Capacity Quantification of Joint-switching-enabled Flex-Grid/SDM Optical Backbone Networks

Rubén Rumipamba-Zambrano, Jordi Perelló, Joan M. Gené, Salvatore Spadaro
Universitat Politècnica de Catalunya (UPC), C/Jordi Girona 1-3, 08034 Barcelona, Spain
rrumipam@ac.upc.edu

Abstract: We quantify the network capacity scaling from 7 to 30 spatial channels. While multi-fiber provides a 5x capacity increase, MCF limits it to 4x and 2x in national and continental backbone networks, respectively.

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1. Introduction

Flex-Grid and Space Division Multiplexing (SDM) [1] technologies arise as the "next-frontier" of fiber optics to scale up the capacity of current Dense Wavelength Division Multiplexing (DWDM) optical fiber systems. Flex-Grid technology allows transmissions at ultra-high bit-rates by the concatenation of multiple flexible sub-channels (Sb-Chs) forming a super-channel (SCh). SDM covers different technological solutions. The simplest one relies on the current telecom operators' infrastructure by means of bundles of single-mode fibers (Multi-Fiber −MF−). However, as in the case of WDM, parallelization is a must for SDM to become economically attractive and so novel fibers are required [2,3]. Technological options to this goal rely on Multi-Mode Fibers (MMF), Few-Mode Fibers (FMF), Multi-Core Fibers (MCFs), and FM-MCF. These novel fibers introduce a new impairment to deal with, that is, the coupling between modes or cores which has to be properly considered in order to determine if Multiple-Input and Multiple-Output (MIMO) equalization is necessary. Among the different technological options, MCFs have become particularly attractive given their extremely low inter-core crosstalk (ICXT) values [2,3] avoiding the need of MIMO-based equalization even over long-haul transmissions. This type of fibers are referred as weakly-coupled MCFs for which we estimated in a previous work [4] the transmission reach (TR) as the most restrictive transmission distance either imposed by worst aggregate ICXT or Amplified Spontaneous Emission (ASE) noise.

Apart from the type of fiber, another key aspect for channel allocation in SDM networks is the switching technology. A cost-effective alternative for the nodes is to jointly switch one spectrum slice of all fibers/cores/modes at once (*Joint-switching* −JoS−) which is mandatory for strongly-coupled fibers. JoS enables a joint digital signal processing (DSP) at different degrees, which can lead to reduction of power consumption and cost [5,6].

With the space dimension a new degree of flexibility is introduced for SCh configuration. As presented in [7], the possible SCh allocation policies are: (a) Spectral-SCh (Spe-SCh), (b) Spatial-SCh (Spa-SCh) and the combination of both (c) spectral/spatial SCh (S2-SCh). Results reported in [6] show that Spe-SChs may yield better Bandwidth-Blocking Probability (BBP), as they can dispense of Guard-Bands (GBs) between Sb-Chs if Nyquist-Wavelength Division Multiplexing (NWDM) is employed. On the other side, the Spa-SChs allocation policy is potentially much less expensive in terms of hardware components, thanks to the utilization of the JoS. Finally, S2-SCh provides full flexibility but predictably at expenses of higher complexity and cost by requiring innovative multi-dimensional nodes to switch both dimensions independently [7].

In this paper, we evaluate the scalability of the network capacity caused by the spatial multiplicity $|S|$ (number of fibers/cores) employing JoS in MCF-enabled backbone optical networks and in the equivalent MF solution.

2. Spatial Super-Channel Allocation Policy

Given an incoming high bit-rate demand d_{br}, the associated Spa-SCh can be formed by splitting the original demand among certain spatial channels $s \subseteq S$, that is $d_{br}/|s|$. The higher $|s|$ used, the lower the resulting bit-rate per Sb-Ch and the higher the possibility to allocate lower spectral resources (frequency slots −FSs−). The Sb-Ch content can be generated/detected by sub-wavelength multiplexing in the electrical domain [8]. The number of electrical subcarriers n_e depends on its *line-rate* which can be set at lower value in order to reduce the impact of ASE noise.

The number of allocated FSs (n_{fs}) per Sb-Ch reads $\lceil line\_rate/SE \times n_e + GB)/\Delta_{fs} \rceil$ which depends on the spectrum occupancy of the n_e sub-carriers (considering the suitable modulation format with highest spectral efficiency −SE−), the necessary GBs per Sb-Ch, and FS granularity (Δ_{fs}). The grid constraint forces the spectral occupancy to be an integer multiple of Δ_{fs}, which may intrinsically produce an excess bandwidth.

Pseudo-code 1 presents a greedy heuristic for the Routing, Modulation Level, Space, and Spectrum Assignment (RMSSA) problem of Spa-SCh connections in Flex-Grid/SDM optical networks with JoS considering the previously introduced methodology and the TR estimations in [4]. Additionally, in order to optimize both the spectral and spatial resources allocated for each Spa-SCh, the unused fibers/cores ($|s'|=|S|-|s(p)|$) can be assigned to other demands. In such situations, JoS can still be applied if the light-paths are reused only for end-to-end spatial traffic grooming (*e2e-grooming*) −demands with the same source and destination nodes that share the same group s and the same spectrum slice along the routing path−. Pseudo-code 2 describes the *e2e-grooming* function, which can be incorporated to RMSSA heuristic. This is, when d_i arrives to the network, the RMSSA first checks if one of the active light-paths has enough spectrum and free fiber/cores to be reused. If so, allocate the d_i; otherwise, the K=3 Shortest Paths (SPs) between the source (*src*) and destination (*dst*) nodes are used to establish a new light-path.

Pseudo-code 1: RMSSA heuristic

1 **Input:**
G=(V,E) //Physical Network
line-rate //pre-fixed electrical sub-carrier bit-rate
GB //assumed guard-band per Sb-Ch
d_i *// demand arriving at the network*
L // Set of active Light-paths
|*S*| *//Total number of spatial channels of MF or MCF*
2 **Begin:**
3 $Y_i \leftarrow e2e\_Grooming(L, d_i, |S|)$ *//binary flag for grooming-function*
4 **If** Y_i is false **then**
5 *P* ←Compute K=3 candidate SPs between src_i and dst_i in *G*
6 X_i ←*false // binary flag to determine if* d_i *is blocked or accepted*
7 **For** each *p* in *P* **do**
8 Find the most efficient modulation format with
9 $TR \geq p_l[Km] \leftarrow line\_rate, SE$
10 $|s| = |S|$ *//initial value: all S spatial channels*
11 Compute $n_e \leftarrow \left\lceil \frac{d_{br}/|s|}{line\_rate} \right\rceil$
12 Compute minimum $n_{fs} \leftarrow \lceil line\_rate/SE \times n_e + GB)/\Delta_{fs} \rceil$
13 **do**
14 Compute $n_e \leftarrow \left\lceil \frac{d_{br}/(|s|-1)}{line\_rate} \right\rceil$
15 Compute $n_{fs\_new} \leftarrow \lceil (line\_rate/SE \times n_e + GB)/\Delta_{fs} \rceil$
16 **If** $n_{fs\_new} = n_{fs}$ **then**
17 $|s| \leftarrow |s| - 1$
18 **else if** break
19 **while** ($n_{fs\_new} = n_{fs}$)
20 **If** continuous and contiguous n_{fs} FSs are free in *p* **then**
21 Allocate the spectral resources
22 Establish new light-path L_i; $|s(L_i)| \leftarrow |s|$
23 $L \leftarrow L \cup L_i$
24 X_i ←*true,* considering d_i as served; break
25 **end if**
26 **end for**
27 **If** X_i is false **then**
28 Consider d_i as blocked
29 **end if**
30 **end if; End.**

Pseudo-code 2: e2e-grooming

1 **Input:**
L // Set of active Light-paths
d_i *// demand arriving at the network*
|*S*| *//Total number of spatial channels of MF or MCF*
2 **Begin:**
3 Find all light-paths $P \subseteq L$ with *src* and *dst* equal to src_i and dst_i
4 *P* ←Sort *P* by length in ascending order
5 Y_i ←*false // binary flag to determine if* d_i *share a light-path*
6 **For** each *p* in *P* **do**
7 $|s'| \leftarrow |S|$-$|s(p)|$ *//Available spatial channels in light-path p*
8 Compute $n_{fs}, |s|$ ←idem as steps from 8 to 19 in RMSSA
9 **If** $n_{fs} \leq n_{fs}$ *(p) and* $|s| \leq |s'|$ **then**
10 allocate the d_i in the current light-path *p*
11 $|s(p)| \leftarrow |s(p)| + |s'|$ *//Update s of the light-path p*
12 Y_i ←*true,* considering d_i as served; break
13 **end if**
14 **end for; return** Y_i
15 **End.**

3. Numerical Results and Discussion

In order to quantify the capacity scalability in Flex-Grid/SDM networks, we consider two topologies: 1) the Deutsche Telekom 12-node network (DT12), with an average link length of 243 km; and 2) the United States 26-node network (US26), with an average link length of 469 km [4,8]. In each network link we scale the spatial multiplicity |*S*| from 7 to 30, which correspond to the best single-mode MCF prototypes found in the literature [2,3]. The worst-aggregate ICXT measurements for the considered cases can be seen in table 1. Each fiber/core is assumed to have 320 available FSs with Δ_{fs}=12.5 GHz and GB=5GHz. The *line-rate* of the electrical sub-carriers is fixed to 20Gb/s to compute n_{fs} and $|s|$. A dynamic scenario is assumed where demand requests arrive at the network following a Poisson process with negative exponentially distributed Inter-Arrival Time. Each request asks for a bidirectional light-path between uniformly distributed source and destination nodes with bit-rate equal to d_{br} during a certain Holding Time, which also follows a negative exponential distribution. We consider two traffic profiles (TPs): TP1 = {100, 400, 1000}Gb/s with probabilities {0.4, 0.3, 0.3}, average 460Gb/s; and TP2 = {400, 1000, 2000}Gb/s with the same previous probabilities, average 1.06Tb/s. Different offered loads (in bits/s) are simulated until we obtain a BBP equal to ~1% for each spatial multiplicity value. To get statistically relevant results, we offer 10^5 demand requests per execution. Fig. 1 shows the traffic volume for different |*S*| values in DT12 and US26 networks with both TP1 and TP2.

For MF solution, the |*S*| increase does not imply the reduction of the allocated spectrum due to the grid constraint. Besides, the JoS penalizes the spectrum occupation because the unused fibers/cores cannot be allocated to other demands. These two factors cause the step-like shape seen in Fig. 1. If *e2e-grooming* is not used (squares −NonGr−)

the spatial multiplicity is poorly exploited (~20% and ~180% increment for TP1 and TP2 respectively, comparing |*S*|=30 vs. |*S*|=7). When considered (circles −Gr−) the network capacity increases considerably in about ~400% for either US26 or DT12 networks. As example, for 1Tb/s demand, PM-64QAM modulation format, TP1, without *e2e-grooming*, in both DT12 and US26 networks from |*S*|=7 to |*S*|=12 the optimum $|s|$ is 5, n_e=10 and n_{fs}=2; and only when $|S|$ becomes equal to 13 the optimum $|s|$ is incremented, n_e=4 and n_{fs}=1. Since no lower values of n_{fs} are possible, no traffic volume increment is evidenced from $|s|$=13 onwards. Another interesting analysis is the impact of the TP. The *e2e-grooming* effect is earlier evidenced for TP1 (e.g. from |*S*|=9 onwards) than in the more demanding −TP2− (e.g. from |*S*|=18 onwards). The larger the d_{br}, the larger the allocated $|s|$ leaving less cores for *e2e-grooming*. It is worth observing that, the network capacity with JoS is TP-sensitive.

Table 1. Measured worst-aggregate ICXT [2,3] at 1550nm

7 cores	12 cores	19 cores	22 cores	30 cores
-84.7 dB/Km	-61.9 dB/Km	-54.8 dB/Km	-56.2 dB/Km	-60 dB/Km

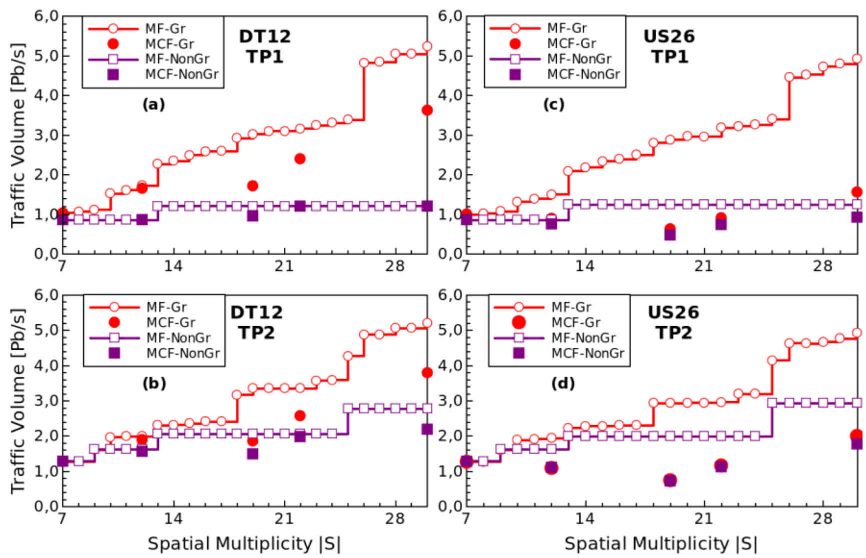

Fig. 1. Traffic Volume (in Pb/s) versus |*S*| for: (a) DT12 & TP1, (b) DT12 & TP2, (c) US26 & TP1, (d) US26 & TP2

In the case of MCFs, as expected, the longer the network size, the higher the ICXT impact. ICXT forces to employ more robust modulation formats in one routing path and may increase both spectral and spatial allocated resources (the lower the bit-rate per Sb-Ch, the larger the $|s|$). In the DT12 network without *e2e-grooming*, the MCF performance is practically equal to the MF equivalent solution. However, when *e2e-grooming* is enabled differences are reported starting from 19-cores MCF onwards. The network capacity increases up to ~4Pb/s (20% penalty regarding MF solution). In the case of US26, the ICXT impact is significant from 12-cores onwards and capacity increases only up to ~2Pb/s (60% penalty regarding MF solution). In long-haul backbone networks, ICXT may cause them to become almost insensitive to *e2e-grooming* given the minimum light-path reuse.

4. Conclusions

When scaling from 7 to 30 spatial channels in Flex-Grid/SDM networks considering JoS and *e2e*-grooming, the MF-based networks capacity is increased 5x, while in the MCF ones we can scale the traffic only 4x and 2x in national and continental-backbone networks, respectively. The capacity scaling reported in MCF-based networks is limited by the ICXT impairment affecting especially in long-haul backbone networks.

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