Evaluating the Impact of the Guard Band Width on the Benefits of Probabilistic Constellation Shaping in Future Flex-Grid over Multicore Fibre Optical Backbone Networks

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ABSTRACT
Probabilistic constellation shaping (PCS) has emerged as an advanced modulation technique that provides a fine-grained software-defined trade-off between achievable spectral efficiency (SE) and transmission reach to deliver optimal channel capacity at any distance. This paper quantifies the network throughput benefits resulting from adopting PCS in future Flex-Grid over multicore fibre optical backbone networks, compared to using traditional uniform modulation formats. In particular, different inter-channel guard band width configurations are accounted in our study, aiming to set guidelines on the technological requirements imposed to network spectrum selective switches (SSS) to take full PCS advantage in future optical backbone networks.

Keywords: Optical networks, Flex-Grid, SDM, guard bands, probabilistic constellation shaping.

1. INTRODUCTION

Elastic optical networks (EONs) joining Flex-Grid and spatial division multiplexing (SDM) technologies [1] are seen as top candidates to realize next-generation optical network infrastructures, in view of their unmatchable flexibility and capacity, far beyond the nonlinear Shannon limit of standard single-mode fibres (SSMFs) [2]. In the near future, Flex-Grid over SDM optical networks are expected to be deployed over multi-fibre link bundles, allowing to scale the Flex-Grid optical network capacity by the number of SSMFs per bundle. Nonetheless, mid- and long-term deployments are envisioned to rely on more advanced optical fibre technologies enabling superior component integration, in order to reduce the cost and energy per transmitted bit, a key challenge for future optical network sustainability and cost-efficiency [3]. Among such advanced fibre technologies, multicore fibres (MCFs) have experienced an impressive evolution along the last decade, with homogeneous MCF designs integrating up to 22 cores with very low inter-core crosstalk (ICXT) being successfully prototyped [4], as well as heterogeneous ones integrating up to 30 cores [5]. These outstanding research achievements have endowed MCFs with the sufficient maturity to become the future SDM technology choice.

In Flex-Grid over MCF networks, ultra-high bit-rate transmissions will be supported over optical super channels, allocated either across the spectral domain (as in pure Flex-Grid over SSMF networks), the spatial domain, or both spectral & spatial domains. In this regard, most works in the Flex-Grid related literature assume that optical signals are transmitted over spectral super channels, modulated by employing traditional polarization-multiplexed (PM) modulation formats (MFs) with uniform symbol probability, e.g., from PM-BPSK up to advanced PM-*m*-QAM ones (all referred to as TrMFs hereafter). The so-called *distance adaptive spectrum allocation* strategy [6] is typically adopted to this end, suggesting the selection of the most efficient yet feasible TrMF for any super channel, given its maximum transmission reach and the transmission distance to be covered.

Unfortunately, TrMFs deliver a coarse spectrum efficiency (SE) granularity. Hence, recent works have also investigated probabilistic constellation shaping (PCS) as a more advanced modulation technology able to provide a fine-grained, software-defined trade-off between achievable SE and transmission distance [7]. Other coded-modulation technologies can also achieve a fine tuning of SE, like rate-adaptable forward error correction (FEC) or time-division hybrid modulation (TDHM). However, PCS pushes the achievable SE closer to Shannon capacity limit, having shown good results in standard fibres already [8][9], with only a moderate complexity penalty [7]. Furthermore, the potential performance benefits of PCS against TrMFs have also been quantified in Flex-Grid over MCF optical backbone networks (e.g., in [10][11]), highlighting a clear superiority in handling a substantial amount of additional load on the network [10] with also noticeable transceiver savings [11], thus lowering the network capital expenditure (CAPEX).

In this context, the present work aims at assessing PCS benefits against TrMFs in future Flex-Grid over MCF optical backbone networks, putting emphasis on the effects of the guard bands introduced in between adjacent super channels as a safety margin, given the potentially imperfect operation (e.g., optical beam steering, filtering) of liquid crystal on silicon (LCoS)-based spectrum selective switches (SSS) in re-configurable optical add & drop multiplexers (ROADMs). In particular, an answer will be sought to the following research question: *assuming reasonably wide guard bands enabling the design and manufacturing of technologically simpler ROADM devices, would PCS be able to match and even improve the performance of TrMFs with 0 GHz guard bands*?

DOI: 10.1109/ICTON59386.2023.10207381

We find this outcome as significant, in view of the high technological complexity (and cost, most probably) of the involved optics required for achieving a very precise SSS operation [12].

2. PERFORMANCE EVALUATION METHODOLOGY

To conduct the targeted performance evaluation, we assume a Flex-Grid over MCF optical backbone network planning scenario, where random incoming traffic demand requests should be incrementally allocated over spectral super channels, one after another upon their arrival. For these purposes, a first-fit lightweight route, modulation format, core and spectrum assignment (RMCSA) is employed, in order to select the most appropriate network resources to be assigned to each spectral super channel.

The RMCSA heuristic is provided with a pre-computed set of K candidate shortest physical paths (in km) between each pair of source-destination nodes in the network. The maximum attainable spectral efficiency (SE) value (in b/s/Hz) along each one of these paths is also pre-computed, using the worst-case path SE estimation methodology for Flex-Grid over MCF networks proposed in [10], considering the same input parameter values as in the reference (values of fibre, crosstalk, amplifier, etc., parameters). These maximum path SE values, which match the optical channel capacity given by the well-known Shannon's formula, are identified as the SE attainable by using PCS. In contrast, when using TrMFs, the SE of the most efficient yet feasible MF along every path is set as its SE value. For example, suppose that the methodology estimates a maximum SE across a certain path equal to 9 b/s/Hz. When PCS is used, the SE of that path will be exactly 9 b/s/Hz. Otherwise, when TrMFs are used (e.g., PM-BPSK, PM-QPSK, PM-16-QAM, PM-64-QAM), the most efficient yet feasible MF would be PM-16-QAM, hence the path SE would fall down to 8 b/s/Hz. Note that this is an estimate that still gives TrMFs a slight advantage, as it neglects the shaping gap due to the lack of Gaussianity in the signal distribution.

For each incoming demand, the RMCSA heuristic explores the K candidate shortest physical paths between its source to destination nodes, starting from the shortest one. For each path, it computes the number of Frequency Slots (FSs) required by a spectral super channel to carry the demand, that is, is $n_{FS} = \lceil (B/SE + GB)/W \rceil$, where B is the demand bit-rate (Gb/s), SE is the spectral efficiency of the path (b/s/Hz), GB is the inter-channel guard band width (in GHz) and W is the FS width (in GHz). Then, it seeks for an available spectral portion of n_{FS} contiguous & continuous FSs along the path, on a first-fit manner. To this end, the heuristic explores from core index 1 to C (i.e., the number of cores in MCF links) and from FS index 1 onwards. If such a spectrum portion is found, it is directly reserved for the spectral super channel on that core along that path and the demand is considered as served. Conversely, if no availability is found on any core of any candidate path, the demand is considered as blocked. Note that the heuristic enforces core continuity along paths. This is motivated by the adoption of more cost-effective SDM-ROADM architectures, as also considered, e.g., in [10][11].

2.1 Network throughput computation approach

One of our key performance metrics will be the total network throughput (carried data traffic) when using PCS or TrMFs under different inter-channel guard band width (GB) values, which will have a direct effect on the required number of FSs by the spectral super channels across the pre-computed paths.

Either using PCS or TrMFs, adequate network resources will be sought for every incoming demand request, using the previously presented RMCSA heuristic. If available resources are found and reserved, the incoming demand will be accounted as served, adding up its bit-rate to the carried data traffic volume. Conversely, if no available resources are found for the specific demand request, its bit-rate will be accounted as blocked, adding up to the blocked data traffic volume. In one case or another, the demand bit-rate will also be accumulated to the offered data traffic volume. Then, the processing of the next incoming demand will follow. This incremental network loading procedure will be stopped upon the blocking of a specific demand, provided that the percentage of blocked demand bit-rate against the total offered one until the moment reaches 1% already. As a result, the total carried data traffic will be considered as the achieved network throughput value.

We are aware that more complex optimization techniques could deliver a more optimal network design and precise throughput calculation. Still, we find this approach very suitable for a preliminary analysis as the one targeted in this work, allowing to reveal initial but insightful conclusions already.

3. NUMERICAL RESULTS AND DISCUSSION

An ad-hoc Python-based network simulator has been implemented to conduct the desired analysis in the DT12 German transport network (with 12 nodes, 20 bidirectional links and average link length of 243km). There, 12-core MCF links are assumed, being a MCF core-count already prototyped and extensively validated [13]. Moreover, 320 FSs of 12.5 GHz width are assumed per MCF core (4 THz C-Band fully available). Regarding the equipped network transceivers, we assume them either PCS-enabled or only TrMF-capable. In the latter case, PM-BPSK, PM-QPSK, PM-16-QAM, PM-64-QAM and PM-256-QAM are candidate MFs to be chosen, offering a SE equal to 2, 4, 8, 12 and 16 b/s/Hz, respectively. Finally, the incoming unidirectional traffic demands are assumed of 400 Gb/s, 800 Gb/s and 1.2 Tb/s with probability equal to 0.4, 0.4 and 0.2, respectively, uniformly distributed across the network (source-destination nodes randomly chosen).

Before offering actual traffic demands to the network, the candidate physical paths to support the spectral super-channels must be pre-computed. As in most optical network design papers, we limit to the number of precomputed paths between every source-destination node pair to 3 at most (i.e., K=3). Then, the maximum attainable SE over each pre-computed path should also be set, as explained in previous section. In particular, we have assumed an Add section SNR (SNR_{TX}) equal to 21dB, as suggested in [10], in order to enable a cost-effective Add section implementation, at expenses of only a slight average maximum path SE degradation.

After the path pre-computation phase, and still before offering traffic demands to the network, a preliminary assessment of the GB value effect on the performance of PCS against TrMFs can be conducted already. For example, Figure 1 (left) depicts the average number of FSs required by a spectral super channel carrying a 400, 800 and 1200 Gb/s demand when using PCS, as a function of the GB value. These averages have been obtained considering the shortest pre-computed physical path between each source-destination node pair in the network (i.e., considering 132 out of 396 paths), being these ones selected for allocating the super channels in the vast majority of cases. Besides, the average FS requirements of TrMFs with GB = 0 GHz have also been plotted as horizontal dotted lines for benchmark purposes. Looking at the figure, the generally higher SE of PCS seem to produce more noticeable reductions on the required FSs for higher demand bit-rates. Indeed, less FSs on average are required for carrying 1200 Gb/s demands with PCS with GB = 20 GHz than when using TrMFs with GB = 0 GHz. And a similar situation occurs with 800 Gb/s demands with GB = 15 GHz. In contrast, as demand bit rates get smaller (e.g., 400 Gb/s), PCS has smaller room for improvement, increasing FS requirements versus TrMFs (with GB = 0 GHz) from GB = 2.5 GHz on.

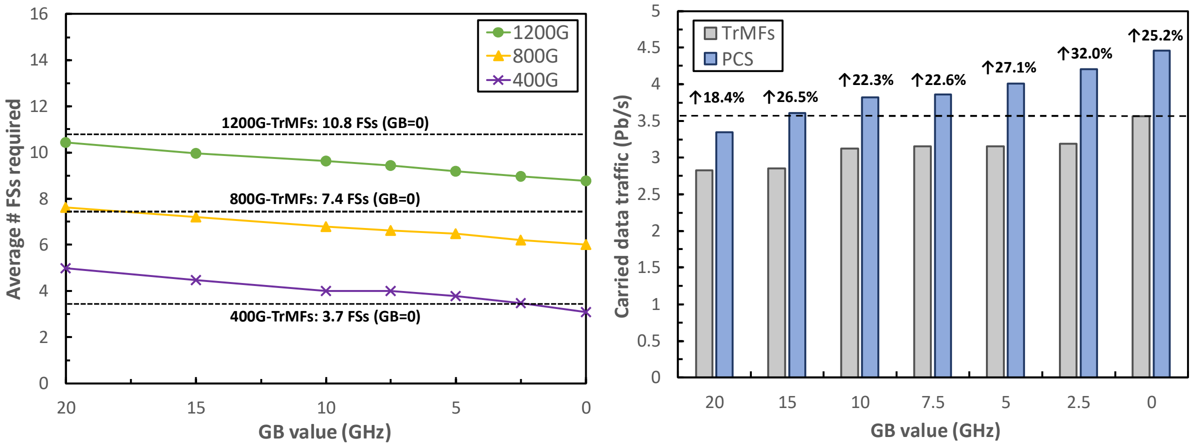

Figure 1. Average number of FSs required by a spectral super channel carrying a 400 Gb/s, 800 Gb/s and 1200 Gb/s demand using PCS, as a function of the GB value (left); total carried data traffic (in Pb/s) as a function of the GB value when using TrMFs or PCS (right).

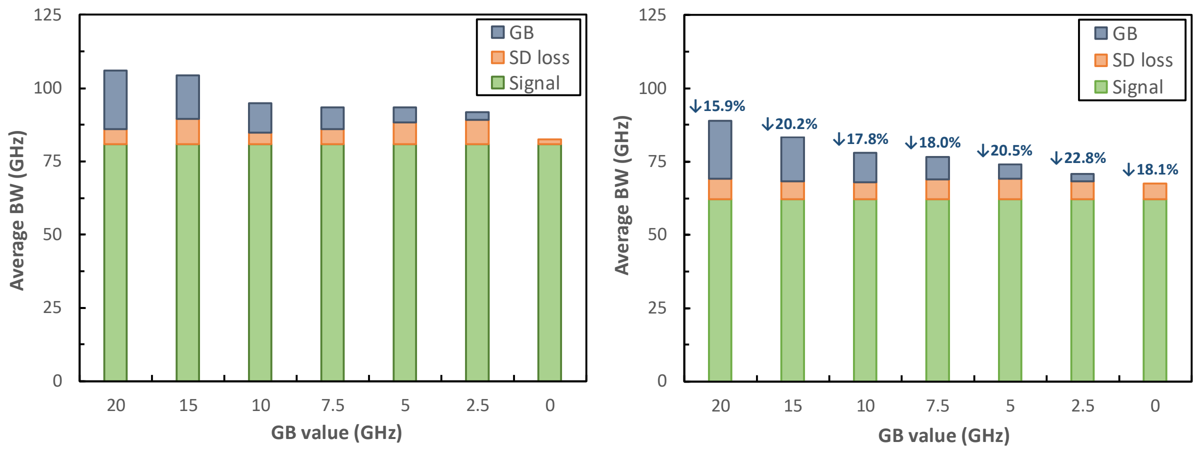

Figure 2. Average required BW by spectral super channels carrying the offered demands when using TrMFs (left) and PCS (right), both as a function of the GB value.

Once obtained these promising preliminary results, we have started to offer traffic demands to the network, in order to measure its throughput, following the approach previously detailed in subsection 2.1. For higher accuracy, we have measured it 20 times offering a new random demand list each time while averaging the obtained results, shown in Figure 1 (right). As can be seen, PCS always yields higher network throughput than TrMFs when assuming identical GB value in both technologies, with relative differences ranging from 18.4% (GB = 20GHz) up to 32% (GB = 2.5GHz). A very remarkable outcome from this figure is that PCS with GB = 15GHz can already outperform TrMFs with GB = 0 GHz.

To better understand these results, we also plot the average bandwidth (BW) allocated to the spectral super channels carrying the supported demands, when using TrMFs (Figure 2, left) or PCS (Figure 2, right) in the network. We divide the allocated BW into that used by the transmitted optical signals (Signal), inter-channel guard bands (GB) and lost due to the spectrum discretization in FSs (SD loss), since an integer number of FSs must always be reserved. Looking at both graphs, relative BW reductions with PCS stay in between 15.9 and 22.8%. It is noteworthy that average BW requirements when using TrMFs with GB = 0 GHz match those of PCS with GB = 15 GHz, in line with the previous throughput outcomes in Figure 1 (right). Regarding the SD loss BW, it seems slightly higher with PCS than with TrMFs. Nonetheless, this does not prevent PCS from providing significantly higher BW efficiency overall.

4. CONCLUSIONS

This paper has evaluated the performance of PCS and traditional polarization-multiplexed modulation formats in Flex-Grid over MCF optical backbone networks, assuming different inter-channel guard band width values. The obtained results show that PCS is able to deliver higher network throughput under all the evaluated inter-channel guard band widths (from 20GHz down to 0GHz). Furthermore, in the evaluated reference backbone network topology, the network throughput achieved by PCS with 15 GHz inter-channel guard band width already matches that one achieved by traditional modulation formats with an ideal 0 GHz guard band. These findings highlight the potential of PCS to keep attaining very remarkable network performance even deploying technologically simpler SSS devices, thus fostering future Flex-Grid over MCF optical network cost-efficiency and sustainability.

ACKNOWLEDGEMENTS

This publication is part of the Spanish I+D+i projects TRAINER-A and TRAINER-B (refs. PID2020-118011GB-C21 and PID2020-118011GB-C22), funded by MCIN/AEI/10.13039/501100011033.

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