0;
        bestIndex = -1;
        if isCCC-ROADM  bestCore = -1;
        foreach pIndex $\in \mathcal{FPL}$ (d) do
            First Fit Spectrum assignment of path(pIndex) and allocation;
            exCarrTraff: Average carried traffic after potential allocation;
            curMetric = exCarrTraff / cost(pIndex);
            if currMetric > bestMetric then
                bestMetric = currMetric;
                bestIndex = pIndex;
                if isCCC-ROADM  bestCore = c;
                atLeastOneLpAdded = true;
            end
            For demand d, allocate bestIndex   comment: Add lightpath
        end
    end
while atLeastOneLpAdded = true;
```

Fig. 3. Heuristic Algorithm pseudo-code

V. RESULTS

This section collects and analyses extensive results for evaluating the network-wide performance of the proposed cost-effective CCC-ROADM architecture for Flex-Grid/MCF networks, comparing it against that of the FNB-ROADM. This evaluation is conducted employing the strategies previously presented in Section IV.

Both ILP and heuristic algorithms have been implemented in a network design and planning tool, Net2Plan [26][27], which includes the JOM library, a Java-based interface for CPLEX solver [28], used in the execution of the ILP algorithm.

The simulation is split in two main parts. The first one presents the validation of the performance of the proposed heuristic, comparing it to the results of optimal ILP formulations in small network instances, for which ILP solutions can be obtained. The second part employs the proposed heuristic to evaluate the performance of the CCC-ROADM in four different large-scale network topologies, always taking that of the FNB-ROADM as a benchmark.

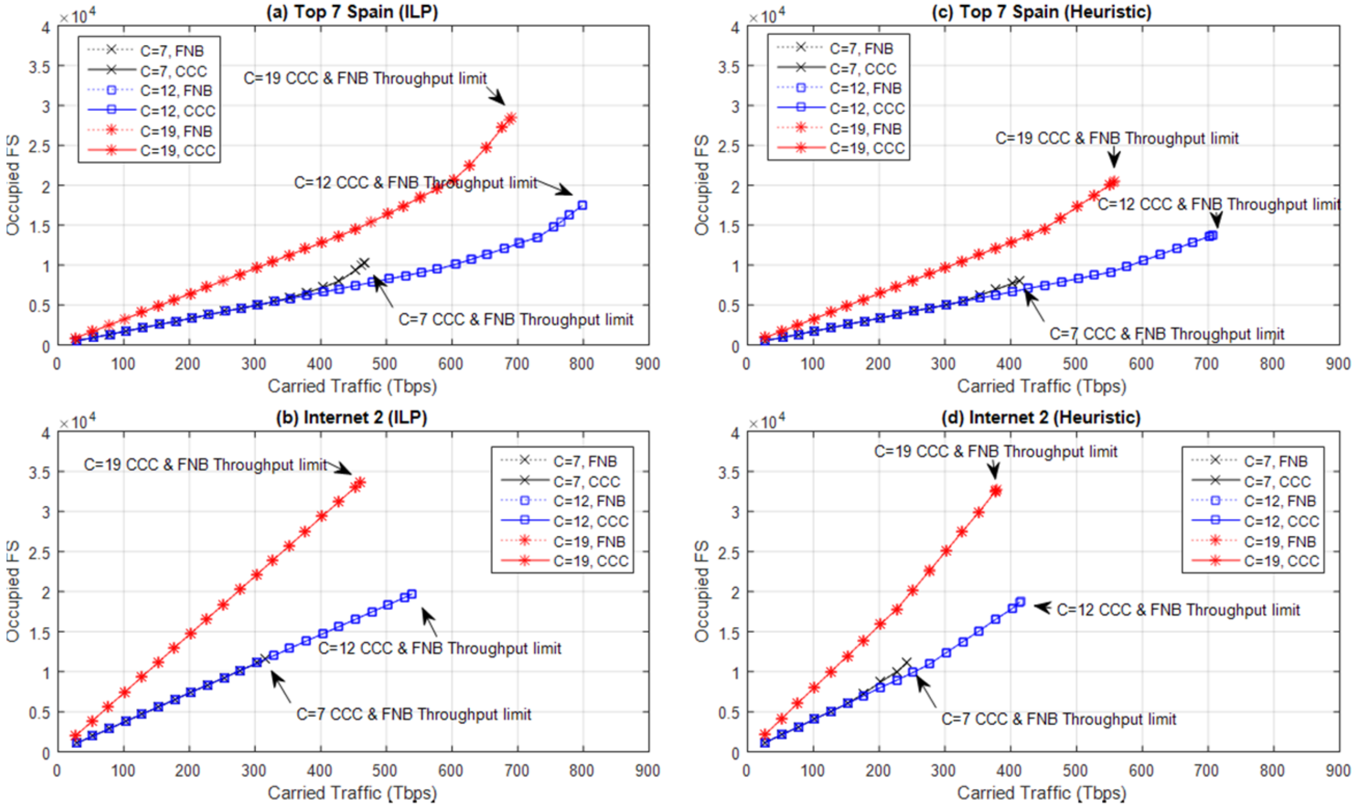

Fig. 4. ILP vs Heuristic Throughput vs. Occupied FS for: (a) Heuristic in T7S, (b) ILP in T7S, (c) Heuristic in I2 and (d) ILP in I2

A. Heuristic validation

The simulations were run in a personal computer with 8-core i7 CPU and 16 GB of RAM. The JOM library was configured so that if the optimal solution is not found after one hour, the best feasible solution so far is returned, if any. The one hour limit is only hit with CCC-ROADMs. The constraint structure in the ILP with FNB-ROADMs seems to be simpler and more favorable for the internal solver branch-and-bound optimizations, and the optimum solution is always returned before an hour; thus it can be used as a performance upper bound to estimate the sub-optimality of the results with CCC-ROADMs.

For testing the performance of the heuristic two reference topologies have been chosen: (i) the Top 7 Spain (T7S) network which has an average node degree of 2.29 and a diameter of 920 km (the longest shortest path between two nodes in the network), and (ii) the Internet 2 network (I2) with an average node degree of 2.89 and a diameter of 4116 km. These topologies can be found in [27]. We assume that the network links are C-core MCFs, where $C = \{7,12,19\}$, with a total available spectrum of $S = 120$ FSs of 12.5 GHz spectral width.

For modeling the traffic, we assume an offered IP traffic represented by a population-based seminal traffic matrix, where the offered traffic between two nodes is proportional to the product of their populations. To satisfy the offered demands, a set of available transponders (T) is defined, that can operate at one of the following line rates $R = \{40,100,400\}$ Gb/s, using different modulation formats (BPSK, QPSK, 16-QAM, 64-QAM), and having the different transmission reach limits. The most efficient modulation format is always selected based on the TR values in Table III. The ILP formulations and the proposed heuristic can choose different lightpaths with different transponders to satisfy the same IP demand. The candidate path list stores the k=5 shortest paths (in km) for each demand. Over these paths, candidate lightpaths are subsequently computed for each transponder modulation format.

Fig. 4 depicts the obtained results with the ILP formulations and heuristic in terms of spectrum occupation for growing IP traffic load. The process stops when one demand cannot be completely satisfied, and thus we assume that the network capacity limit is reached. Both ILP and heuristic results are presented with FNB- and CCC-ROADMs in the two reference topologies aforementioned.

Results show that there is not significant difference between any of the settings analyzed for C=7 and C=12. The fact that the lines for 7 and 12 cores have almost the same slope means that the spectrum allocation is very similar with these two MCFs. However, for C=19 cores more problems appear when trying to allocate the lightpaths due to the ICXT, that implies a transmission reach reduction.

Besides, Fig. 4 shows an increasing slope changing close to the throughput limit, especially noticeable in the T7S network [Fig. 4(a,b)]. This change in the spectrum occupation trend appears because both strategies mainly choose the shortest path to allocate the lightpath under low traffic loads. Nevertheless, as the network traffic increases, shortest paths may become fully occupied, being necessary to explore longer paths with less efficient modulation formats, and thus increasing the spectrum occupation.

It is important to note that results are very sensitive to the traffic matrix. Therefore, it would be inappropriate to

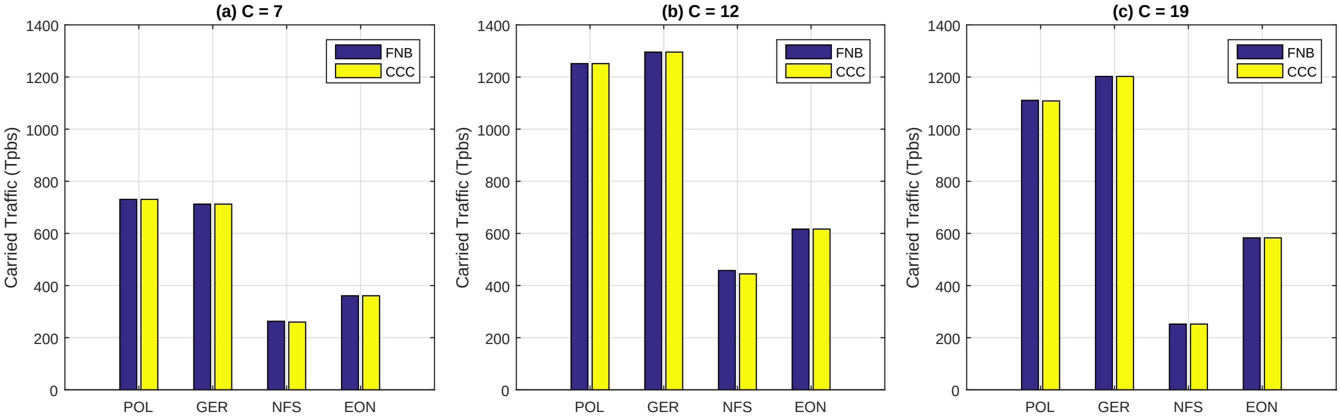

Fig. 5. Maximum carried traffic by heuristic algorithm for different topologies and number of cores: (a) 7, (b) 12 and (c) 19 cores.

get a general conclusion when comparing behaviors in different topologies.

Tables V and VI show the network throughput (maximum total carried traffic with zero blocking) when using the ILPs and heuristic with FNB- and CCC-ROADMs. The values for the FNB in the ILP method are measured in Tbps. The values for (i) the CCC-ROADMs or (ii) FNB-heuristic cases, are relative respect to the FNB-ILP ones. For instance, a value of -10.7% represents that using such an approach the network throughput is a 10.7% less than the analogous network (same C parameter) with non-blocking ROADMs computed with an ILP.

TABLE V

MAXIMUM THROUGHPUT IN T7S USING ILP VS. HEURISTIC (IN TBPS)

	FNB	CCC	FNB	CCC	FNB	CCC
	C=7		C=12		C=19	
ILP	460.0	0.0%	798.7	-0.1%	689.7	-0.5%
Heuristic	-10.7%	-10.7%	-11.4%	-11.6%	-19.2%	-19.5%

TABLE VI

MAXIMUM THROUGHPUT IN INTERNET 2 USING ILP VS. HEURISTIC (IN TBPS)

	FNB	CCC	FNB	CCC	FNB	CCC
	C=7		C=12		C=19	
ILP	315.6	-0.1%	539.6	-0.1%	460.3	-0.2%
Heuristic	-23.1%	-23.1%	-23.2%	-23.3%	-17.8%	-18.2%

Comparing the results of the ILPs against the ones obtained with the heuristic, ILPs naturally provide better performance although, as explained before, at an expense of a large computational complexity. For example, the heuristic can carry, at most, -19.53% in T7S and -23.3% in Internet 2 less traffic than its equivalent settings in the ILP. However, only a few seconds are needed to execute the algorithm instead of an hour for the ILP.

Comparing FNB vs. CCC cases, differences in terms of maximum network throughput are minimal, only slightly noticeable as the number of cores grows, the CCC option became more significant as C increases.

B. Heuristic Algorithm Performance Analysis

Subsequent simulations have been performed in an 8-core and 16 GB RAM computer. The heuristic algorithm has been tested in four reference topologies with different node degree and network diameter, namely, the Poland (POL), Germany50 (GER), NFSNet (NFS) and European Optical Network (EON) topologies. Two of these have a diameter less than 1000 km. Hence, they could be considered small networks. The other two have a diameter close to the largest transmission reach of a transponder over 19-core MCFs, where the highest limitation is found. These topologies are available in [29] and summarized in Table VII.

TABLE VII

REFERENCE NETWORKS

	Nodes	Links	Node Degree	Diameter (km)
POL	12	36	3.00	810
GER	50	176	3.52	934
NFS	14	42	3.00	4500
EON	18	66	3.67	3837

In this part, incoming IP traffic demands are generated by a uniform random (0,1) distribution for each node pair. The rest of the assumptions are the same to that in the subsection V.A. Maximum network throughputs are shown in Fig. 5, obtained using the proposed heuristic in the 4 considered network topologies As expected, we can see that topologies with lower diameter can carry a larger amount of traffic with the same link capacity. Specifically, the larger the diameter of the network the lower the average spectrum efficiency due to transmission reach limitations in MCFs. Also a slight difference can be noticed in those networks with a larger number of links. In fact, in networks with a similar diameter, more links facilitate finding available paths to solve the RMCSA problem. This is more visible in EON vs. NFS than in GER vs. POL topologies, but it is very dependent to the traffic matrix. There are not major differences (even inexistent) when comparing the deployment of FNB- vs. CCC-ROADM, as happened in the previous subsection. This highlights the profit-cost balance in favor of deploying CCC-ROADMs in Flex-Grid MCF networks.

To evaluate the performance of the heuristic in the different topologies, *network economic efficiency* is presented as the ratio between the maximum network throughput in Tbps and the total number of cores in the network (CxE with C number of cores and E number of links). The role of this metric is capturing the trade-off between profit (network throughput) and cost (links and cores). Our interest is using it for comparing their values among different settings.

Economic efficiency helps us to evaluate the merits of each alternative. As an example, although the GER topology has a significantly higher throughput than POL, the economic efficiency in GER is clearly lower as it needs a much higher investment in number of links to achieve similar revenues. This effect is smoothed in NFS vs. EON for C=7 and 12 cores because in spite of the carried traffic in EON network is higher than in NFS one, the EON topology has much more links, so the balance between profit and cost is similar in both cases.. However, in this last comparison, for C=19 the trend is inverted, as in this environment, the lack of options to carry traffic in long-haul paths for NFS is decisive in the network economic efficiency (in comparison with the EON value, for example).

Table VIII shows that in the C=19 scenario, the network efficiency value drops in all the networks, but this does not happen in C=7 and C=12 cases. This is a direct consequence of the higher ICXT values, and therefore the transmission reach reduction.

TABLE VIII

NETWORK ECONOMIC EFFICIENCY

Topology	C=7	C=12	C=19
POL	2.9	2.9	1.6
GER	0.6	0.6	0.4
NFS	0.9	0.9	0.3
EON	0.8	0.8	0.5

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we exhaustively evaluate the cost-performance trade-off in FlexGrid-MCF networks, between using fully non-blocking (FNB) ROADMs or using simpler ROADMs subject to the core-continuity-constraint (CCC). In the cost side, we illustrate with numerical examples how broadcast-and-select based FNB ROADMs require an impractical size of the SSS in number of ports, well beyond the state-of-the-art limits, and involve higher splitting losses that would require higher amplification, when compared to that of CCC-ROADMs.

For evaluating the performance side of the trade-off, an efficient RMCSA local search-based heuristic algorithm has been presented. The comparison focused on FlexGrid/MCF networks with MCFs of 7, 12 and 19 cores, in two different scenarios. The heuristic quality has been validated by comparing its results (needing <5 seconds to complete) to those of an ILP-based optimal solution for two small network instances (stopped after one hour of running time), with MCFs of 7, 12 and 19 cores.

For larger network topologies, ILPs become impractical, and the comparative analysis between FNB and CCC-based networks is completed with the heuristic. We evaluated the maximum throughput achievable in 4 large-scale reference network topologies deploying FNB- and CCC-ROADMs. Heuristic running times were still in the order of a few seconds, supporting the scalability of the method. Results support the three main conclusions of the paper: (i) A minimal loss in throughput was found, less than 1%, in CCC compared to FNB-ROADMs. This supports CCC ROADMs as a favorable cost-performance alternative for FlexGrid/MCF networks. (ii) Results suggest avoiding the use of 19-core MCFs, since the effect of the associated ICXT is high, especially in networks with a diameter similar to the transmission reach. (iii) The network economic efficiency study recommends using 7 and 12-core MCFs in small high-capacity networks.

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