Mutual Shaping and Pre-emphasis Gain Magnification in the Throughput Maximisation for Ultrawideband Transmission

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Abstract: We demonstrate that in ultrawideband transmisison over 20THz, the added value of joint probabilistic shaping and power pre-emphasis is a factor of two higher than their individual contributions and gives a 20% increase in total mutual information.

1. Introduction

Ultrawideband (UWB) optical fibre transmission, utilising the full low-loss spectral window of the single mode fibre, is a promising direction for towards higher throughput in both installed and future optical fibre infrastructure. Using the conventional (C) together with the neighbouring short- (S) and long-wavelength (L) bands allows for the transmission bandwidth of up to 20 THz, comparing to around 5 THz for C band only [1,2], albeit with higher losses in the S- and L-bands.

In the UWB transmission, the magnitude and impact of noise varies across the transmission bandwidth because of the wavelength-dependence of fibre properties, specific amplification scheme design and, most of all, because of the presence of inter-channel stimulated Raman scattering (ISRS) [3,4]. The launch power spectral profile shaping and constellation shaping are effective and widely applied techniques for the compensation of the varying noise influence and to maximise throughput [5–7]. However, the throughput maximisation is a multi-input optimisation task, so extensive numerical simulations of the propagation of individual modulated waveforms (such as the split-step method) is not practical. For such optimisation, it is sufficient to have the quality of transmission (QoT) metrics as a cost function, averaged over the input waveforms. Thus, analytical and integral models are faster for the estimation of the function for the optimisation. Gaussian noise (GN) model [8] and its generalisation involving ISRS impact [4] allow to estimate the signal-to-noise ratio (SNR) of the received signal. These models use the first-order perturbation with respect to nonlinearity, and assume the Gaussian noise nature of nonlinearity-caused distortion, allowing to to estimate the nonlinearity contribution to the total SNR.

The ISRS GN model exists in integrable form [4] and closed form [9], where the latter significantly reduces the computation complexity by setting more assumptions on the signal properties. Fortunately, even the closed-form model is sufficiently flexible to account for the arbitrary launch power and gain-loss profiles determined by the amplification scheme. This is important because the current state-of-the-art UWB amplifiers cannot provide similar noise characteristics for different transmission bands [2,10,11].Typically one can maximise the achievable throughput by using different modulation formats in different bands, exploiting the least distorted channels.

In this work, we generalise this approach and perform both *channel-wise* power pre-emphasis and constellation shaping, instead of doing this in a band-wise manner, as for example, in [2]. Combining these two techniques, the goal is to maximise the throughput, in terms of total mutual information (MI), for a range of transmission distances. In addition to the increase in the total MI achieved, the added value from the joint pre-emphasis and shaping when applied simultaneously, is higher than the individual gains from these two techniques applied independently. This gives a greater dynamic range in the input power shaping to maximise improvement by means of probabilistic shaping (and vice versa) due to interplay between power transfer and signal-noise interaction. We show that this approach results in up to 20% total MI gain achieved through maximisation, for a realistic UWB transmission system beyond 1000 km, 20 THz bandwidth and approximately 180 Tbit/s total transmitted data rate.

2. Methodology to maximise system throughput

The starting point is the ISRS GN model for the estimation of the system output SNR, given the launch power profile and the constellation points' probability. We assume the amplification design based on combined EDFA and TDFA from [2], covering the C-, S- and L- bands separated by guard bands. Therefore, it is natural to consider system parameters in each band (i.e. in each group of channels separated by the amplification gaps) independently. The optimisation strategy is shown schematically in fig. 1, and can be described as follows.

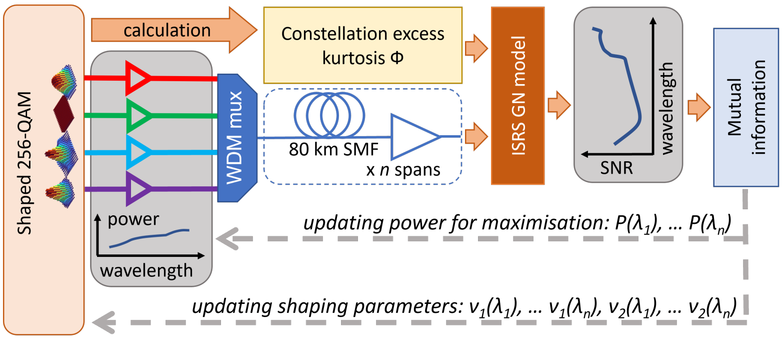

Fig. 1. Algorithm for data throughput maximisation via channel-wise power and constellation probability using ISRS GN model as a QoT estimator.

The launch power in each band is represented by 4th degree polynomial. This allows keeping the number of parameters relatively low, while providing highly nonlinear and spread profile. For the channel-wise probabilistic shaping, we need to vary the constellation points' probabilities. Setting the probability p for point x_i as:

$$p(x_i) = \frac{\exp(-\nu_1|x_i|^2 - \nu_2|x_i|^4)}{\sum_j p(x_j)}, \tag{1}$$

it is sufficient to specify only two parameters $\nu_{1,2}$ to obtain the probability distribution across the constellation. Similarly to the launch power, the probability parameters $\nu_{1,2}$ are given by 4th degree polynomials in each band separately [6].

Overall, such parametrisation leads to 36 coefficients, resulting in a 36-parameters optimisation task. To perform the numerical optimisation, we applied the trust-region algorithm, known for its reliable performance for nonlinear multi-parameters tasks [12].

In the GN model paradigm, the total SNR of the received signal includes contributions from transceiver noise, amplifier spontaneous emission noise and nonlinear interference, also assumed to be a Gaussian noise source [4,8].

The inter-channel interference is accounted for in the ISRS GN model by including the ISRS-caused power transfer for the estimation of nonlinear effects [4]. The signal is commonly assumed to be Gaussian modulated, which provides inaccurate results, especially for higher-order formats [2, 13]. To account for the constellation shape (regardless of whether it is a conventional constellation, geometrically or probabilistically shaped), one needs to involve a measure of the deviation of a given constellation from a Gaussian one. The excess kurtosis parameter $\Phi = \mathbb{E}[|x|^4]/(\mathbb{E}[|x|^2])^2 - 2$ is a standardized fourth-order moment of the points distribution [2, 13].

Because $\Phi < 0$, taking into account the constellation shape, provides a more accurate and more *optimistic* estimation of the noise impact. As a statistical parameter, kurtosis is defined to be zero for Gaussian distribution, and negative for tail-less distributions, so for the constellation, located compactly within the complex plane.

Cross-phase modulation contribution to the total SNR is derived for a pair of interfering channels (ith channel under the influence of kth channel). The correction, coming from the non-Gaussian modulation, is given as follows:

$$\begin{aligned}\mathrm{SNR}^{-1}_{\mathrm{NLI},ik} = \frac{32}{47}\frac{\gamma^2 P_k^2}{B_k}\Bigg[\frac{n+5/6\Phi_i}{\phi_{ik}\bar{\alpha}_k(2\alpha_k+\bar{\alpha}_k)}\left(\frac{T_k-\alpha_k^2}{\alpha_k}\operatorname{atan}\left(\frac{\phi_{ik}B_i}{\alpha_k}\right)+\frac{A_k^2-T_k}{A_k}\operatorname{atan}\left(\frac{\phi_{ik}B_k}{A_k}\right)\right)+ \\ +\frac{5}{3}\frac{\Phi_i \pi n T_k}{|\phi|B_k^2\alpha_k^2A_k^2}\left(2B_k+(2\Delta f_{ik}-B_k)\log\left(\frac{2\Delta f_{ik}-B_k}{2\Delta f_{ik}+B_k}\right)\right)\Bigg].\end{aligned} \tag{2}$$

In the expression above some parameters are taken from the transmission design (such as Δf and B related to channels spacing, or ϕ accounting for the fibre link properties), some are computed numerically for a given gain-loss and launch power profiles. The varied parameters - launch power and constellation kurtosis - are denoted as P and Φ, respectively, however, the input power distribution also influences the gain-loss properties α, A and T [2, 11]. Reader can refer to [9] for notations and explicit expressions.

3. Achievable mutual information results

We applied the ISRS GN model to study the performance of the UWB transmission system with 401 50-GBd WDM channels, spaced by 50.005 GHz, with approximately 20 THz total transmission bandwidth. The signal was modulated using a geometrically shaped (as by eq. (1)) 256 QAM constellation. The modulated signal is sent over the standard single-mode fibre with dispersion parameter $D = 18$ ps/km/nm, dispersion slope $S = 0.067$ ps/km/nm^2, and nonlinearity $\gamma = 1.2$ 1/W/km. The fibre attenuation is considered as a wavelength-dependent parameter and included in the numerical solution of the Raman equations. We assume a combined EDFA/TDFA amplification scheme with 80-km spans between amplifiers. The amplifies noise figures are as $\mathrm{NF}_S = 7$ dB, $\mathrm{NF}_C = 4$ dB, and $\mathrm{NF}_L = 6$ dB, as in [2]. The number of spans n was varied from $n = 6$ to $n = 16$.

Combining the GN model with the maximisation throughput task, we found the achievable MI at different link lengths for various optimisation scenario, see fig. 2(a). It can be seen that the combined gain achieved by probabilistic shaping and by pre-emphasis independently is lower than the total gain from the joint optimisation. To demonstrate it more clearly, the relative gain with respect to the unshaped constant power case, was plotted in fig. 2(b) where it can be seen that individual gains are lower than 10% and 5%, correspondingly, but the joint optimisation leads to 20% improvement in terms of mutual information.

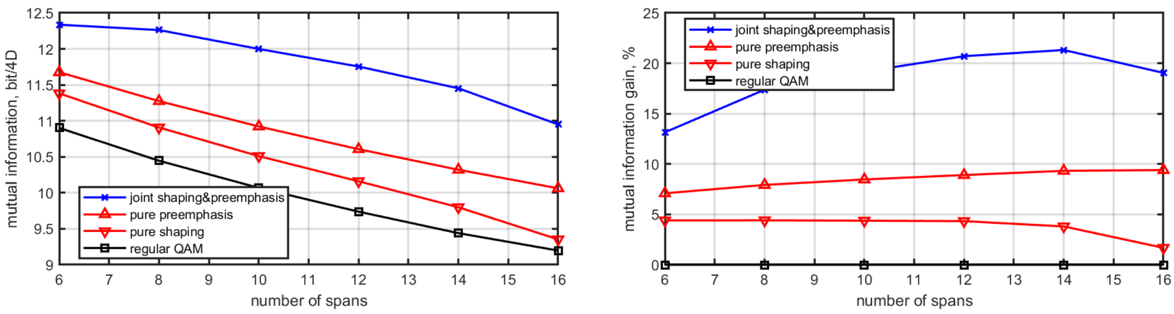

Fig. 2. (a) Achievable MI for different throughput maximisation strategies (probabilistic shaping, pre-emphasis or both) and without optimisation; (b) Relative MI gain achieved by different strategies, both as a function of the number of fibre spans.

The total gain is significantly below the joint optimisation one, so the maximisation of the achievable throughput by means of shaping and pre-emphasis provides greater flexibility. The highest gain was obtained at $n = 14$, corresponding to 1120 km link length. We also note that this mutual magnification effect is clearly observed across the studied range of n. For longer distances, the coherent accumulation of a nonlinear distortion leads to the reduced impact of shaping to the MI improvement, leading to a reduction in the MI gain for higher than $n = 16$ spans.

4. Conclusions

We show that in UWB transmission, maximising throughput via joint probabilistic constellation shaping and launch power pre-emphasis, providing up to 20% increase in the achievable total MI, almost twice comparing to the independent optimisations. Having this knowledge, we can design UWB systems with uneven distribution of the embedded information across the available channels, reaching a higher total data throughput.

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