Launch Power Optimisation for Ultrawideband Transmission: Achievable Throughput Improvement under Practical Constraints

Anastasiia Vasylchenkova*, Henrique Buglia, Eric Sillekens, Robert I. Killey and Polina Bayvel

Optical Networks Group, Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, UK *a.vasylchenkova@ucl.ac.uk

Abstract *We report the penalty in SNR resulted from deviation of the input power profile from capacity-maximising one in ultrawideband transmission. We identify this penalty for a fixed per-channel power uncertainty and demonstrate the upper bound for achievable SNR gain for a piecewise-constant launch power per sub-band.*

Introduction: role of the launch power optimisation in ultrawideband communication

Joint efforts of the research community during the last decades have allowed the gap to the Shannon limit to be reduced by advanced DSP, modulation and amplifier designs. One of the promising paths for the increase in the achievable data rates is to expand the optical bandwidth within single-mode fibre with the potential to allow for almost linear scaling of the total throughput[1],[2].

In ultrawideband (UWB) systems, the total throughput is limited by the noise arising from amplifiers, transceivers (TRx) and nonlinear effects, namely Kerr nonlinearity and stimulated Raman scattering (SRS)[3]–[6]. The latter becomes relevant as the total signal bandwidth extends beyond the C-band, requiring intense computational efforts for system design and optimisation. This is because, in the presence of SRS, no fully analytical model is available for the evolution of UWB signal in the optical fibre[1],[5] and additionally, optimising the launch power (LP) is a multidimensional non-convex optimisation problem[6],[7].

The frequency-dependent channel parameters combined with the SRS power leakage from the shorter to the longer wavelengths leads to additional noise variations between subchannels and, as result, in the SNR spectral distribution[1],[5]. This uneven noise distribution is often compensated by optimum LP profile, which is shaped to mitigate the anticipated quality of transmission (QoT) degradation[2],[5],[6],[8].

However, LP optimisation is often based on several idealistic assumptions. First, one relies on the exact match between the optimal LP and achieved at Tx. However, in practical systems, this power can deviate noticeably from the optimum one, given equipment constraints or sub-optimal LP estimations. Secondly, the LP profile is assumed to be reproduced at the beginning of each span, through the use of ideal gain shaping filters or ideal Raman amplification, which is also not the case in practical installed systems. Furthermore, determining the optimal LP requires computationally demanding optimisation algorithms, like evolutionary algorithms, particle swarm optimization or neural network[6], and usually one relies on sub-optimal strategies[9],[10] to speed up computation.

Therefore, it is not sufficient to calculate the optimal LP, as is commonly carried out[5],[6]; the tolerance to deviations from the optimal LP must also be studied. This is one of the reasons for the simulation-experiment discrepancy, observed by many groups[1],[2],[5],[8]. For field applications, it is not reasonable to use costly wavelength selective switches based on reprogrammable liquid crystal cards[1],[11] to achieve the optimum LP profile, instead, spectrally uniform LP profile can be assigned per sub-bands using attenuators[2],[5].

In this work, we studied the penalty in performance resulting from deviations from the capacity-maximising LP, which we refer as optimum LP, for two practical cases: inaccurate per-channel LP assignment with a fixed uncertainty, and piecewise-constant LP profiles for different sub-bands. We identify an average performance penalty of 1 dB for a maximum per-channel deviation window of 0.5 dB, and uncompensatable 0.06 dB SNR penalty by using a piecewise-constant LP, i.e. not featuring the optimum LP tilt to compensate for SRS effect and the spectrally uneven fibre noise characteristics.

Methodology: QoT model, optimisation and constraints within it

Similarly to the works in[4],[6],[9],[12], we used closed-form semi-analytical models to estimate the NLI noise and the following QoT metrics: SNR

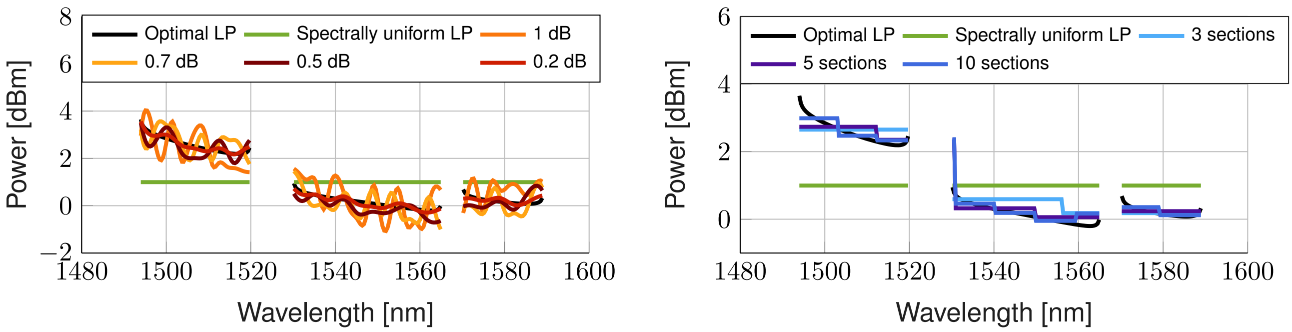

Fig. 1: The LP profile for (a) a per-channel deviation from the optimum LP within a given margin, and (b) per sub-band deviation, i.e, a fixed number of uniform LP segments.

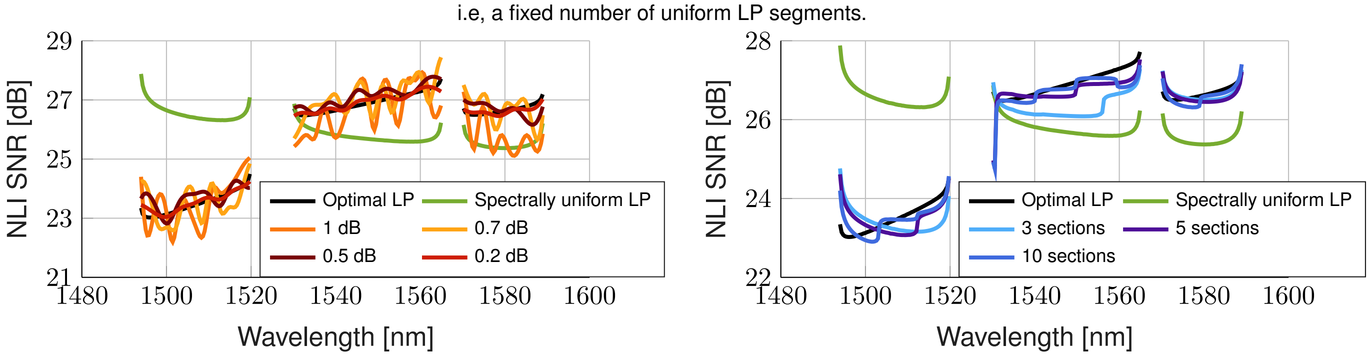

Fig. 2: The spectral distribution of the resulting NLI contribution to the total SNR for the LP profiles shown in Fig. 1 (a) and (b).

and mutual information. Gaussian noise (GN) models are now widely used and have proved to be an effective and flexible tool for the design and optimisation of UWB transmission systems, taking into account arbitrary LP profiles (via numerical fitting)[4]. Among the recent results on the application of the SRS GN model for the UWB studies, the work in[9] demonstrates LP optimisation algorithm based on a redefinition of the optimisation objective to obtain a convex function improving the speed of computation. In this paper, we studied the impact of the deviation of practical and achievable LP profiles, representing limitations of installed equipment, from the one which is optimal to maximise the achievable total MI. This later is calculated as in[9].

To study the penalties in performance achieved by LP deviations, we considered two scenarios. In the first, we expect that the LP is uncontrollably assigned with a given uncertainty window, so the actual input powers may deviate from the capacity-maximising one. The typical range for the LP profile variation is given in Fig. 1(a). The width of the uncertainty window was varied between 0.2 dB to 1 dB, representing the range from the reasonable accuracy for a calibrated setup to the accuracy of a LP assignment without calibration. We computed the worst-case per-channel NLI SNR among the LP profiles within the given uncertainty window to characterise the penalty.

In the second scenario, instead of assuming the LP profile deviation being assigned per subchannel, as a result of the gain shaping filters or wavelength selective switch technologies, we considered piecewise-constant LP spectral profiles. We compare the capacity-maximising LP with a piecewise-constant fit of it, achieved by least-squared error method. The number of constant-power sections was varied, mimicking the number of the power attenuators in the installed systems which are used to set the desired LP profile. This allows the impact of the number of attenuators to be quantified[1] for a given SNR penalty. The typical LP distributions for different numbers of sections/attenuators are presented in Fig. 1(b). For both scenarios, the capacity-maximising LP is calculated as in[9] for the range of 6-18 spans.

Results: penalty from the LP deviation and a reasonable number of attenuators

The transmission setup consists of 80 km SMF, where each span is amplified with EDFA and TDFA with the following noise figures: NF_S=7 dB, NF_C=4 dB and NF_L=6 dB[2], respectively for the S, C and L band. The WDM signal consists of 240 Nyquist-spaced channels at the symbol rate of 50 GBd covering 12 THz total bandwidth; the channels are modulated with a regular 256-QAM constellation. The TRx SNR is considered to be spectrally uniform at the value SNR_{TRx}=23 dB.

In Fig. 2, we compute the NLI SNR for the launch power profiles shown in Fig. 1. For the first scenario where a per channel deviation from the optimum LP is allowed, Fig. 2(a) shows that the NLI noise massively increases in the S-band in exchange of a reduction in the C and L band; despite that, the total system throughput decreases because of the utilisation of non-optimal LP profiles, which do not optimally compensate for the nonlinear interaction between SRS-caused power transfer and wavelength-dependent channel parameters. The same trend is observed in the second scenario where a piecewise-constant spectral LP profile was used per sub-band, as shown in Fig. 2(b).

For the first scenario, it is shown that the per-channel NLI SNR can deviate from the optimal by up to 1 dB even for low uncertainty values in the range of 0.2-0.5 dB. In the second scenario, where a piecewise-constant spectral profile was used a lower penalty in the NLI SNR is observed. Furthermore, for both scenarios, it is shown that ingenious deviations in the LP profile using the current installed available resources, demonstrate better compensation for the fibre impairments when compared to the case of using a spectrally uniform LP.

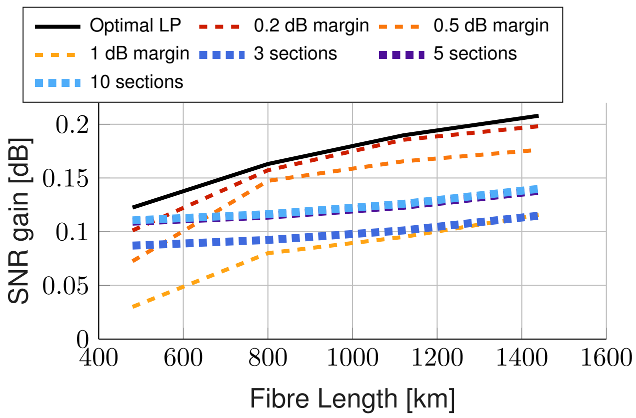

Fig. 3: The total SNR gain for the per-channel LP deviation with a fixed uncertainty window (dashed), and for the piecewise-constant LP profile per sub-band (dotted) as a function of the fibre length.

Fig. 3 shows the gains in the total SNR, obtained by using the LP profiles shown in Fig. 1. The gains are relative to the spectrally uniform LP profile also shown in this same figure. As mentioned, both optimal and spectrally uniform LP were obtained by maximising the total channel capacity for each distance. Note that, these results effectively represent the benefits of using other non-optimum LP profiles instead of a spectrally uniform one.

As is widely reported, because of the TRx noise, non-uniform LP profiles provide more QoT improvement for longer link lengths[6]. We identified that the UWB transmission is sufficiently tolerant to the LP deviations for a calibrated setup, i.e., for uncertainty levels in the range of 0.2-0.5 dB, see dashed lines in Fig. 3. We also observed a larger drop in the SNR gain for large values of uncertainty. For an uncertainty window of 1 dB, the SNR gain is diminished; for this large uncertainty, the SNR is reduced even below that for piecewise-constant LP profile with 3 sections, i.e. when S, C and L bands have uniform power for the entire band.

For the second scenario, shown in dotted lines in Fig. 3, we also varied the number of sections in the piecewise-constant LP. By limiting the number of sections, i.e. the number of power attenuators, the achievable total SNR gain is reduced, insignificantly at shorter distances, but reaching 0.1 dB for 3 sections for larger distances. When increasing the number of sections, we observed the gap between the SNR obtained by using the optimum LP and that achieved with the piecewise-constant LP, with the same dependency on the transmission distance. We attribute this gap mainly to the non-optimum compensation of optical fibre impairments such as SRS effect, because the optimum power spectral distribution cannot be matched with constant-power sections when the number of sections is significantly smaller than the number of channels.

Conclusions

In this work, we identified the tolerance of the UWB systems to the mismatch between optimal and practical LPs. We found the reasonable upper bound for LP uncertainty of 0.5 dB per-subchannel to maintain the capacity penalty within a few percent. This trend was observed for a wide range of transmission distances. We also found the fundamental gap between the capacity-maximising SNR of the UWB system and that achievable using a limited number of power attenuators implementing the piecewise-constant LP profile. While the number of constant sections is significantly lower than the number of channels (the equivalent of 5-10 power attenuators), the total capacity is upper-limited. It allowed us to conclude that for the UWB transmission systems limited by SRS[6], the match between the LP tilt and the SRS-caused power transfer is critical for maximising the system throughput.

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References

[1] T. Hoshida *et al.*, "Ultrawideband systems and networks: Beyond $C+L$ -Band", *Proceedings of the IEEE*, 2022.

[2] L. Galdino *et al.*, "Study on the impact of nonlinearity and noise on the performance of high-capacity broadband hybrid Raman-EDFA amplified system", *Journal of Lightwave Technology*, vol. 37, no. 21, pp. 5507–5515, 2019.

[3] D. Christodoulides and R. Jander, "Evolution of stimulated Raman crosstalk in wavelength division multiplexed systems", *IEEE Photonics Technology Letters*, vol. 8, no. 12, pp. 1722–1724, 1996. DOI: 10.1109/68.544731.

[4] D. Semrau *et al.*, "The benefits of using the S-band in optical fiber communications and how to get there", in *IEEE Photonics Conference (IPC)*, 2020.

[5] A. Ferrari *et al.*, "Assessment on the achievable throughput of multi-band ITU-T G.652.D fiber transmission systems", *Journal of Lightwave Technology*, vol. 38, no. 16, pp. 4279–4291, 2020. DOI: 10.1109/JLT.2020.2989620.

[6] H. Buglia *et al.*, "On the impact of launch power optimization and transceiver noise on the performance of ultra-wideband transmission systems [Invited]", *J. Opt. Commun. Netw.*, vol. 14, no. 5, B11–B21, May 2022.

[7] I. Roberts, J. M. Kahn, J. Harley, and D. W. Boertjes, "Channel power optimization of wdm systems following gaussian noise nonlinearity model in presence of stimulated raman scattering", *Journal of Lightwave Technology*, vol. 35, no. 23, pp. 5237–5249, 2017. DOI: 10.1109/JLT.2017.2771719.

[8] F. Hamaoka *et al.*, "Ultra-wideband WDM transmission in S-, C-, and L-bands using signal power optimization scheme", *Journal of Lightwave Technology*, vol. 37, no. 8, pp. 1764–1771, 2019. DOI: 10.1109/JLT.2019.2894827.

[9] D. Semrau, "Modeling of fiber nonlinearity in wideband transmission", in *Optical Fiber Communication Conference (OFC)*, 2022.

[10] B. Correia, R. Sadeghi, E. Virgillito, *et al.*, "Optical power control strategies for optimized c+l+s-bands network performance", in *2021 Optical Fiber Communications Conference and Exhibition (OFC)*, 2021, pp. 1–3.

[11] N. K. Fontaine *et al.*, "36-THz bandwidth wavelength selective switch", in *European Conference on Optical Communication (ECOC)*, 2021.

[12] D. Semrau *et al.*, "Modulation format dependent, closed-form formula for estimating nonlinear interference in S+C+L band systems", in *European Conference on Optical Communication (ECOC)*, 2019. DOI: 10.1049/cp.2019.0892.