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# Hyperaccelerated Power Optimization in Multi-Band Elastic Optical Networks

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**Abstract:** We show that solving interrelated inverse differential equations can address pre-tilt power optimization, resulting in a few-second-computed optimal power for each span and boosting average channel generalized signal-to-the-noise ratio (GSNR) by up to 0.5 dB. 

## 1. Introduction, Related works, and Motivations

Recent studies have addressed the challenge of determining the optimal launch power for multi-band optical networks [1–4]. These studies have explored various objective functions, including maximizing link capacity, maximizing minimum generalized signal-to-noise ratio (GSNR), and achieving a flat GSNR profile within and across bands. However, solving this optimization problem while considering the effect of inter-channel stimulated Raman scattering (ISRS) is complex, as it is an NP-hard and non-convex problem. To tackle this challenge, researchers have proposed strategies such as the brute-force heuristic approach [1], meta-heuristic ones such as genetic algorithm [2], simulated annealing [3], and exhaustive search particle swarm optimization [4]. Some approaches consider parameters for each band, like fixed tilt and offset, to speed up the solution [1,2]. However, these methods involve extensive search spaces and may not be suitable for dynamic planning scenarios. In specific cases like C-band dense wavelength division multiplexing (DWDM) systems, maintaining a uniform power level at the end of each span has been found to enhance link capacity (or total GSNR summation) compared to optimizing GSNR flatness [5]. This approach offers rapid power optimization, improved average GSNR per span, and increased utilization of higher modulation formats across the network. Practically, the optical signal-to-noise ratio (OSNR) per span proves to be a more manageable parameter, making OSNR uniformity, rather than GSNR, crucial especially in the case of channels or lightpaths addressed to different destinations, leading to varying GSNR values. In this regard, this paper presents a methodology for determining the optimal launch power across the C+L-band, emphasizing the attainment of a consistent power level at the end of each span, roughly equivalent to a uniform OSNR, while maximizing span capacity. Our research findings demonstrate that the proposed hyperaccelerated power optimization (HPO) method consistently achieves a uniform OSNR, characterized by a maximum standard deviation of 0.15 and a flatness factor of 0.5 dB, across a range of amplification span lengths from 50 km to 100 km. Additionally, it yields an average GSNR improvement of around 0.5 dB. Furthermore, our network-wide analysis reveals that implementing this power optimization approach in a large-scale network like the US backbone can lead to approximately a 30% increase in the utilization of higher-order modulation formats.

## 2. System Model, and HPO Algorithm

In a DWDM system consisting of $N$ channels with center frequencies $f_1 < f_2 < \cdots < f_N$, the power evolution over distance for each channel can be described using a system of coupled differential equations, such as:

$$\frac{\partial P(f_j,z)}{\partial z} = \kappa P(f_j,z)\left\{\sum_{i=1}^{N}\zeta\left(\frac{f_j}{f_i}\right)C_r(f_i-f_j)P(f_i,z)-\alpha(f_j)\right\}, j\in[1,N], \tag{1}$$

where $z$ is the DWDM signal propagation distance, $\alpha(f_j)$ is the fiber attenuation at frequency $f_j$, $P(f_j,z)$ is the power of the $j^{th}$ DWDM channel at distance $z$, and $\kappa$ is set to $+1$ for a DWDM signal propagating along the $+z$ direction (forward propagating), while $\kappa=-1$ for signals propagating in the $-z$ direction (backward propagating). $\zeta(x)$ returns $x$ for $x>1$, 0 for $x=0$, and 1 for $x<1$. $C_r$ exhibits odd symmetry with respect to the frequency difference $\Delta f = f_i - f_j$. This variable characterizes the gain profile of the Raman effect within the fiber and is contingent on the fiber's physical attributes, such as the Raman gain coefficient and the effective area of the fiber. A viable approach to counteract the ISRS effect is to incorporate a tilt in the output spectrum

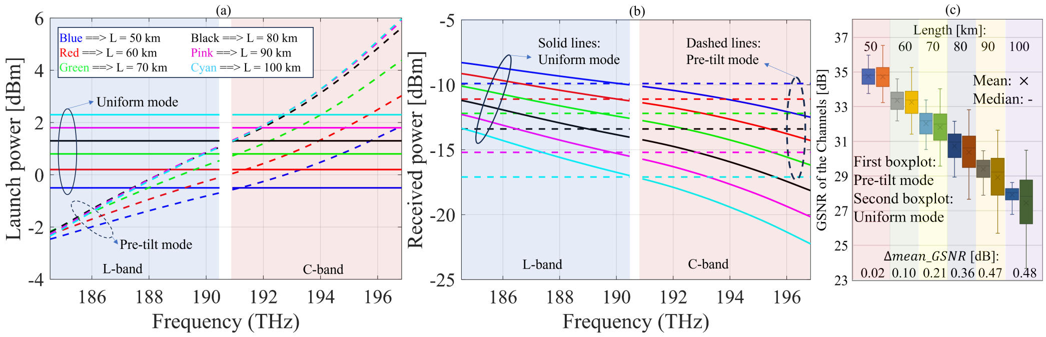


Fig. 1. (a) Launch and (b) received power profiles for the pre-tilt and uniform modes for span lengths from 50 km to 100 km. (c) GSNR boxplots of all channels for span lengths from 50 km to 100 km.

Table 1. GSNR and OSNR standard deviation (STD) and flatness factor (Δ) for all channels spanning the C+L-band in terms of the span length L. ($x$, $y$) represents pre-tilt and uniform mode, respectively.

| L [km] | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|
| $\mathrm{STD}_{\mathrm{GSNR}}$ | (0.57, 0.77) | (0.64, 0.90) | (0.78, 1.06) | (0.89, 1.24) | (0.70, 1.24) | (0.50, 1.70) |
| $\Delta GSNR_{\text{max-min}}$ [dB] | (2.21, 3.30) | (2.42, 3.84) | (2.86, 4.45) | (3.21, 5.15) | (2.55, 5.94) | (1.84, 6.81) |
| $\mathrm{STD}_{\mathrm{OSNR}}$ | (0.12, 1.19) | (0.12, 1.42) | (0.13, 1.65) | (0.13, 1.87) | (0.14, 2.11) | (0.15, 2.38) |
| $\Delta OSNR_{\text{max-min}}$ [dB] | (0.47, 4.48) | (0.47, 5.31) | (0.48, 6.13) | (0.48, 6.92) | (0.48, 7.79) | (0.48, 8.77) |

of the optical amplifiers in use. This tilt aims to ensure a nearly uniform input spectrum into the subsequent optical amplifier, thus maintaining a consistent optical OSNR after each span and at the receivers. To achieve this, we set $\kappa = -1$ and restrict the range of acceptable launch power values to ensure a practical amplifier gain and total output power while managing nonlinear Kerr effects like self-phase modulation (SPM) and cross-phase modulation (XPM). Our objective is to determine the highest possible span capacity under these conditions. We initiate our search with a starting channel power after propagation over a span of length $L_{\mathrm{span}}$ derived from the equation $P_{\mathrm{start}} = P_{\mathrm{uni,Opt}} - \alpha_{\max} L_{\mathrm{span}}$, where $P_{\mathrm{uni,Opt}}$ represents the optimal uniform launch power attainable through the local optimization global optimization (LOGO) method [6], and $\alpha_{\max}$ is the maximum attenuation across all channel frequencies.

## 3. Simulation Results, and Discussions

This paper uses identical fiber parameters as those presented in [7], and we consider a maximum launch power per channel of 6 dBm [8]. For simplicity, we only examine the scenario of a fully loaded C+L-band, assuming extended C and L spectral bands spanning 6 THz each, for a total of 12 THz, with 400 GHz guard band between them. However, our proposed HPO strategy can also be applied to other bands as well as to partially loaded scenarios. In the following simulations, we investigate two power optimization techniques: *(i)* uniform launch power mode (with $\kappa = +1$), and *(ii)* pre-tilt launch power mode, by using the proposed HPO, which assumes $\kappa = -1$ (uniform received power). The objective function is to maximize the total capacity of a span, which can be calculated based on $C = 2B_{\mathrm{ch}} \sum_{i=1}^{N} \log_2(1 + GSNR_i)$, where $GSNR_i = [OSNR_i^{-1} + SNR_{\mathrm{NLI},i}^{-1}]^{-1}$, $OSNR_i = P(f_i, 0)/P_{\mathrm{ASE},i}$, and $SNR_{\mathrm{NLI},i} = P(f_i, 0)/P_{\mathrm{NLI},i}$. $P(f_i, 0)$ is the launch power of channel $i$, $P_{\mathrm{ASE},i} = h f_i B_{\mathrm{ch}} N_{\mathrm{F}} [P(f_i, 0)/P(f_i, L_{\mathrm{span}}) - 1]$ is the power of the amplified spontaneous emission (ASE) noise of the erbium-doped fiber amplifier (EDFA), with $B_{\mathrm{ch}} = R_{\mathrm{s}}(1 + \rho)$ being the optical noise bandwidth at the receiver, and $P_{\mathrm{NLI},i}$ is the power of the nonlinear interference (NLI) noise obtained from equation (2) in [7]. The channel spacing is $\lceil B_{\mathrm{ch}}/12.5\,\mathrm{GHz} \rceil \times 12.5\,\mathrm{GHz}$=75 GHz, where $R_{\mathrm{s}}$=64 GBaud, and $\rho$=5%, so 80 + 80 = 160 channels can be accommodated in the available spectrum. The average noise figure ($N_{\mathrm{F}}$) of the amplifiers is considered to be 4.5 dB and 5 dB in the C- and L-band, respectively [2]. In Fig. 1(a) and (b), we plot the optimal launch and received power profiles for spans ranging 50-100 km with 10 km increments. Contrary to previous related works (e.g., [1]), these figures show that the power profiles (received power in the uniform mode and launch power in the pre-tilt mode) do not have a fixed tilt in each band since $\alpha$ and $C_r$ depend on the frequency. Moreover, by increasing the span length, the ISRS effect accentuates the tilt. Additionally, for spans longer than 80 km, there is no significant change in the launch power profile of the pre-tilt mode due to the maximum launch power constraint. Fig. 1(c) represents the box plots of the GSNR profile for the entire channel plan after transmission over spans with lengths ranging from 50 to 100 km for the pre-tilt and uniform launch power modes. We observe that the pre-tilt mode achieves up to 0.5 dB mean GSNR improvement per span in comparison to the uniform mode. It is important to note that the pre-tilt mode requires optical gain equalizers deployed in ROADM and inline amplifier sites. Consequently, the strategic application of

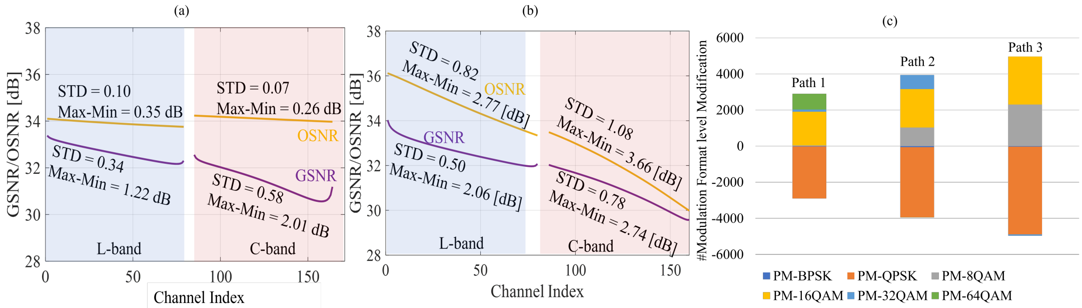


Fig. 2. GSNR and OSNR profiles throughout the C+L-band for (a) the pre-tilt mode and (b) the uniform mode. (c) Change in modulation format usage between power optimization modes from uniform to pre-tilt mode for the $k = 3$ shortest paths.

these tools within a network, considering the timing and location, holds significant importance to prove techno-economic benefit. The optimum pre-tilt launch power based on the proposed HPO method can be obtained in a few seconds (lower than 3 seconds) per span by using a 32 GB RAM Core i7 PC. As shown in Table 1 the GSNR and OSNR flatness is significantly improved which is very important for monitoring tasks. The flatness factor represents the difference between the maximum and minimum OSNR/GSNR values. However, the spans with 90 km and 100 km do not follow the lower GSNR flatness trend by increasing the span length from 50 km to 80 km as shown in Table 1 due to the maximum launch power constraint. A fixed standard deviation and OSNR flatness are approximately attained by using the pre-tilt mode in HPO. Fig. 2(a) and (b) display the GSNR and OSNR profiles of a 70 km span for pre-tilt and uniform mode, respectively. These findings become particularly valuable when considering the practical aspect, as the OSNR is a parameter that can be readily observed, measured, and incorporated into the control plane span-by-span. Therefore, the focus should be on ensuring the uniformity of OSNR, as opposed to GSNR. In order to assess the impact of HPO on network performance, we conducted numerical analyses involving a national-scale network by adopting the United States backbone topology (USB24) [9] consisting of 24 nodes and 43 links, and average lightpath distance of $3,425$ km. This topology results in a total capacity of $(3\times24\times23)/2 = 828$ connections/lightpaths, where $k = 3$ shortest paths have been considered for each source-destination pair. Therefore, the total channel-lightpath resources were calculated at $160\times828 = 132,480$. For our analysis, we considered maximum span lengths of 90 km. The evaluation of the network performance involved the assessment of the required GSNR for six commonly used modulation formats in commercial embedded transceivers, including polarization multiplexing (PM){-BPSK, -QPSK, -8QAM, -16QAM, -32QAM, and -64QAM}, aiming to achieve a soft decision pre-forward error correction bit error rate equal to $1.5\times10^{-2}$. Our results reveal that the introduction of the pre-tilt mode leads to an increase in the utilization of higher-order modulation formats, indicating an improvement in spectrum efficiency. Fig.2(c) shows the changes in modulation format level usage. We observe that the obtained average GSNR improvement of approximately 0.5 dB per span in Fig.1(c) translates to the possibility of upgrading about 30% of all channel-lightpath resources in all paths that use PM-BPSK/QPSK in the uniform mode to PM-16QAM, -32QAM, or -64QAM modulation formats in the pre-tilt mode.

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