# Reducing the Number of Transceivers with Probabilistic Constellation Shaping in Flex-Grid over MCF Optical Backbone Networks

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***Abstract*—This paper quantifies the potential reduction in the number of required transceivers that the use of probabilistic constellation shaping (PCS) can bring to Flex-Grid over multicore fiber (MCF) optical backbone networks, which can directly lead to a reduction in network capital expenditure (CAPEX). Results from two different backbone networks illustrate that PCS can significantly decrease the number of required transceivers compared to using traditional modulation formats, thanks to the finer granularity in spectral efficiency. The observed reduction becomes more prominent (up to 22.3%) as the traffic profile bit-rates and the network physical distances increase.**

***Keywords—Optical networks, Flex-Grid, SDM, transceivers, cost-efficiency, probabilistic constellation shaping.***

## I. INTRODUCTION

Elastic optical networks (EONs) employing both Flex-Grid and spatial division multiplexing (SDM) technologies [1] have emerged as a promising solution to realize next-generation optical backbone network infrastructures, thanks to their unsurpassable flexibility and capacity, allowing to overcome the fundamental Shannon capacity limit (capacity crunch) of standard single mode fibers (SSMFs) [2].

Flex-Grid [3] yields superior flexibility in the spectrum allocation, permitting the assignment of spectral resources tightly adjusted to the bandwidth requirements of the allocated super-channels. Such bandwidth requirements come from the carried traffic bit-rate, the spectral efficiency (SE) of the modulation format (MF) employed for the transmission, plus the spectral width of the guard-bands added to mitigate the interference between adjacent super-channels. In particular, MFs are typically selected in a *distance-adaptive* fashion, which consists in selecting the most efficient yet feasible MF, given its maximum transmission reach and the end-to-end physical distance of the path to be traversed.

Unfortunately, pure Flex-Grid networks over SSMFs will most likely fail in meeting the unprecedented traffic demand volumes expected in the years to come. In light of this, several technological solutions have been proposed along the recent years to realize SDM, as a means for scaling optical networks capacity. At first, independent parallel spatial paths can be deployed over multi-fiber link bundles. This approach, however, is unlikely to yield any reduction in cost or energy per bit, by scaling the number of required components linearly with the network capacity.

To address this challenge for future cost-effective optical networks, component integration becomes essential [4]. This goal is pursued, for example, by multi-core fibers (MCFs), which integrate multiple single-mode cores within the same fiber cladding. Note that MCF technology has already achieved substantial matureness to date, with some existing prototypes showing very low inter-core crosstalk (ICXT) values even integrating up to 30 cores in a heterogeneous core arrangement [5]. Such impressive achievements position MCFs as very strong candidates for implementing future SDM-enabled optical networks.

In the meantime, probabilistic constellation shaping (PCS) has recently appeared as a modulation technology that can provide a fine-grained, software-defined trade-off between achievable SE and transmission distance [6]. While some other coded-modulation technologies have also been proposed to achieve fine tuning of SE, like rate-adaptable forward error correction (FEC) or time-division hybrid modulation (TDHM), PCS pushes the achievable SE closer to Shannon capacity limit, having shown good results in standard fibers already [7][8].

Given the anticipated potential benefits of PCS compared to traditional polarization-multiplexed (PM) MFs with uniform symbol distribution, from PM-BPSK up to advanced PM-*m*-QAM ones (all referred to as TrMFs hereafter), our previous work [9] proposed a methodology to estimate the maximum SE achievable with PCS across end-to-end paths in a Flex-Grid over MCF network. This methodology was subsequently used to compare the performance of PCS and TrMFs in dynamic Flex-Grid over MCF backbone networks, highlighting the superiority of PCS in handling a substantial amount of additional load on the network, while still ensuring the same grade of service.

The ability of PCS to provide higher SE to serve incoming super-channel requests may also be translated into requiring fewer transceivers in those Flex-Grid over MCF networks.

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Therefore, given that the cost of a PCS-capable transceiver is almost the same as that of a standard transceiver employing TrMFs [10], PCS deployment could additionally have a beneficial effect on reducing the network capital expenditure (CAPEX). We cite this initial argument as the motivation for the present work, which aims at quantifying and comparing transceiver requirements when using PCS versus TrMFs in Flex-Grid over MCF backbone networks. In contrast to [9], the present work targets and offline (i.e., static) network scenario, addressing a network dimensioning problem in essence. To the best of our knowledge, no previous work has conducted a similar transceiver requirement analysis in the scientific literature, hence the novelty of the pursued goal.

The remainder of the paper continues as follows. Section II summarizes the methodology proposed in [9] to estimate the maximum paths' SE in Flex-Grid over MCF networks. Section III details the procedure adopted to precompute the end-to-end physical paths and set their SE, when using PCS or TrMFs. Moreover, it also presents the route, modulation, core and spectrum assignment (RMCSA) heuristic used during the evaluation to select the network resources to allocate the required super-channels. Section IV presents the evaluation scenarios, obtained results and key outcomes. Finally, section V concludes the paper.

## II. Path Spectral Efficiency Estimation

The detailed procedure to estimate the SE for any source to destination path can be found in [9]. A simplified version of it is included here to provide the essential ideas behind the model. The key concept is what is known as the *Gaussian noise model* [11], according to which the nonlinear interference noise (NLIN) generated in a fiber-optic link with no inline chromatic dispersion compensation behaves like additive white Gaussian noise (AWGN). On the other hand, the amplified spontaneous emission (ASE) introduced by optical amplifiers is also known to have a Gaussian nature [12], as well as the inter-core crosstalk (ICXT) generated in low-crosstalk multicore fibers [13]. Since NLIN, ASE and ICXT are the three dominating noises in optical fiber links, the overall noise statistics can be assumed to be AWGN. Note that any electronic noise is considered insignificant in determining the overall performance and is therefore ignored in this work. The channel capacity is in this case given by the well-known Shannon's formula [14]. In particular, due to the inherent nature of fiber optic links, in that NLIN and ICXT vary with signal power ($P_S$), the channel capacity is determined by the signal-to-noise ratio ($SNR_C$) that is maximized to a specific value at [13]:

$$SNR_C = \frac{1}{3[\chi P_{ASE}^2/4]^{1/3} + \kappa \cdot L}, \quad (1)$$

where $P_{ASE}$ refers to the ASE power within the channel's bandwidth, $\chi$ and $\kappa$ are the NLIN and ICXT parameters, respectively, and $L$ is the link's length.

In fiber-optic networks, the path followed by the light in an end-to-end connection (i.e., lightpath) includes many inline amplifiers, several (de)multiplexers (depending on how many intermediate nodes the signal has to go through), and add/drop modules. A simplified model is illustrated in Fig. 1. Both the add/drop and the (de)multiplexer modules are modeled as ideal lossy elements (no distortion). Erbium-doped fiber amplifiers (EDFAs) are assumed to have constant gain ($G$) and noise factor ($F$) in the whole C-band (4 THz centered at 1550 nm). The fiber-optic spans are based on SSMFs with an attenuation parameter $\alpha = 0.2\, dB/km$, chromatic dispersion parameter $D = 17\, ps \cdot nm^{-1} km^{-1}$ and nonlinear parameter $\gamma = 1.3\, W^{-1} km^{-1}$. Three separate parts are defined: the add section, the link section, and the drop section. The add section is composed of a transmitter, a passive add module (essentially a 1:N combiner) and a booster amplifier. $P_{TX}$ is the transmitted signal power, $A_{ADD}$ is the attenuation, $G_{TX}$ is the gain, and $F_{TX}$ is the noise factor. The signal power at the output $P_{OUT}$ is adjusted to set the required level when introduced into the link. Even though the output signal-to-noise ratio $SNR_{TX}$ includes ASE noise only, it is independent of $G_{TX}$. On the other hand, the product $P_{TX} A_{ADD}$ has a direct impact on it. The maximum $SNR_{TX}$ in a realistic scenario without add module is assumed to be 30 dB.

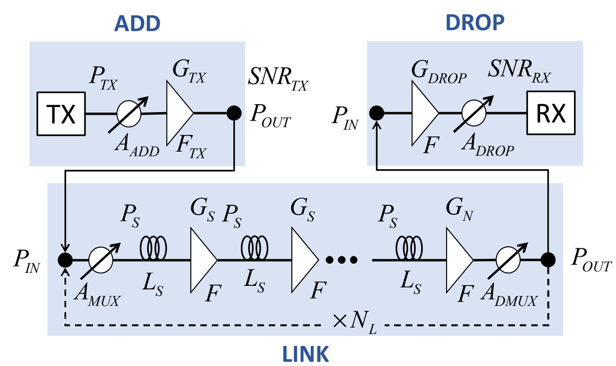


Fig. 1. Lightpath model. Top left: add section. Top right: drop section. Bottom: link section.

The link section in Fig. 1 consists of $N_L$ inter-nodal sub-links each one of them composed by several spans. All spans include an SSMF fiber with length $L_S = 85\, km$ plus an EDFA with gain $G_S$ and noise factor $F = 5\, dB$. The node's (de)multiplexers are considered as part of the link to simplify the drawing. The signal power $P_S$ at the input of every fiber span is assumed to be the same. Even though this is suboptimal, it reduces complexity dramatically and the performance degradation is only marginal. Notice that the gain corresponding to the node's front-end amplifier $G_N$ needs to compensate for not only the previous span losses but also the attenuation introduced by the (de)multiplexers.

The drop section includes a passive dropping element (essentially a 1:N splitter) together with a pre-amplifier whose gain $G_{DROP}$ perfectly compensates for the losses $A_{DROP}$. For the sake of simplicity, the noise factor is assumed to be the same as the inline amplifiers. The signal-to-noise ratio at the receiver $SNR_{RX}$, the one setting the link capacity, can be expressed in terms of $SNR_{TX}$ and the channel's signal-to-noise ratio $SNR_C$, which includes the link and the drop module. It reads:

$$\frac{1}{SNR_{RX}} = \frac{1}{SNR_{TX}} + \frac{1}{SNR_C}. \quad (2)$$

As explained before, $SNR_C$ can be maximized by selecting the optimum $P_S$ and follows Eq. (1). $P_{ASE}$ is essentially the one introduced by a single span multiplied by the number of spans $N_S$ plus the one introduced at the drop section:

$$P_{ASE} = h \cdot f(G_S N_S + A_{MUX}) F \cdot R_S\,, \qquad (3)$$

where $h$ refers to Planck's constant, $f$ is the signal's frequency assumed to be the central channel ($1550\ nm$) in all cases, and $R_S$ is the per-polarization symbol rate, which corresponds to the minimum bandwidth when ideal Nyquist pulses are used.

The NLIN and ICXT parameters $\chi$ and $\kappa$ depend only on the signal propagation through fiber spans. All other contributions are neglected. $\chi$ can also be expressed as the one of a single span $\chi_S$ multiplied by the number of spans $N_S$. Following [11], $\chi_S$ can be written as:

$$\chi_S = \frac{16}{27}\gamma^2 \frac{c}{\lambda^2 D R_S^2}\frac{10^4}{\alpha \ln 10}\, asinh\left(\frac{\pi}{4}\frac{\lambda^2 D B_W^2}{c}\frac{10^4}{\alpha \ln 10}\right), \qquad (4)$$

where $c$ stands for the speed of light and $B_W$ is the total bandwidth in use. A fully loaded C-band is assumed which corresponds to the worst case. Notice that the product $\chi P_{ASE}^2$ is symbol rate independent, which makes $SNR_C$ symbol rate independent as well.

The aggregate ICXT generated at any given core is calculated by multiplying $\kappa$ (crosstalk per unit distance) by the total propagation distance $L$. It is assumed that all cores are active the entire time, which is, once again, a worst-case scenario. As shown in [15], there exists an optimum XT level of about $-55\ dB/km$ that maximizes the aggregate capacity. This corresponds to an optimum number of cores for each MCF outer diameter. This value is taken as a reference in our calculations, assuming an optimized 12-core MCF that corresponds to a moderate 200 μm cladding diameter (60% larger than the current standard).

The last span in every inter-nodal link is, in general, a fraction of $L_S$ and deserves special attention when calculating $P_S$ and $\chi$. For the sake of clarity, this has been omitted in the precedent explanation. A more detailed description is provided in [9]. The resulting lightpath's SE, assuming 2 polarizations, is then calculated using:

$$SE = 2 \cdot \log_2(1 + SNR_{RX}). \qquad (5)$$

To reach the SE supremum, ideal Gaussian modulation is required. PCS has shown to approach the theoretical limit within a fraction of a dB and new coding strategies are expected to close the gap to under the 0.1 dB mark [6]. It is assumed in the conducted simulations that PCS can fully exploit the potential SE. TrMFs, on the other hand, rely solely on FEC codes to adapt to the required SE. This procedure is very demanding from the computational point of view and typically a fixed code rate is selected for it as the most cost-effective solution [10]. For the sake of simplicity, it is assumed that the SE obtained with uniform modulations follows an all or nothing rule; namely, flat (and maximum) SE is considered for all QAM orders as the transmission distance increases until their respective Shannon limit is reached, beyond which no SE can be obtained. The intrinsic shaping gap of about 1 dB present in TrMFs is neglected, and thus the benefit of PCS estimated in this work is conservative.

Finally, it is noteworthy that the computational complexity required for implementing the latest PCS techniques is totally marginal in comparison with the unavoidable FEC codes [10]. Such unmatched performance-simplicity combination makes PCS a key technology for the next generation transceivers.

## III. Network Resource Assignment

In this section, we detail the procedure that we follow to precompute the candidate physical paths between every source-destination node pair in the evaluated networks, as well as the attainable SE across them. Secondly, we present the RMCSA heuristic that we later employ to find out the route, modulation, core and spectrum portion for the provisioning of the spectral super-channels carrying the offered demands.

### A. *Offline Path Precomputation*

The RMCSA heuristic presented in the next subsection III.B assumes that the $k$ physical shortest paths between every pair of source-destination nodes in the network are precomputed. To this goal, the well-known Yen's algorithm [16] is used. Moreover, the SE of each precomputed path must also be set, based on whether PCS or TrMFs are employed in the network. For this reason, we apply the presented methodology in section II to every precomputed path. When PCS is used, the SE value obtained with the methodology (i.e., the maximum SE matching the Shannon limit) is directly assigned as the SE value attainable across that path. In contrast, when TrMFs are employed in the network (as benchmark), the SE of the most efficient yet feasible MF across that path is set as its SE value.

For example, suppose that the methodology estimates that the maximum SE attainable across a certain path is 9 b/s/Hz. When PCS is used in the network, the SE of that path will be exactly equal to 9 b/s/Hz. Otherwise, when TrMFs are used (e.g., standard PM-BPSK, PM-QPSK, PM-16-QAM and PM-64-QAM), the most efficient yet feasible MF across that path would be PM-16-QAM. Hence, the SE of the path would be 8 b/s/Hz, i.e., 11% lower than with PCS.

### B. *RMCSA Heuristic*

Regarding the RMCSA heuristic to select the route, modulation, core and spectrum to be assigned to the super-channels carrying the offered demands, we use the lightweight cumulative RMCSA heuristic like in some previous works on Flex-Grid over MCF network design (e.g., [17][18]). While more complex (meta-)heuristics would also be usable, we find this heuristic very suitable for an initial analysis as the one pursued in this work, providing a good trade-off between optimality of the results and execution times.

The heuristic manages the Flex-Grid over MCF network as a graph and is provided with the list of offered demands and the set of the precomputed physical paths. For higher efficiency, it is assumed that physical paths are already stored separately for every source-destination node pair, ordered by increasing physical distance end-to-end.

As a first step, for each one of the offered demands, the heuristic obtains the minimum number of FSs required for a spectral super-channel to carry it. In general, the number of FSs required to serve a demand is $n_{FS} = \lceil (B/SE + \Delta)/W \rceil$, where $B$ is the demand bit-rate (Gb/s), $SE$ is the spectral efficiency of the end-to-end path (b/s/Hz), $\Delta$ is the width of the guard-bands between adjacent spectral super-channels (in GHz) and $W$ is the FS width (in GHz). The attainable SE across the shortest candidate physical path from the source to the destination node of each demand is typically used to obtain such a minimum number of FSs. Once this value is obtained for all demands, they are sorted by their minimum FS requirements, in decreasing order. Then, the heuristic performs as described in Fig. 2.

As observed, sufficient network resources to serve the entire list of offered demands are assumed to exist (i.e., no blocking occurs when designing the network). In addition, note that the heuristic enforces core continuity along the selected paths. This is motivated by the adoption of more cost-effective SDM-ROADM architectures delivering close performance to fully flexible ones, also in static Flex-Grid/MCF scenarios as the ones targeted in this work [19].

1: Set *maxFS* = 0, as the highest allocable FS index in any core of any MCF link in the network.
2: **While** any demand still pending in the list **do**:
3: *maxFS* += Minimum number of FSs required by the first pending demand in the list (i.e., with highest FS needs). Note that *maxFS* can at most be equal to the number of available FSs in MCF cores.
4: **For each** pending demand in the list **do**:
5: Obtain the set of precomputed paths from source to destination node of the demand.
6: **For each** obtained path **do**:
7: Compute $n_{FS}$ required by a spectral super-channel carrying the demand across that path, taking the maximum attainable SE across the path into account.
8: Seek for an available spectral portion of $n_{FS}$ contiguous & continuous FSs along the path, on a first-fit manner. The heuristic starts exploring from core index 1 to $C$ (i.e., the number of cores in MCF links) and from FS index 1 to *maxFS* in each core.
9: If an available contiguous & continuous portion of $n_{FS}$ FSs is found on any core along the path, reserve that spectral portion end-to-end and set the demand as served. Then proceed to the next pending demand.

Fig. 2. RMCSA heuristic steps to serve the entire list of offered demands.

## IV. Numerical Evaluation

A Python-based network simulator has been developed to assess the benefits of PCS versus TrMFs in Flex-Grid over MCF networks, with special emphasis on the number of transceivers required to serve the list of offered demands.

Two reference network topologies have been evaluated, namely, the DT12 German transport network, with 12 nodes and 20 bidirectional links (with average link length of 243 km), and the NSFNET, with 14 nodes and 21 bidirectional links (with an average link length of 1080km). Readers interested in these topologies are referred to [9] and [20]. In both networks, 12-core MCF links are deployed, namely, a MCF core-count already prototyped and extensively validated [21]. Moreover, 320 FSs of 12.5 GHz width are assumed available per MCF core (4 THz C-Band fully available).

Two traffic profiles (TP1 and TP2) are considered when generating the list of offered demands to these networks. TP1 represents a short-term traffic profile, including demands at 400 Gb/s, 800 Gb/s and 1.2 Tb/s with probability equal to 0.4, 0.4 and 0.2, respectively. In contrast, TP2 represents a mid/long-term one, including demands at 1 Tb/s, 1.5 Tb/s and 2 Tb/s with probabilities also equal to 0.4, 0.4 and 0.2. Specifically, for each offered demand, its source-destination nodes are randomly chosen (traffic is assumed to be uniformly distributed in the network). Then, depending on the traffic profile (TP1 or TP2), the bit-rate of the demand is also randomly chosen among its included bit-rates with the aforementioned probabilities.

All demands are carried by spectral super-channels, adding $\Delta$ = 10 GHz guard-bands between adjacent ones. Regarding the transceivers equipped at network nodes, we assume them of 50 GBaud per polarization under the short-term TP1, and of 100 GBaud per polarization under the mid/long-term TP2. In this way, we account for modem technologies in line with the expected TP1 and TP2 time periods. Note that we assume programmable transceivers, capable of operating at lower bandwidth so as to match the specific baud-rate requirements of the offered demands. Moreover, transceivers can be either PCS-enabled or only traditional MF-capable (benchmark scenario). In the latter case, completely standard PM-BPSK, PM-QPSK, PM-16-QAM, PM-64-QAM and PM-256-QAM are candidate MFs to be chosen, offering each one a SE equal to 2, 4, 8, 12 and 16 b/s/Hz, respectively.

### A. *Offline Path Precomputation Analysis*

Prior to offer actual traffic demands to DT12 and NSFNET networks, the candidate physical paths to support the spectral super-channels carrying them must be precomputed. 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). This results in a total number of 396 (12*11*3) paths in the DT12 network, as well as 546 (14*13*3) paths in the NSFNET. Secondly, we set the maximum attainable SE over each precomputed path using the presented methodology, as explained in subsection III.A. We have assumed $SNR_{TX}$ equal to 21 dB in the DT12 and 18 dB in the NSFNET. These values should enable a cost-effective Add section implementation, at expenses of only a slight average maximum path SE degradation (10% lower, when using PCS) against the ideal $SNR_{TX}$=30dB.

After completing these procedures, we have analyzed the maximum attainable SE across the resulting paths, aiming to identify potential trends that help us better understanding the eventual network designs performed later on in subsection IV.B. Let us remark again that we are still not offering any traffic demand yet, but only focus on the characteristics of such precomputed paths. Indeed, a very illustrative way to appreciate the attainable SE across the end-to-end paths is by means of histograms, which are depicted in Fig. 3 for the DT12 (top) and NSFNET (bottom) networks, depending on whether PCS or TrMFs are employed there.

Looking at Fig. 3 (top), it is remarkable that when using TrMFs in the DT12, PM-16-QAM is the most efficient MF that can be used across most precomputed paths (in 88% of them), leading to an attainable SE equal to 8 b/s/Hz. In the rest of the paths (12%), PM-64-QAM becomes feasible, thus increasing their efficiency up to 12 b/s/Hz. In contrast, when using PCS in the same DT12, the attainable SE across the precomputed paths generally increase, in most cases between [10, 12) b/s/Hz and sometimes close to 14 b/s/Hz. All in all, the average path SE with TrMFs in the DT12 becomes 8.48 b/s/Hz, and raises to 11.14 b/s/Hz when using PCS.

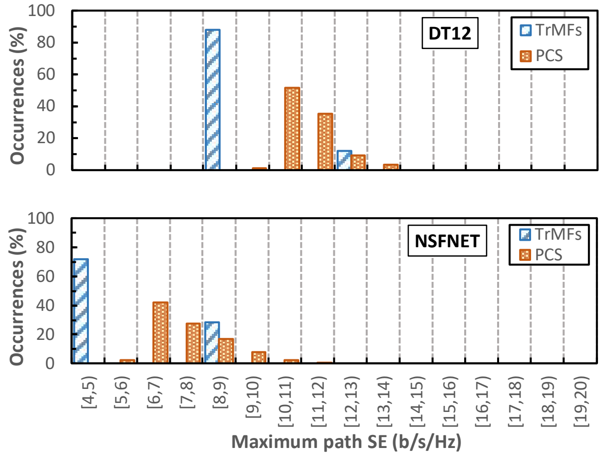


Fig. 3. Maximum attainable path SE histograms in the DT12 (top) and NSFNET (bottom) networks when TrMFs or PCS is used.

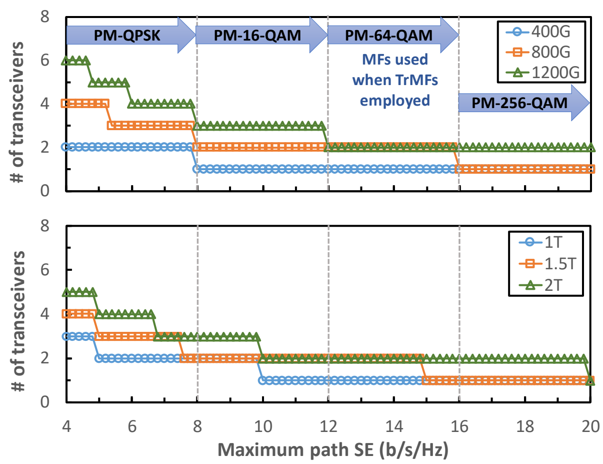


Fig. 4. Number of 50 GBaud transceivers required by a super-channel carrying a 400G, 800G or 1200G demand (top); number of 100 GBaud transceivers required by a super-channel carrying a 1T, 1.5T or 2T demand (bottom).

Moving now to Fig. 3 (bottom), the longer physical distances in the NSFNET reduce the attainable SE across the precomputed paths. With TrMFs, PM-QPSK becomes mandatory in around 70% of the paths, with their attainable SE being 4 b/s/Hz. And PM-16-QAM (8 b/s/Hz) is the chosen one in the remaining 30%. PCS yields again increased path SE values, in most cases between [6, 8) b/s/Hz, and sometimes above 10 b/s/Hz. On average, an attainable path SE equal to 5.13 and 7.4 b/s/Hz is obtained with TrMFs and PCS, respectively, in the NSFNET.

The potential for PCS to increase the SE when provisioning the super-channels across paths seems evident. Nonetheless, its potential to lower the number of required transceivers in the network still remains unclear. To provide further insight into this matter, Fig. 4 depicts the number of required transceivers for a spectral super-channel supporting any of the bit rates in TP1 (top) and TP2 (bottom). Recall that 50 GBaud transceivers are assumed under TP1 and 100 GBaud ones under TP2. These plots have been analytically obtained as $N_{TX} = \lceil (B/SE)/R_s \rceil$, with $N_{TX}$ being the number of transceivers, $B$ the bitrate of the demand (Gb/s), $SE$ the attainable SE along the end-to-end path (b/s/Hz) and $R_s$ the modulators' symbol rate (GBaud).

Noteworthy information can be extracted from Fig. 4. For example, we have previously identified that in the DT12 with TrMFs most paths provide a SE equal to 8 b/s/Hz, and some of them up to 12 b/s/Hz. Focusing now on Fig. 4, we can see that under TP1 (top), even though PCS increases path SE values versus TrMFs, no reduction in the number of transceivers is achievable. This is because the plots for 400G, 800G and 1200G demands remain constant in the range [8, 12) b/s/Hz. Hence, even though the maximum path SE (achievable with PCS) increases, the same number of transceivers as using PM-16-QAM (8 b/s/Hz) are required to carry any demand of these bit-rates. When the maximum path SE exceeds 12 b/s/Hz PM-64-QAM starts being feasible, observing again no differences on the number of required transceivers when PCS is used.

Still focusing on the DT12 but now under TP2, things start to be quite different. As seen, the reduction of one transceiver occurs with maximum path SE of 10 b/s/Hz for 1T and 2T demands. Coming back to Fig. 3 (top), a very significant number of paths deliver attainable SE values in [10,12). Hence, with PCS, demands of such bit-rates over these paths are expected to require one less transceiver than with TrMFs, as PM-16-QAM will still be employed. Reductions on the number of required transceivers also occur with maximum path SE in [15,16) b/s/Hz, but no path offers it in the DT12.

Following the same reasoning, transceiver reductions when using PCS are very likely in the NSFNET, both under TP1 and TP2. For example, many paths show a maximum SE in the range [6,8). With TrMFs, PM-QPSK is still required, limiting their SE to 4 b/s/Hz, which results in a reduced number of transceivers when using PCS to carry most of the demand bit-rates. Further reductions also exist with maximum path SE values in the range [10,12) under TP2, although only a few paths can provide them.

### B. *Network Design Analysis*

We now offer the traffic demands to both networks and allocate them using the RMCSA heuristic introduced before. Under TP1, we offer them a list of 3k randomly generated demands, while under TP2 we limit to 1.5k demands, since the average bit-rate per demand in TP2 is almost doubled (720 Gb/s in TP1 vs. 1400 Gb/s in TP2). For high accuracy, we solve each network design 20 times offering a new random demand list each time, while averaging the obtained results.

Fig. 5 depicts the number of transceivers required in the DT12 and NSFNET to provision the super-channels carrying the offered demands, either using PCS or TrMFs. As can be observed, no transceiver requirement differences between PCS and TrMFs exist in the DT12 under TP1, which matches our previous expectations (from Figs. 3 and 4). Conversely, still in the DT12 but under TP2, PCS already brings a very significant 22.1% reduction compared to TrMFs, most likely resulting from the super-channels carrying 1T and 2T demands over those paths with maximum SE in [10,12) b/s/Hz. Moving now to the NSFNET, reductions in the number of required transceivers are already appreciable under TP1 (14.2%), being even more noticeable under TP2, up to 22.3%, given the multiple transceiver reduction possibilities pointed out in Fig. 4.

To better understand these results, Fig. 6 discloses the number of transceivers that super-channels require to carry the demands under TP1 and TP2. Due to the space constraints, only the two extreme scenarios in terms of transceivers reduction are depicted: DT12 under TP1 (no PCS benefits) and NSFNET under TP2 (highest PCS benefits). In line with the previous results, Fig. 6 (top) shows that in the DT12 under TP1, demands require the same number of transceivers, regardless of whether

TrMFs or PCS are employed. Looking now at Fig. 6 (bottom), differences become much more noticeable in the NSFNET under TP2, leading to the 22.3% transceiver reduction observed in Fig. 5. Envisioning PCS-enabled transceivers in a similar cost range as standard ones (employing TrMFs), the obtained results highlight the potential of PCS to lower CAPEX for future cost-effective optical networks, which adds up to its superior SE.

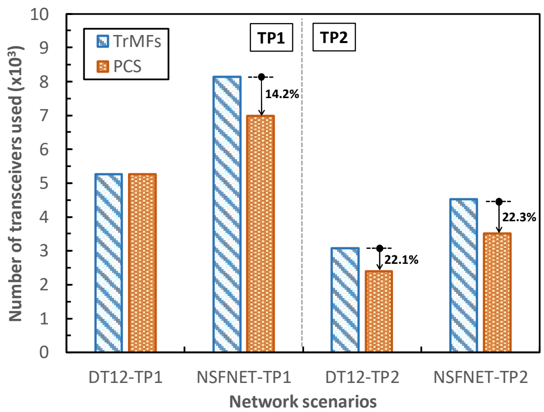


Fig. 5. Number of required transceivers in the DT12 and NSFNET under TP1 (3000 demands, $R_s$= 50 GBaud) and TP2 (1500 demands, $R_s$= 100 GBaud).

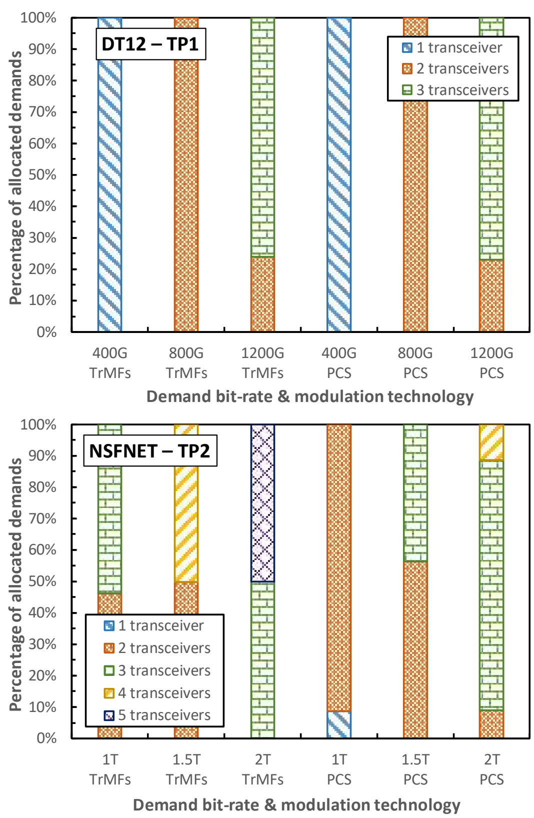


Fig. 6. Number of required transceivers by super-channels carrying the demands in the DT12 under TP1 (top) and NSFNET under TP2 (bottom).

Note that the methodologies presented in this paper could also be useful to analyze the potential transceiver savings from using PCS in Flex-Grid over SSMF networks and even over multi-fiber links. For these purposes, the $\kappa$ parameter of the proposed path SE estimation methodology (Eq. 1) should be set to 0, being ICXT inexistent there. Due to space restrictions, however, these studies have been left for future work.

## V. Conclusions

This paper quantifies the potential of PCS modulation technology for reducing the number of required transceivers in Flex-Grid over MCF networks. The obtained results show that PCS succeeds in this endeavor, particularly in large (long-haul) networks under very high bit-rate traffic profiles.

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