

Influence of the Spatial Super Channel Guard-band Width on the Performance of Dynamic Flex-Grid/SDM Optical Core Networks

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ABSTRACT

Spatial Division Multiplexing (SDM) arises as the only solution to overcome the capacity limits of single-mode optical fibres (SMFs). Among the different SDM flavours, Multi-Core Fibres (MCFs) are gaining interest thanks to their low inter-core crosstalk (XT). In this context, Flex-Grid is envisioned as the technology that enables the efficient allocation of connections in SDM-based optical networks. Despite the benefits that the combination of Flex-Grid/SDM brings, the necessary guard-bands between connections can limit the performance, especially when allocating spatial super channels. In this paper, we evaluate the influence of the guard-band width on the performance of dynamic Flex-Grid/SDM optical networks when allocating spatial super-channel connections. The obtained results reveal that significant improvements can be achieved for reduced guard-band requirements.

Keywords: Flex-Grid, SDM, multicore fibres, spatial super channel, guard-band

1. INTRODUCTION

The growth of the traffic in optical networks is pushing the capacity boundaries of standard SMFs [1]. In such a context, SDM is considered as the only viable solution to go beyond such limits [2]-[4]. The foundation of SDM is based on exploiting the spatial dimension of optical fibres by establishing several simultaneous connections onto the same fibre structure. The simplest SDM realization consists on employing multiple SMFs in a bundle in what is known as Multi-Fibre (MF) optical networks. Recent research on SDM focuses on new ways to exploit the spatial dimension of optical networks, such as fibres with several cores supporting independent optical channels per core (i.e., Multi-Core Fibres (MCFs)) or the propagation of several transverse guided modes through the same fibre (i.e., Multi-Mode Fibres (MMFs)).

Although both MCFs and MMFs can multiply the capacity of optical networks by several factors, they present some drawbacks that may limit their implementation. For instance, MCFs suffer from inter-core XT in which part of the signal traveling on one core leaks to adjacent cores, adding additional interference reducing the transmission reach (TR) of signals. On the other hand, MMFs suffer severe mode coupling requiring the utilization of expensive Multiple Input Multiple Output (MIMO) Digital Signal Processing (DSP) techniques for its compensation. Nevertheless, recent research has demonstrated that the influence of the inter-core XT in MCFs is relatively low for a moderate number of cores, allowing establishing high bitrate connections up to several hundreds of kilometres [5]-[7]. For this reason, MCFs are an appropriate technology for the realization of SDM-based optical networks.

To maximize the utilization of the available spectrum in each core of a MCF, the implementation of Flex-Grid technologies is envisioned. The combination of Flex-Grid/SDM brings several ways to compose super channels (SCh) depending on how their sub-channels (Sb-Ch) are arranged [8]: 1) spectral SCh (Spe-SCh), where the Sb-Chs are arranged contiguously in the spectral domain of a single core without guard-bands (GBs) in between; 2) spatial SCh (Spa-SCh), where the Sb-Chs are distributed across all cores of the MCF over the same spectrum portion with a given GB; and 3) the combination of Spa- and Spe-SChs (S2-SCh), in which Sb-Chs may be arranged in different spectrum portions over a selected sub-set of the fibre cores. In this context, Spa-SChs are an interesting option due to the possibility to exploit novel optical devices for the joint switching of all fibre cores [9], reducing the cost of the associated hardware.

The presence of GBs in between spectrum portions of a Spa-SCh is imposed by current switching devices, which require some separation among spectrum channels to properly perform the switching of the connections. As a rule of thumb, the width of the GBs is directly related to the filtering capacity of the network devices. In this context, future optical technologies using e.g. Nyquist multiplexing will require less stringent GB values. Then, Spa-SChs could benefit from reduced GBs as less spectral resource would be required to allocate a high capacity connection.

In this work, we evaluate the influence of the Spa-SCh GB width on the performance of dynamic Flex-Grid/SDM networks to illustrate how the performance of such kind of networks could be improved by a reduction of the GB requirements. The paper is structured as follows: section 2 explains our approach to the allocation of Spa-SChs and the related hardware. For this, sub-section 2.1 presents a method for estimating the TR in MCF-SDM networks as a function of the inter-core XT, while sub-section 2.2 presents a heuristic mechanism for the resource allocation of Spa-SChs. Next, section 3 proceeds on the evaluation of the influence of the GB considering several values of XT as well as different network topologies. Finally, section 4 draws up the main conclusions of the presented work.

2. SPATIAL SUPERCHANNEL ALLOCATION

To allocate a Spa-SCh in the network, one modulator per core plus a shared laser source is required (Fig. 1). Thus, given an incoming high bitrate connection, the associated Spa-SCh is formed by splitting the original connection among the total predefined core count $|C|$. The resulting Sb-Chs (one per core) can exploit more robust modulation formats due to their lower bitrate, increasing the TR of the whole Spa-SCh. At their turn, the different Sb-Chs may be further divided onto several lower bitrate sub-carriers thanks to electrical multiplexing (e.g. Nyquist multiplexing), extending even more the TR of the Spa-SCh. The resulting subcarrier bitrate will be $Rb_s = d_{br}/(|C| \cdot n_s)$, where d_{br} is the original demand bitrate and n_s the number of employed subcarriers, resulting in a total number of frequency slots (FSs) to allocate the whole Spa-SCh equal to $\lceil (Rb_s/SE * n_s + GB)/\Delta_{fs} \rceil$, with SE being the spectral efficiency of the employed modulation format and Δ_{fs} the spectral width of a single FS. It can be seen that the imposed GBs increase the necessary number of FSs, leading to potential underutilization of the spectrum. For example, in Fig. 1 we consider a 400 Gb/s connection, employing DP-64QAM modulation format ($SE = 12\text{bits/symbol}$) and $\Delta_{fs}=12.5\text{ GHz}$. If a GB of 10 GHz is employed (Fig. 1(a)), two FSs are employed (25 GHz) with most of the spectrum being unutilized. However, if lower GBs are considered, like in Fig. 1(b), where $GB=5\text{ GHz}$, only one FSs is employed (12.5 GHz). Thus, the value of the imposed GBs plays a critical role in the resource utilization of Spa-SChs.

Additionally, as it will be shown in subsection 2.1, the TR in MCFs may depend on either Amplified Spontaneous Emission (ASE) noise or inter-core XT limitations depending on the length of the path, the geometry of the fibre and the number of cores. This opens up the optimal selection of the necessary number of sub-carriers per Sb-Ch to meet the desired TR depending on the modulation formats as well as to maximize the available spectrum. Next subsection details the procedure employed for the inter-core XT estimation.

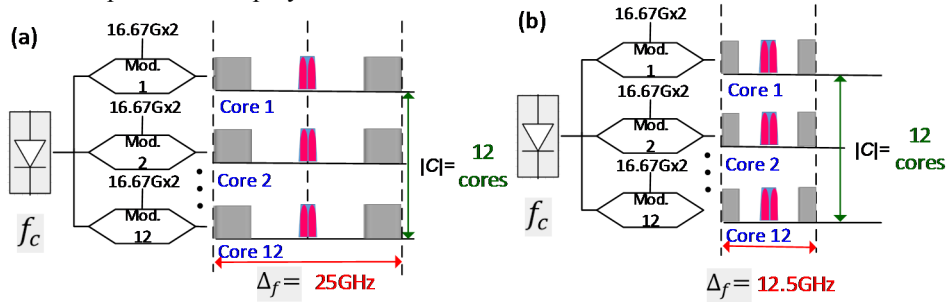


Figure 1. Spa-SCh allocation with different GB: (a) $GB=10\text{GHz}$ and (b) $GB=5\text{GHz}$

2.1 Spatial super channel transmission reach estimation

The TR of an optically-amplified single-core fibre link is limited by several factors [4]. Nowadays, DSP capabilities of coherent receivers can compensate both chromatic and polarization-mode dispersion. Intra-channel nonlinear effects can also be corrected by using nonlinear channel backpropagation which leaves inter-channel nonlinearities as the limiting factor [1]. The optimum optical transmitted power per channel can be assumed constant for a given baud rate and channel spacing (independent on modulation format). In a typical transport network, the optical power per channel is limited to avoid entering the nonlinear regime. Under these assumptions, noise becomes the ultimate limiting impairment being ASE the most relevant source. Depending on the modulation format, the minimum Signal-to-Noise Ratio (SNR) that guarantees a given Bit Error Ratio (BER) is determined. The maximum TR limited by ASE noise using erbium-doped fibre amplifiers (EDFA) can be estimated as [1]:

$$L_{max,SNR} = \frac{P_s \cdot L_{span}}{SNR_{min} \cdot h \cdot f \cdot G \cdot NF \cdot R_s} \quad (1)$$

where P_s is the optical power per channel at the transmitter, L_{span} is the distance between (equally-spaced) amplifiers, G is the amplifiers' gain, NF is the amplifiers' noise factor and R_s is the symbol rate. SNR_{min} stands for the required SNR at the receiver side which corresponds to 4.2 dB, 7.2 dB, 13.9 dB, and 19.8 dB for BPSK, QPSK, 16-QAM, and 64-QAM, respectively, for a $BER = 10^{-2}$ [1]. Transmission through MCFs is also affected by inter-core XT. Worst aggregate inter-core XT values (measured at 1550 nm and referenced to 1 km of fibre) for state-of-the-art 7, 12, and 19-core MCFs are -84.7 dB [5], -61.9 dB [6], and -54.8 dB [7], respectively. As can be appreciated, the inter-core XT levels are extremely low. The maximum transmission distance limited by XT reads:

$$L_{max,XT} = 10^{\frac{XT_{max} - XT_{1km}}{10}} \quad [km] \quad (2)$$

where XT_{max} and XT_{1km} refer to the maximum XT allowed at the receiver and to the fibre's unitary inter-core XT (after 1km), respectively. XT_{max} for a 1-dB penalty is -14 dB, -17 dB, -23 dB, and -29 dB for BPSK, QPSK, 16-QAM, and 64-QAM, respectively [3]. Note that the higher the modulation complexity the lower the tolerance. As can be seen, the limitation induced by noise is inversely proportional to the bitrate, while the impact of XT is

independent of it. Therefore, noise limitations can potentially be overcome by splitting the signal into reduced bitrate subcarriers while XT limitations can only be reduced by using simpler modulation formats.

2.2 Route, Modulation Format and Spectrum Assignment (RMSA) heuristic

In this section we present a greedy heuristic for the RMSA of Spa-SCh connections in Flex-Grid/SDM optical networks with MCFs, considering the previously introduced hardware architecture and the methodology for inter-core XT estimation. The details are depicted in Pseudocode 1. For each incoming demand, $K=3$ candidate Shortest Paths (SPs) are computed between source and destination nodes, employing the physical length as metric. For each one of them, the most appropriate modulation format and number of subcarriers is selected to meet the TR requirements, which depend on the subcarrier bitrate and the considered path length. Following this selection, the number of necessary FS is calculated. Next, the candidate path is tested for the allocation of the computed number of FSs, guaranteeing both the spectrum continuity and contiguity constraints. If the path has enough resources, the demand is considered served. If not, the next candidate path is explored until no more candidates are available (in such a case, the demand is considered blocked).

Pseudocode 1: RMSA heuristic		
1 Input: $G=(V,E)$ //Physical Network	10	If continuous and contiguous n_{fs} FS are free in p then
2 Begin:	11	Allocate the spectral resources
3 For each demand d_i that arrives to the network do	12	$X_i \leftarrow true$, considering d_i as served
4 $P \leftarrow$ Compute $K=3$ candidate SPs between src and dst of d_i		end if
5 $X_i \leftarrow false$ //binary flag to determine if d_i is blocked or accepted		end for
6 For each p in P do	13	If X_i is false then
7 Find optimum subcarrier bitrate $Rb_s \leftarrow d_{br}/(C \cdot n_s)$	14	Consider d_i as blocked
8 Find the most efficient modulation format with $TR \geq p_{length[Km]}$		end if
9 Compute $n_{fs} \leftarrow$ Number of FS to serve d_{br}		end for

3. RESULTS AND DISCUSSION

In order to evaluate the impact of the GB width when allocating Spa-SCh connections and how this influences the performance of the network, we have carried out several simulations considering a dynamic network scenario where demands arrive to the network following a Poisson distribution with a given mean inter-arrival and holding times (IAT and HT, respectively), with traffic distributed uniformly between all pairs of source-destination nodes. All demands request a bidirectional lightpath, with the requested bitrate distributed among $\{100, 400, 1000\}$ Gb/s with probabilities $\{0.4, 0.3, 0.3\}$. As for the assumed network topology, we considered two well-known scenarios: 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 [10]. Each link in the networks consists in a 12-core MCF link with an available spectrum per core of 320 FSs of width 12.5 GHz.

Given this scenario, we firstly evaluate the impact of the GB width on the Blocked Bandwidth Probability (BBP) (i.e., the blocked bitrate) of demands for increasing values of the offered load (load=HT/IAT) considering values of $GB=\{0, 2.5, 5, 10\}$ GHz. All results through this section have been obtained considering the TR estimation procedure presented in section 2 as well as considering 10^5 offered demands per data point. Fig. 2 (a, b) depict the obtained results, where a MF baseline scenario has been also depicted for comparison purposes (TR is limited only by ASE noise). Indeed, it can be appreciated that reduced values of the GB can yield to substantial improvements on the BBP/accepted load when compared to GBs found in the literature (i.e. 10 GHz) [11]. For instance, in the US26 scenario, going from a $GB=10$ GHz to 5GHz, the accepted load for a $BBP=5\%$ is 20% higher, while in the DT12 scenario, for the same reduction in GB and same value of BBP, the accepted load is 60% higher. In this regard, we can see that while the reductions in the US26 scenario are more or less smooth for decreasing values of GB, there is a huge improvement in the DT12 scenario when going from 10 to 5/2.5 GHz of GB. This is due to the length of the links in the network, since shorter distances allow to exploit more efficient modulation formats. In this regard, in long-span networks (US26), all GB reductions have a clear impact due to the fact that modulation formats with significantly wide spectrums are employed, thus, saving some GHz may spare the utilization of extra FSs. On the other hand, in networks with shorter spans (DT12), where very efficient modulation formats can be employed, initially saving some GHz may reduce the necessary FSs, but further reducing the GBs does not yield to additional FS savings as the employed total spectrum results in the same number of occupied FSs.

After having seen that, indeed, reducing the GB width can improve the performance of the network in terms of BBP, we proceed on analysing the influence of the inter-core XT. For this, we focus our attention on how much the inter-core XT should be reduced in order to match the performance of the equivalent MF scenario for the two intermediate GB values, 2.5 and 5GHz. To this end, we fixed the offered load to the one which produces a BBP around 1% for the MF benchmark scenario and varied the worst-aggregate inter-core XT for MCFs (XT_{12MCF}). Fig. 2 (c, d) shows that, on the one hand, as the network backbone length decreases, lower XT reduction values are necessary to match the results obtained with MF at its corresponding GB value. For example, while for US26 $GB=2.5$ GHz, the XT should be reduced by 7dB, for DT12 $GB=2.5$ GHz a 3dB reduction is enough. Furthermore, we can appreciate that while there are still some BBP differences between the 2.5 and 5 GHz curves in the US26 scenario for the worst considered XT, both curves become the same when reducing the XT, as in the case of the

DT12 network, since the modulation formats used for all lightpaths allow to allocate the same number of FSS in each case.

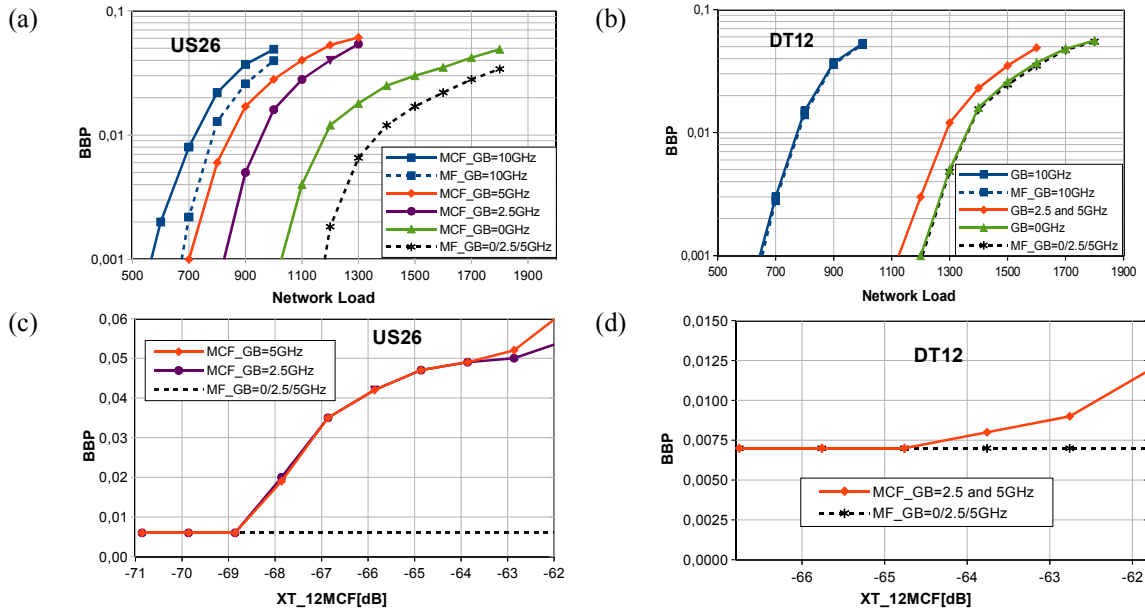


Figure 2. BBP vs. Load: (a) US26 and (b) DT12 networks; BBP vs. XT_{12MCF}: (c) US26 and (d) DT12 networks.

4. CONCLUSIONS

In this paper we have shown that reducing the GBs of spatial super channels in Flex-Grid/SDM-enabled transport networks has a strong impact on the efficiency of spectral utilization, independently from the network size. As a result, potential gains in the range of 20-60% in terms of accepted load can be achieved, hinting that more efficient optical devices in terms of needed GBs are worth to be developed. On the other side, the impact of inter-core XT has been shown to be relevant only for large-scale networks, even with reduced GBs. In such scenario fewer core fibres should be employed at expenses of less available FSS unless some sort of XT management is employed.

ACKNOWLEDGEMENTS

This work has been partially funded by the Spanish National Project SUNSET (TEC2014-59583-C2-1-R), which receives funding from FEDER.

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