Ultra-Wideband Nonlinearity Compensation Performance in the Presence of PMD

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Abstract *We investigate the performance of multi-channel digital backpropagation for 1 THz bandwidth optical fibre transmission in the presence of polarisation-mode dispersion. We show that the average SNR performance rapidly saturates as a function of the compensation bandwidth.*

Introduction

The potential of future optical fibre systems to increase their transmission rates ultimately relies on the ability to compensate for nonlinear fibre propagation effects over ever larger bandwidths. One of the most studied receiver-side nonlinear compensation (NLC) schemes is known as digital backpropagation (DBP)[1], and its effectiveness is primarily impaired by the fibre polarisation-mode dispersion (PMD)[2]. Previous works[1–5] have analysed the impact of PMD on the performance of both single-channel and multi-channel DBP, producing in some cases either an analytical[2] or heuristic[5] model. However little validation of such models has been presented so far, particularly under very large optical bandwidth transmission scenarios. Numerical simulations appear to be the only tool available to test multi-channel DBP gains in the presence of PMD, when vast compensation bandwidths are considered. In[2], a numerical study on a 500 GHz optical bandwidth corroborated the proposed model. However, both the model and the numerical results only refer to the full-field DBP case. Therefore the role of PMD on the relationship between DBP compensation bandwidth and performance remains to be understood. In this work, we present a numerical study on the effectiveness of multi-channel DBP over a 1 THz bandwidth optical fibre transmission affected by PMD.

Background

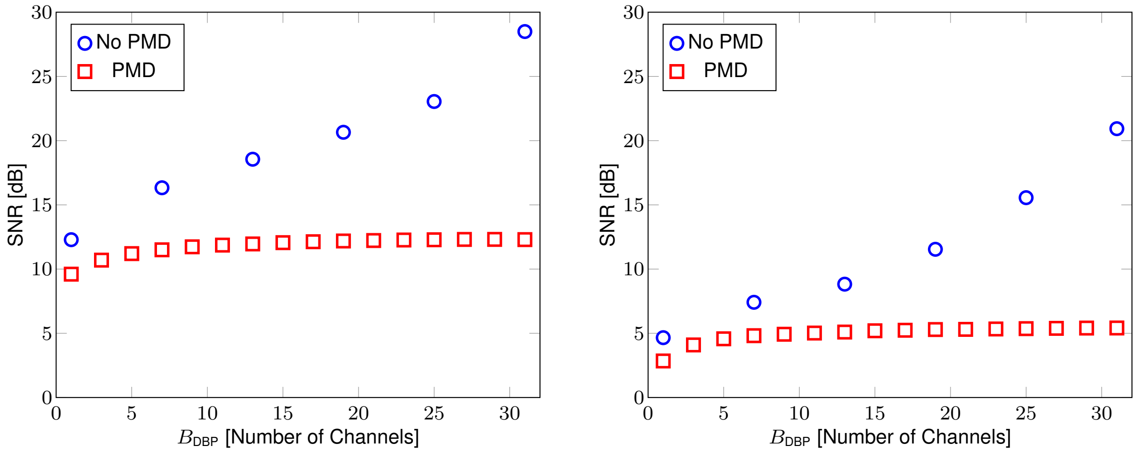
The detrimental impact of PMD on the effectiveness of DBP to compensate nonlinear distortions can be explained resorting to a frequency domain study of the polarisation evolution in optical fibres[2]. Using this approach, the linear effect of PMD can be thought as a polarisation state drift among different frequency components of the propagating signal. The magnitude of the four-wave mixing (FWM) products generated by these frequency components depends on their relative positions on the Poincaré sphere. These positions are unknown in the typical implementation of DBP, which is only aware of the polarisation states at the receiver. In the backward propagation, this mismatch generates a different FWM product from the one produced in the forward propagation, thus decreasing the effectiveness of the NLC algorithm. This can be reflected in the signal-to-noise ratio (SNR) expression after DBP as

$$\text{SNR} \approx \frac{P}{N_\text{s} P_\text{ASE} + N_\text{s}[\eta - \alpha_\text{PMD}(B_\text{DBP}, \bar{\tau})\eta_\text{DBP}]P^3} \quad (1)$$

where P is the transmitted power per channel, N_s is the number of fibre spans, P_ASE denotes the amplified spontaneous emission (ASE) noise, η is the nonlinear parameter accounting for the fibre propagation nonlinearity as in[6], and η_DBP is a parameter accounting for the nonlinearity compensated by DBP in the absence of PMD. Notice that in (1), coherent accumulation of nonlinearity in assumed[6], and the signal-ASE term has been neglected for simplicity. α_PMD is a coefficient accounting for the DBP loss of efficacy in the presence of PMD, and thus, taking values in $[0, 1]$. It is also reasonable to assume that α_PMD should, in general, depend on both the backpropagation bandwidth B_DBP and the average differential group delay (DGD) of the link $\bar{\tau}$. From[2,5], α_PMD appears to be a monotonically decreasing function of $\bar{\tau}$. Specifically, in[5], an inverse relationship between $\bar{\tau}$ and the maximum B_DBP over which α_PMD stays approximately equal to 1, was heuristically assumed. However, since this approach seems to be reasonable only for first order PMD effects, a more accurate characterisation is required to either confirm or disproof this behaviour. In the following, we will use numerical results on the SNR in (1) to give a qualitative idea on how α_PMD should depend on $\bar{\tau}$ and B_DBP.

Numerical setup

Split-step Fourier (SSF) simulations of large bandwidth optical fibre systems can be performed using a non-uniform spatial step size distribution



(a) 800 km ($\bar{\tau}$=2.83 ps) **(b)** 3200 km ($\bar{\tau}$=5.66 ps)

Fig. 1: Average SNR performance of multi-channel DBP vs. B_{DBP} with and without PMD and for P=5 dBm.

to guarantee the required accuracy, while maintaining reasonable computational times[7]. On the other hand, the emulation of the fibre PMD requires equally spaced steps to mimic the correct evolution of the principal states of polarisation while keeping control of the Maxwellian DGD distribution at the fibre output. Our numerical approach combines the two requirements. The SSF step distribution is initially derived based on the log-step approach shown in[7]. The number of steps was set to a value providing the required accuracy for the chosen performance metric (SNR). The PMD section length was instead set independently to 100 m. This value corresponds to the correlation length of the fibre and indicates the length scale over which the fibre birefringence orientation varies. Typical values of this parameter have been reported in the range of 0.3 and 300 m. For each PMD section the common "wave-plate" approach is adopted, where the output polarisation state of each section is uniformly scattered over the Poincare' sphere and is uncorrelated to all previous sections. The DGDs of each section were instead drawn from a normal distribution with standard deviation set to 20% of the mean[8]. The SSF steps and PMD sections are eventually merged, forming a new step distribution.

The simulated transmission scenario consists of 31 polarisation-multiplexed 16QAM quasi-Nyquist channels at 32 Gbaud and 33 GHz spacing, occupying an overall optical bandwidth of approximately 1 THz. The fibre link is composed of 80 km SMF fibre spans with a loss of 0.19 dB/km and PMD parameter of 0.1 ps/$\sqrt{\text{km}}$. An Erbium-doped fibre amplifier with a noise figure of 4.5 dB compensates for the span loss at the end of each span. At the receiver, after filtering out the required compensation bandwidth B_{DBP}, DBP is performed with the same SSF step distribution as in the forward propagation. A matched filter is then used to detect the central channel. An ideal equalisation stage subsequently recovers the signal polarisation and compensates for the linear PMD effects. The signal is finally down-sampled and the output passed to a data-aided SNR estimation block.

Results and Discussion

In order to study the impact of both B_{DBP} and $\bar{\tau}$, two transmission distances were considered: 800 (10x80) km and 3200 (40x80) km, yielding $\bar{\tau}$=2.83 ps and $\bar{\tau}$=5.66 ps, respectively. In the absence of PMD, for each of these two systems, each B_{DBP} will result in a different optimum P. However, in this preliminary study, due to the intensive computational effort required to sweep P, we chose to fix P at 5 dBm which corresponds to the optimum P for the 3200 km system, when full-field DBP is applied. Also, by fixing P beyond the optimum power, larger SNR differences are expected among the different B_{DBP} tested. In order to statistically characterise the impact of PMD, 50 fibre realisations were reproduced.

In Fig. 1, we show the average output SNR as a function of B_{DBP} at 800 km (Fig. 1a) and 3200 km (Fig. 1b) in a fibre with and without PMD. It is clear how, when PMD is present, the SNR quickly saturates and that the SNR penalty, compared to the case where no PMD is present, grows as B_{DBP} is increased. From (1), it can be seen that for a fixed transmission distance, this penalty can only be dependent on α_{PMD}, which therefore must be monotonically decreasing with B_{DBP}. This is consistent with the idea illustrated in the Background section which explains why PMD decreases the compensation efficiency for frequency components located far apart from each

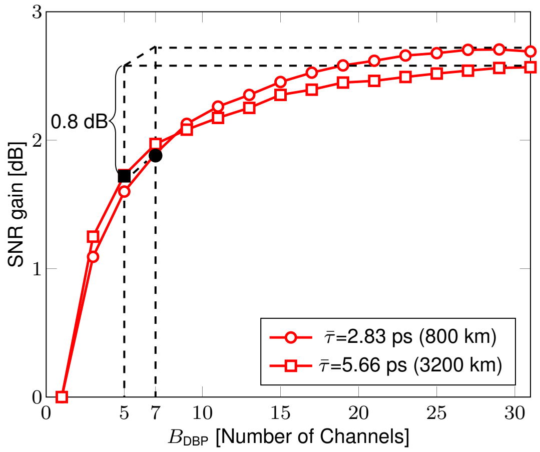


Fig. 2: DBP SNR gain vs. B_{DBP} relative to B_{DBP}=1 Ch., with PMD, at 800 (10x80) km and 3200 (40x80) km for P=5 dBm.

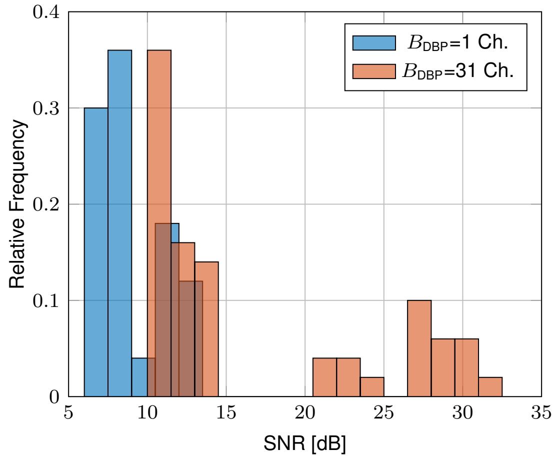


Fig. 3: SNR values histograms obtained for B_{DBP}=1 Ch. and B_{DBP}=31 Ch. at 800 km transmission distance ($\bar{\tau}$=2.83 ps).

other. From a comparison between Fig. 1a and Fig. 1b, it can be observed that the SNR penalties between the PMD and no PMD cases are approximately preserved. Specifically, at 800 km (Fig. 1a) the SNR penalty grows up to 16.2 dB in the full-field DBP case, while the same penalty is reduced to 15.5 dB at 3200 km (Fig. 1b). This difference can be, for the most part, attributed to the much larger signal-ASE noise term in the case of the results plotted in Fig. 1b.

The impact of $\bar{\tau}$ on the DBP performance is instead highlighted in Fig. 2, where the SNR gain, relative to the single-channel DBP case, is shown as a function of B_{DBP}, for the two transmission distances already analyzed. Although the differences appear to be marginal, it can still be seen that: i) a larger value of $\bar{\tau}$ corresponds to a faster saturation (B_{DBP}= 5 Ch. vs. B_{DBP}= 7 Ch. at 0.8 dB from the maximum gain); ii) for a larger $\bar{\tau}$, the maximum gain, achievable for the full-field DBP, case decreases.

Finally, in Fig. 3, the histograms of 50 different simulated fibre realisations and their relative SNR values are shown for single-channel (B_{DBP}=1 Ch.) and full-field DBP (B_{DBP}=31 Ch.), for a transmission distance of 800 km. It can be deduced that full-field DBP, compared to the single-channel DBP case, incurs a much larger spreading of the SNR values. Moreover, the two histograms overlap, indicating that for a transmitted power per channel of $P = 5$ dBm, some fibre realisations after full-field DBP, lead to SNR values as low (or lower) than the best case single-channel DBP scenarios. Therefore, although the average SNR represents the most natural way to summarise the performance of DBP over the fibres ensemble, Fig. 3 highlights the importance of showing best and worst case performance scenarios, particularly for large B_{DBP}.

Conclusions

The performance of multi-channel DBP in the terahertz optical bandwidth regime has been shown. The ability to compensate for nonlinear effects over ultra-wide bandwidths is limited by the fibre PMD. For a typical transmission scenario, this results in a performance improvement of $\leq$ 1 dB beyond an NLC bandwidth of approximately 150 GHz. For a fixed PMD parameter, this saturation behaviour appears to have weak dependence on the average link DGD. Further investigation is required with regard to the performance dependency on DGD and transmitted powers.

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