Analytical modelling of system impairments in ultrawideband transmission context

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Abstract: Analytical models for the estimation of nonlinearity-caused impairments enable effective maximisation of total data throughput. We demonstrate a 3 times improvement in per-channel mutual information when data is redistributed from the L-band to the S-band.

1. Introduction and motivation

For optical fibre transmission systems, a larger data rate can be reached either by the increase of the quality of transmission (namely, the resulting signal-to-noise ratio), or by the expansion of the signal bandwidth. The latter attracts considerable researchers' attention as it potentially allows linear scaling for the achievable data rate [1]. In this approach, referred to as ultrawideband (UWB), the data carriers occupy wavelength ranges beyond the conventional (C) band, for example, in the neighbouring long-wavelength band (L-band) and in the short-wavelength band (S-band). However, the study and design of UWB transmission systems are challenging because of frequency-dependent channel properties and stimulated Raman scattering (SRS) [2].

In the UWB case, the resulting signal-to-noise ratio (SNR) is distributed unevenly across the spectral window. Up to several dB drop is observed for per-channel SNR (and therefore in the achievable information rate) if comparing channels in the S-band and C-band [3]. The SNR difference and the degradation of the transmission quality are usually compensated by the launch power pre-emphasis [4, 5] and constellation shaping techniques. These methods are proven to be effective for mitigating the SRS-caused power transfer. However, the S-band is less favoured to be used for data transmission because of its low performance [3, 6]. Therefore its usage is limited and requires additional adjustment (for example, lowering the constellation order when modulating channels within this band) [3]. This low quality of the transmission quality in the S-band is caused by SRS, leaking signal power out of the band, and worse noise performance of the amplifiers in this band, still being on research stage, while the amplifiers for the C-band and L-band are commercially available [7].

In this work, we demonstrate that the S-band has more potential for transmission than community consensus claims, and conclude that the worse performance of the channels within the band is an artefact of the optimisation task setting. Conventionally, the analysis of the UWB transmission systems is carried out from the perspective of maximising the total data throughput [4, 6]. However, in practice, different wavelengths are attributed to different users. So, it is highly undesirable to have bouncing transmission quality for different subcarriers. To compensate for this disbalance, the communication system design should be based not only on the maximisation of any accumulated metric of the AIR, but also on the levelling of this metric' spectral distribution.

The high data throughput with spectrally uniform transmission quality can be achieved by artificially prioritising the S-band subcarriers, i.e., increasing their SNR by adding more launch power and applying constellation shaping. In this way, the S-band can be used more effectively for the cost of the SNR penalty in the L-band. By studying this gain-penalty balance, we demonstrate 3 times increase in per-channel mutual information (MI) when the SNR in the S-band is manually increased by means of lowering SNR in the L-band.

2. Methodology and results

In this study, we simultaneously target the maximal total throughput of the transmission line and the flattening of the throughput's spectral distribution. These two targets are contradicting and need to be balanced within a single objective function f, taking individual channels' mutual information (MI) as an input: $f = \langle MI \rangle - 0.5\sigma_{MI}$, where $\langle\cdot\rangle$ stands for averaging over all channels, and σ for standard deviation. It reflects the trade-off between maximisation and flattening. Apart from the objective function expression, this optimisation task includes objective function's evaluator. The main requirement for the evaluator is its reliability and speed of operation. These are primordial as the optimisation task, i.e, the estimation of the optimal launch power profiles and constellations

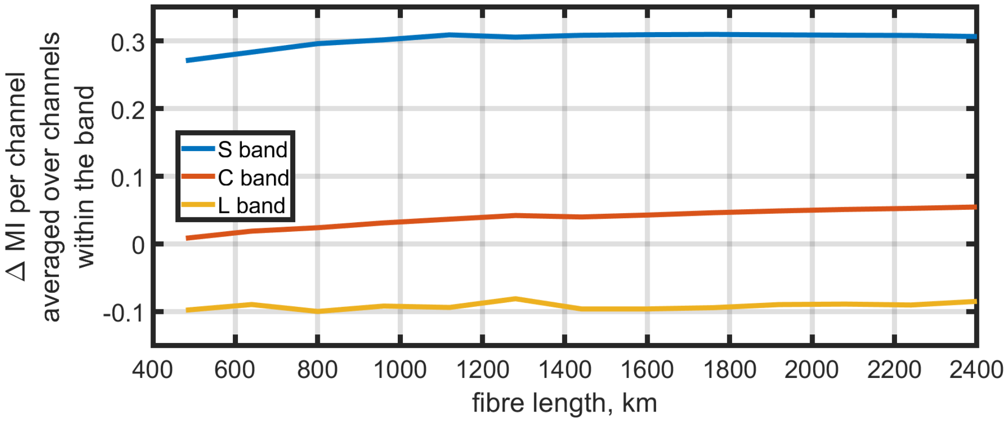

Fig. 1. Difference in MI achieved through maximising the objective function f (balancing flatness and maximisation) and through maximising total throughput by constellation shaping.

are subject to the transmission setup, which involves many parameters, especially for the UWB cases where many channels are modulated.

We apply the SRS GN model in closed-form for the per-channel SNR estimation [2], which is demonstrated to be well suitable for modelling UWB transmission systems [3–5]. Fortunately, the SRS GN model allows accounting for the arbitrary launch power profiles and constellation shapes [1,3,5]. Using the SRS GN model, we optimise the launch power and the constellation shape to increase transmission throughput and make the SNR profile less varying across the transmission window.

We study the point-to-point transmission based on SMF line with wavelength-dependent channel parameters' S+C+L bands. This line consists of identical 80-km spans with the amplifiers in the end. The signal is fully-loaded and consists of 400 WDM channels, covering 20 THz total bandwidth. The amplifiers are assumed to ideally reconstruct the launch power profile from the transmitter. We use realistic amplifiers' noise characteristics to account for the worse performance of amplifiers in the S-band [1, 7].

In Fig. 1, we quantify mutual information difference ΔMI between two scenarios - when a constellation shaping is applied for spectrally uniform launch power, and when the pre-emphasis is applied together with the constellation shaping, favouring the S-band channels by insreasing their per-channel SNR. The objective function used in the optimisation leads to the flattening of the SNR profile. This difference is positive for the S-band, almost zeros for C-band, and negative for the L-band. Qualitatively, we can say that the gain in MI achieved in the S-band, goes for the cost of MI penalty in the L-band.

This trade-off is observed across all studied link lengths (up to 30 spans). We also see a slight trend of increase of ΔMI in the S-band: for longer links, the advantage of the S-band channels is larger than for shorter links.

3. Conclusions

The S-band channels, despite SRS-caused power leakage and more noisy amplifiers, have more potential as a data carrier than we may expect. The low SNR values are a consequence of the target towards data rate maximisation and can be mitigated by redefining the optimisation objective. If aiming for flat transmission quality profile, tilting the launch power profile, the MI gain in the S-band is 3 times larger than the counterpart penalty in MI for the L-band channels.

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References

1. L. Galdino *et al.*, "Study on the impact of nonlinearity and noise on the performance of high-capacity broadband hybrid Raman-EDFA amplified system," *IEEE JLT*, vol. 37, no. 21, 2019.
2. D. Semrau *et al.*, "The Gaussian noise model in the presence of inter-channel stimulated Raman scattering," *IEEE JLT*, vol. 36, no. 14, 2018.
3. D. Semrau *et al.*, "The benefits of using the S-band in optical fiber communications and how to get there," *2020 IEEE Photonics Conference* .
4. H. Buglia *et al.*, "Challenges in Extending Optical Fibre Transmission Bandwidth Beyond C+L Band and How to Get There," *ONDM 2021*.
5. H. Buglia *et al.*, "On the impact of launch power optimization and transceiver noise on the performance of ultra-wideband transmission systems," *JOCN*, vol. 14, no. 5, 2022.

6. B. Puttnam *et al.*, “0.61 Pb/s S, C, and L-Band Transmission in a 125um Diameter 4-Core Fiber Using a Single Wideband Comb Source,” *IEEE JLT*, vol. 39, no. 4, 2021.
7. L. Rapp and M. Eiselt, “Optical Amplifiers for Wideband Optical Transmission Systems,” *OFC 2021*, Th4C.1.