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Service-Aware Genetic Algorithm for Link Power Control in Multi-band Optical Transmission Systems

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Abstract *We propose a service-aware genetic algorithm for launch power optimization in meshed multi-band optical networks. Results show that adopting different launch power optimization criteria per link enables to selectively increase capacity compared with using a single criterion. ©2022 The Author(s)*

Introduction

Increasing the transmission bandwidth of optical fibre infrastructure by using multi-band transmission (MBT) systems is a promising strategy to cope with the ever-increasing traffic demand[1]. To be as efficient as possible, careful launch power optimization is critical. In typical C-band only systems, the interchannel stimulated Raman scattering (ISRS) may be neglected and the optimum channel power can be calculated using the simple Gaussian Noise (GN) model[2] approach. However, for wider transmission bandwidths, the ISRS becomes dominant, making proper power optimization much more difficult[3]. Several works have addressed the power optimization problem in MBT systems[3]–[5]. However, the same optimization criterion is always used for all links when assessing the benefit of the optimized power level in a network-wide scenario (e.g. through a Statistical Network Assessment Process[3] or average channel capacity[4]).

In this work, we propose a service-aware genetic algorithm for launch power optimization in MBT systems. A MBT system composed of the C-, L- and part of the S-bands comprising a total transmission bandwidth of 15.5 THz is considered. Results show that using different launch power optimization strategies in different fibre spans enables to selectively increase the capacity of target services when compared to using the same optimization criterion in all links.

Network-wide Power Optimization Strategy

This section describes the genetic algorithm proposed for power optimization in MBT systems. We consider a disaggregated approach, i.e., we assume that the optical performance of each fibre span and, therefore, the optimum launch power, is independent of the remaining ones. To simplify the analysis, but without loss of generality, it is assumed that spans directly connecting two network nodes have the same length and, therefore, same optimum launch power profile. In this way, the genetic encoding of a candidate solution determines the launch power profile of every link in the network. For example, for a three-band MBT system in a network that has 71 links and assuming that the launch power profile can be defined by an average value and tilt in each band[3], thus requiring the definition of 6 variables, each candidate solution has $71 \cdot 6 = 426$ chromosomes. The first step to evaluate the fitness of candidate solutions is to estimate the quality of transmission (QoT) of every lightpath in the network. This can be done by estimating the generalized signal-to-noise ratio (GSNR) using, e.g., well known perturbative models such as the generalized GN (GGN) model or other approximations[2],[6],[7]. For simplicity, but without loss of generality, we consider a fitness function that depends on the average network capacity[8]. This approach simplifies the analysis by assessing the most spectral efficient modulation format in the shortest routing path between each node pair. Therefore, the capacity of the lightpath between nodes s and d is given by:

$$C_{sd} = \{\max C_i : i \text{ is feasible}\} \times \gamma_{sd}, \tag{1}$$

where C_i is the bit rate enabled by the modulation format i and γ_{sd} is the expected utilization ratio of lightpath sd. A lightpath sd is feasible for a given modulation format if the shortest path between the two nodes can be bridged transparently. Hence, the network-wide average channel capacity (C_{NET}) can be calculated as:

$$C_{NET} = \sum C_{sd} / \sum \gamma_{sd}. \tag{2}$$

Another figure of merit that may be useful is the utilization of a given modulation format i (U^i_{NET}), which is given by the sum of the expected utilization ratio of the lightpaths using it. Different optimization criteria may be enforced via these figures of merit. In order to achieve the maximum capacity across the entire network, we should aim at maximizing C_{NET}. On the other hand, maximizing U^i_{NET} for a subset of all available modulation formats may be helpful to prioritize the transmission of certain modulation formats matching a common client rate, such as 400 Gb/s, instead of maximizing the overall capacity. Furthermore, the utilization ratio γ_{sd} is a measure of the expected traffic between network nodes that can be used to prioritize certain lightpaths.

Launch Power Optimization and Lightpath QoT Estimation

To illustrate the operation of the optimization algorithm, we select a C+L+S MBT system. Only part of the S-band is used for data transmission, namely in the range between 196.6 THz and 201.4 THz. In this case, each band accommodates 64 data channels transmitted in the 75-GHz spectrum grid and with a 64-GBd symbol rate. The signals are Nyquist-shaped with a roll-off factor of 0.15. Optical amplifiers modelled with a noise figure (NF) of 4.7, 4.3 and 6.4 dB are used for L-, C- and S-bands, respectively. These average NF values were obtained from the experimental characterization of commercially available Erbium-doped fibre amplifiers (EDFAs) for the C- and L-bands[3] and from a benchtop Thulium-doped fibre amplifier (TDFA) for the S-band[9], respectively. The optical amplifiers are assumed to perfectly compensate for the losses accumulated in every fibre span, which include insertion losses of 2 dB and 1 dB for the band demultiplexer and multiplexer at every amplification stage. The optical fibre is modelled as described in[4].

The per-channel GSNR calculated using the GNPy library[10] is used as QoT estimator. This QoT metric includes the impacts of the amplified spontaneous emission (ASE) noise introduced by optical amplifiers, the nonlinear interference (NLI) due to the nonlinear crosstalk, and the ISRS occurring along optical fibre propagation. To reduce the execution time, the per band central channel optical power and power tilt optimization[4] were pre-computed following 6 different strategies and the genetic algorithm was used to select the best strategy for each link.In this way, a single chromossome value (integer value between 0 and 5) determines the launch power profile of a given link. Although not considered in this work, the genetic algorithm could also be used to optimize the launch power profile directly. The following objective function was maximized to optimize the

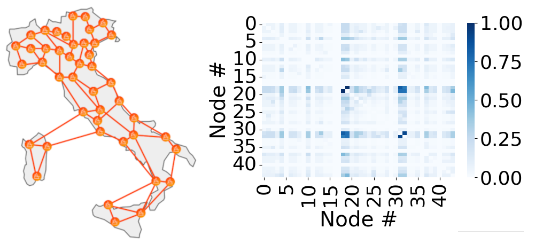

Fig. 1: TI network topology (left) and traffic matrix (right).

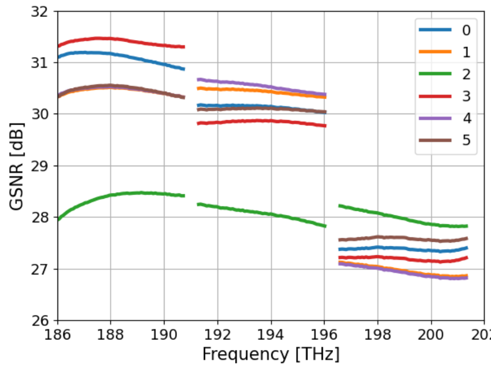

Fig. 2: Estimated GSNR for all six launch power optimization strategies.

launch power in each span of every link:

$$\begin{aligned} F = & w_0 \cdot \text{GSNR}_L + w_1 \cdot \text{GSNR}_C + \\ & + w_2 \cdot \text{GSNR}_S - w_3 \cdot \Delta\text{GSNR} - \\ & - w_4 \cdot \Delta\text{GSNR}_{C,L} - w_5 \cdot \Delta\text{GSNR}_{C,S} \end{aligned} \quad (3)$$

where GSNR_X is the worst GSNR in band X, ΔGSNR is the sum of the difference between the best and worst GSNR in each band, $\Delta\text{GSNR}_{X,Y}$ is the absolute difference between the worst GSNR in bands X and Y and w_x are weights that control the behaviour of the optimization algorithm.

The Telecom Italia (TI) reference network presented in the IDEALIST project[11] is considered in this work. The network topology and its traffic matrix are presented in Fig. 1. This network is composed of 44 nodes, 71 fibre links, and 946 lightpaths with lengths varying from 5 km to 2380 km, with an average of 798 km. Span lengths vary from 5 km to 85 km. For each band, the GSNR of a lightpath that traverses N_{span} spans is given by:

$$\text{GSNR}_{Rx} = \left[\text{OSNR}_{Tx}^{-1} + \sum_{n=1}^{N_{span}} \left[\text{GSNR}_{opt}^{L_n} \right]^{-1} \right]^{-1} \quad (4)$$

where $\text{GSNR}_{opt}^{L_n}$ is the per-band optimized GSNR of the worst channel for a span with length L_n and OSNR_{Tx} is the transmitter OSNR, set to 36 dB in agreement with Open ROADM MSA[12]. We consider signals from 200 Gb/s to 600 Gb/s in steps of 100 Gb/s[13].

Tab. 1: Weight set for each power optimization strategy.

Pow. Opt.	w_0	w_1	w_2	w_3	w_4	w_5
0	1	1	1	1	0	0
1	1	1	1	1	1.5	0
2	1	1	1	1	1.5	3
3	4	1	1	1	0	0
4	1	4	1	1	0	0
5	1	1	4	1	0	0

Tab. 2: Use of each bit rate. The uniform strategy is used as reference for the other strategies.

Rate	Link Power Selection Strategy			
[Gb/s]	Unif.	Max. Cap.	Max. 600	Max. 400
200	10.6	-23.6%	+5.7%	-4.7%
300	33.2	+2.4%	+3.6%	+5.7%
400	62.7	+0.0%	-4.1%	+19.1%
500	31.2	+3.2%	-0.3%	-33.3%
600	18.3	+4.4%	+5.5%	-16.9%

Tab. 3: Network-wide average channel capacity. The uniform strategy is used as reference for the other strategies.

Unif.	Max. Cap.	Max. 600	Max. 400
408 Gb/s	+1.1%	+0.0%	-2.7%

Tab. 4: Percentage of links using each power optimization strategy for different link power selection strategy .

Pow.	Link Power Selection Strategy			
Opt.	Unif.	Max. Cap.	Max. 600	Max. 400
0	0	23.9	23.9	15.5
1	0	12.7	7.0	9.9
2	0	0	1.4	31.0
3	0	28.1	53.5	16.9
4	100	21.1	8.4	11.2
5	0	14.1	5.6	15.5

Results

We start our analysis by computing the GSNR in all fibre spans using the different weight distributions shown in Table 1 in (3). The strategy #0 maximizes the GSNR of each band while minimizing simultaneously the per band GSNR variation. Strategies #1 and #2 additionally minimize the difference between the C- and L-bands and between the three bands, respectively. Strategies #3, #4 and #5 are similar to strategy #0, but prioritize the maximization of the QoT of specific bands. Figure 2 depicts an example of the optimized GSNR values for a 60-km span. The analysis of Fig. 2 shows that the optimization strategy #2 is the one that maximizes the QoT in S-band. This result is achieved by reducing the launch power in the L- and C-bands to reduce the ISRS power transfer from the S-band to the other ones. However, this approach leads to a degradation of the QoT in the remaining bands. Indeed, when compared to strategy #0 (the simplest one), the L- and C-band GSNR were reduced by about 2.9 and 2.2 dB, respectively, whereas the GSNR of the S-band only improved by 0.5 dB. This result suggests that this optimization approach has limited interest. Moreover, the analysis of Fig. 2 shows also that the best optimization strategies for L- and C-band are the #3 and #4, respectively, as expected.

After computing the GSNR of each link, the genetic algorithm is used to select the best power optimization strategy for each fibre link. The obtained results are summarized in Table 2, which shows the utilization of each bit rate, Table 3 which shows the network-wide average channel capacity and Table 4 that shows the percentage of links using each power optimization strategy. The uniform (Unif.) strategy, corresponding to the traditional approach that uses the same power optimization strategy in all links, is used as reference. In this case, from the 6 considered power optimization strategies, strategy #4 resulted in the highest average network-wide channel capacity. If, instead, we try to maximize the network capacity but allowing the use of different power optimization strategies in the different links (referred to as Max. Cap.), we found that it is possible to increase the average channel capacity by 1.1% and also the traffic transported using 500 Gb/s and 600 Gb/s formats. The more often used power optimization strategies in this case are #0 are #3 whereas strategy #2 is never used. We have also evaluated the impact of prioritizing the use of specific bit rates i.e., 600 Gb/s (Max. 600) and 400 Gb/s (Max. 400). Interestingly, strategy #2 becomes dominant when prioritizing 400 Gb/s channels. The availability of this format grows significantly (19%), albeit at the expense of adopting more often a strategy that reduces the GSNR in the C- and L-band, thus impacting the availability of 500 Gb/s and 600 Gb/s channels and reducing the average channel capacity by 2.7%.

Conclusions

We proposed and demonstrated a service-aware genetic algorithm that can combine different strategies to set the average launch power and tilt of each transmission band to optimize a target figure of merit. We show that the amount of traffic transported by the more spectral efficient modulation formats may be increased when compared to using the same power optimization criteria in every link. We also show that the proposed approach can be effectively used to prioritize the traffic transported in a subset of the available bit rates/modulation formats.

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