Polarization-Mode Dispersion Aware Digital Backpropagation

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Abstract *We study a modified DBP algorithm that accounts for PMD. Based on the accumulated PMD at the receiver, the algorithm distributively compensates for PMD in the reverse propagation and outperforms the conventional approach by up to 2.1 dB.*

Introduction

Digital signal processing (DSP) allows modern coherent fiber-optical systems to fully recover all degrees of freedom of the optical field, improving receiver sensitivity and allowing the use of higher-order modulation formats. Having access to the entire optical field, linear impairments are effectively mitigated using DSP, whereas fiber nonlinearity is viewed as the ultimate obstacle towards higher transmission rates. Various techniques are available in the literature to mitigate fiber nonlinearities, among which digital backpropagation (DBP) has proved to be promising[1]. DBP compensates for the deterministic fiber nonlinear impairments by solving the nonlinear propagation equation using the split-step Fourier (SSF) method and backpropagating the received optical field with inverted channel parameters, whereas the remaining stochastic impairments, such as polarization-mode dispersion (PMD), are compensated after DBP.

Having exact knowledge of the fiber parameters, it is believed that the deterministic nonlinear signal–signal interactions are completely removed using DBP and the performance of a fiber-optical system is limited by the uncompensated stochastic effects such as amplified spontaneous emission noise, which leads to signal–noise interactions[2], and PMD leading to polarization-dependent interactions[3,4], which considerably decrease the effectiveness of DBP. In order to account for the signal–noise interactions, a modified DBP[5] has been proposed that takes into account noise, getting the performance of the optical fiber channel closer to the fundamental limits. However, no such modification exists in the literature that takes into account the stochastic polarization-dependent interactions due to PMD.

PMD introduces a frequency-dependent delay that accumulates as a random-walk-like process along the fiber length. DBP applied the entire reverse propagation with the accumulated delay over the entire link; therefore the nonlinear compensation is mismatched and its accuracy degrades with the backpropagated distance. In order to remove this effect, PMD should be compensated for as it naturally occurs, i.e., in a distributed fashion along the link, rather than doing it at once after DBP. It has been shown numerically that compensating for PMD on a per span-basis decreases its impact on DBP significantly[3]. However, this approach requires *a priori* PMD knowledge for every span, which is challenging to realize.

In this work, we propose for the first time a modified DBP algorithm to account for the interplay between nonlinearities and PMD. Besides the nonlinear and chromatic dispersion blocks, the modified algorithm applies the reverse propagation also using PMD blocks that mimic the forward propagation. Simulation results show the effectiveness of the algorithm, providing signal-to-noise ratio (SNR) gains of 0.3–2.1 dB for a 1000 km link with 0.05–0.3 ps/$\sqrt{\text{km}}$ PMD parameter, compared to the traditional setup where the entire PMD is undone at once after DBP.

Proposed Method

The conventional DBP algorithm is modified such that the signal is backpropagated also through N_{PMD} PMD sections that concatenated have the same frequency-dependent Jones matrix over the signal spectrum as the inverse of the total accumulated PMD in the forward propagation. The ac-

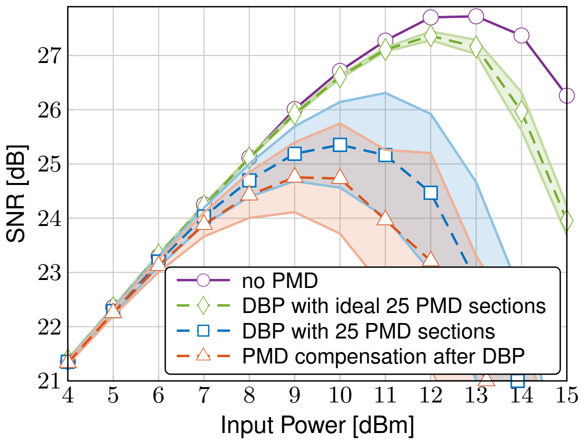

Fig. 1: The SNR versus input power. The dashed lines represent the mean SNR obtained over 120 PMD realizations, whereas the shaded areas represent the standard deviation. For comparison, the performance of DBP without PMD and with ideal knowledge of 25 PMD segments are shown.

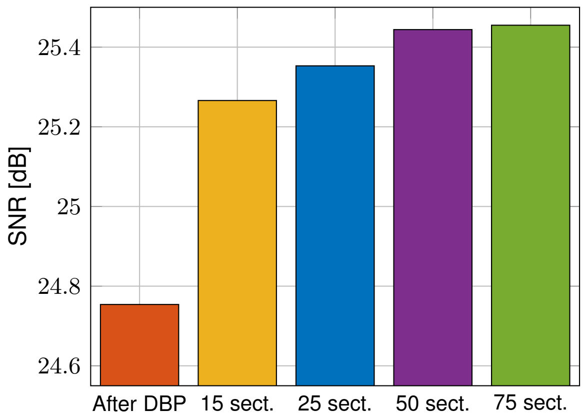

Fig. 2: Average SNR obtained over 120 PMD realizations at the optimal input power by compensating for PMD after DBP, and by the modified DBP scheme with various number of PMD sections N_{PMD}.

cumulated PMD at the receiver can be obtained from blind channel equalizers, such as the constant modulus algorithm.

Each PMD section consists of a polarization scrambler and a retardation plate uniformly interleaved with the total number of DBP steps N_{DBP}. Each of the N_{PMD} retardation plates is equally divided into $N_{\text{DBP}}/N_{\text{PMD}}$ plates and distributed in each DBP step between two consecutive polarization scramblers that are placed at every $N_{\text{DBP}}/N_{\text{PMD}}$ DBP steps starting from step one. Knowing the mean accumulated differential group delay (DGD), the N_{PMD} sections are randomly initialized such that the overall expected mean DGD is the same. Subsequently, the sections are oriented such that the inverse of the frequency-dependent Jones matrix over the signal spectrum in the forward propagation is obtained. The orientation of the sequence is done using the Nelder–Mead simplex optimization method[6] over the $4N_{\text{PMD}}$ degrees of freedom (three for each polarization scrambler and one for each retardation plate) by minimizing over the entire frequency range the mean-squared error of i) the Jones matrices and ii) the DGD obtained from the first derivative of the Jones matrices, with equal weighting factors. It should be noted that the domain of this optimization is not convex and has many possible solutions; therefore the obtained orientation of the PMD sections is sensitive to the initialization. Even though the obtained orientation of the PMD sections matches closely the accumulated PMD, it might not necessarily reflect the orientation in the forward propagation. As we will see in the Results section, this mismatch leads to a performance penalty.

In this work, we focus on the potential gain by DBP in the presence of PMD; therefore we assume ideal knowledge of the accumulated PMD, rather than obtaining this information from equalizers.

Simulation Setup

We consider a single-channel point-to-point link consisting of an ideal transmitter and coherent receiver, and 10×100 km spans of standard single mode fiber with one erbium doped fiber amplifier per span, compensating for the exact span loss, having a noise figure of 4.5 dB. The transmitted signal was 50 Gbaud polarization-multiplexed 16-ary quadrature amplitude modulation shaped using a root-raised cosine (RRC) pulse with roll-off factor 0.01. The signal propagation was simulated by solving the Manakov-PMD[7] equation using the SSF approach with steps of 0.1 km. PMD was emulated at every SSF step consisting of a polarization scrambler that uniformly[8] scatters the state of polarization and a retardation plate. The DGD introduced by each retardation plate was Gaussian distributed[9] $\mathcal{N}(\Delta\tau_p, (\Delta\tau_p/5)^2)$ with mean $\Delta\tau_p$; thus the mean accumulated DGD is $\sqrt{8N_{\text{SSF}}/(3\pi)}\Delta\tau_p$, where N_{SSF} is the total number of SSF steps.

We considered two receiver DSP setups: i) DBP followed by an ideal linear PMD equalizer that is assumed to operate under perfect knowledge, and ii) modified DBP described in the previous section. For both setups $N_{\text{DBP}} = N_{\text{SSF}} =$ 10000, and are followed by an ideal matched RRC filter applied to the signal, after which the SNR is estimated by comparing the transmitted and received symbols.

Results and Discussion

Fig. 1 shows the achieved performance obtained for a PMD parameter of 0.1 ps/$\sqrt{\text{km}}$, resulting in a ~3.16 ps expected DGD. As can be seen, the performance of DBP degrades by 3 dB in

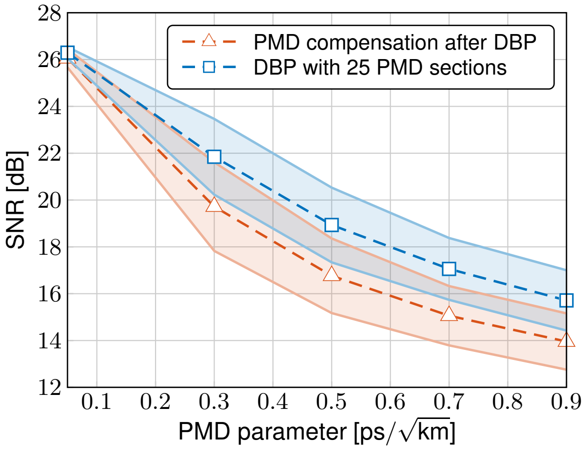

Fig. 3: SNR versus fiber PMD parameter obtained for 10 dBm input power. The dashed lines represent the mean SNR obtained over 120 PMD realizations, whereas the shaded area represents the standard deviation.

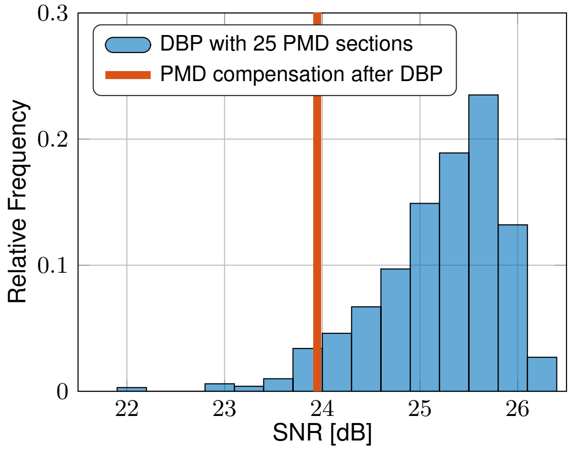

Fig. 4: Histogram of the SNR values obtained at 10 dBm input power and 0.1 ps/$\sqrt{\text{km}}$ PMD parameter by 330 different solutions of the optimization algorithm for a fixed PMD realization in the forward propagation. The red bar marks the obtained SNR by compensating for PMD after DBP.

the presence of PMD. The modified DBP consists of 25 PMD sections and improves the SNR by 0.6 dB compared to the classical DBP approach. However, the proposed scheme is 2 dB worse compared to the case with perfect knowledge of the 25 PMD sections. The loss in performance is due to the mismatch of the PMD evolution along the fiber in the backward propagation compared to the one in the forward propagation.

The achieved SNR at the optimal input power is shown in Fig. 2 as a function of N_{PMD}. As can be seen, the performance increases with the number of sections, providing a gain of 0.7 dB with 75 sections.

Fig. 3 shows the performance of the two schemes as a function of the PMD parameter. As the PMD parameter increases, the performance of both schemes degrades. However, the proposed DBP provides an SNR gain that increases from 0.3 dB at 0.05 ps/$\sqrt{\text{km}}$ to 2.1 dB at 0.3 ps/$\sqrt{\text{km}}$, after which it saturates. The saturation may occur due to the number of PMD segments being insufficient to accurately emulate the higher amount of accumulated PMD.

The histogram of the achieved SNR with the proposed algorithm obtained for different optimization solutions of the PMD sections starting from different initializations is shown in Fig. 4. The PMD realization in the forward propagation is fixed and the red bar marks the obtained SNR by compensating for PMD after DBP. As can be seen, most (95%) of the realizations have better performance than the conventional approach, with the histogram peak at 25.5 dB achieving a 1.5 dB SNR gain.

Note that the algorithm's efficiency can be improved by running in parallel different PMD realizations in the backward propagation and selecting the best candidate at a latter stage.

Conclusions

We demonstrated, as a proof of concept, a modified DBP algorithm that blindly reverses the PMD effects in the backward propagation by gradually passing the signal through N_{PMD} PMD sections, rather than doing the entire PMD compensation at once after DBP. Based on an optimization algorithm, the N_{PMD} PMD sections are oriented such that the inverse of the accumulated PMD at the receiver is obtained. The algorithm provides SNR gains of 0.3–2.1 dB for a 1000 km link with 0.05–0.3 ps/$\sqrt{\text{km}}$ PMD parameter.

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