Polarization Effects in Nonlinearity Compensated Links

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Abstract *We experimentally assess the impact of PDL and PMD on the performance of nonlinear compensation algorithms in dispersion unmanaged links. We show that perturbative nonlinear compensation is more robust to PDL, but more sensitive to PMD compared to filtered digital-backpropagation.*

Introduction

Wavelength division multiplexing (WDM) fiber-optic transmission systems performance is limited by fiber nonlinear Kerr effect[1]. Digital nonlinear compensation (NLC) techniques have been studied for almost a decade to improve system performance. The reference NLC algorithm is the digital backpropagation (DBP), which is prohibitively complex for hardware implementation. Filtered DBP (FDBP) was introduced to reduce the complexity of DBP[2]. Recently, the perturbative nonlinear compensation (PNLC) technique has attracted special attention due to its significantly reduced complexity[3,4]. The derivation of both DBP and PNLC is based on the Manakov equation for modelling nonlinear wave propagation in fiber, which ignores polarization mode dispersion (PMD) and polarization dependent loss (PDL). The contribution of the present work is to experimentally investigate the impact of such polarization effects on the performance of FDBP and PNLC in dispersion unmanaged systems for the first time to the authors' knowledge. In [Ref.5] we showed that the impact due to PMD on NLC gain is small as even large values of differential group delay (DGD) of 5 times the symbol duration lead to 0.1 dB gain penalty while using PNLC, and negligible gain penalty while using FDBP. On the other hand, it is well-known[6,7] that PDL induces Q^2-factor (Q^2) fluctuations due to both random OSNR degradation and interaction with nonlinear distortions. In this work we extend [Ref.5] by studying the impact of PDL and PDL + PMD on the gain degradation of PNLC and FDBP.

Experimental test-bed

The transmitter consisted of a WDM loading comb of 64 C-band distributed feedback lasers spaced at 50 GHz. They were modulated with a polarization-multiplexed IQ-modulator (PM IQ-MOD) driven by a 88 GSamples/s digital-to-analog converter (DAC), and coupled to the measurement channel, which was a tuneable laser source at 1545.72 nm, (located exactly in the middle of the WDM comb) modulated by a second PM IQ-MOD. All channels were modulated with 32 GBd PDM-16QAM root-raised cosine pulses with roll-off 0.01. Decorrelated binary De Bruijn sequences of length 2^{15} were used to synthesise symbols. An optical fiber piece with 100 ps of chromatic dispersion was added after the loading channels for further decorrelation of about 3 symbols between adjacent channels.

Fig. 1a illustrates the recirculation loop consisting of 12 spans of 55 km Corning® Vascade® EX3000 fiber ($D = 20$ [ps/nm/km], $\gamma = 0.62$ [1/W/km] and $\alpha = 0.16$ [dB/km]). Fiber loss was compensated by in-line EDFAs working in constant output power mode. At the

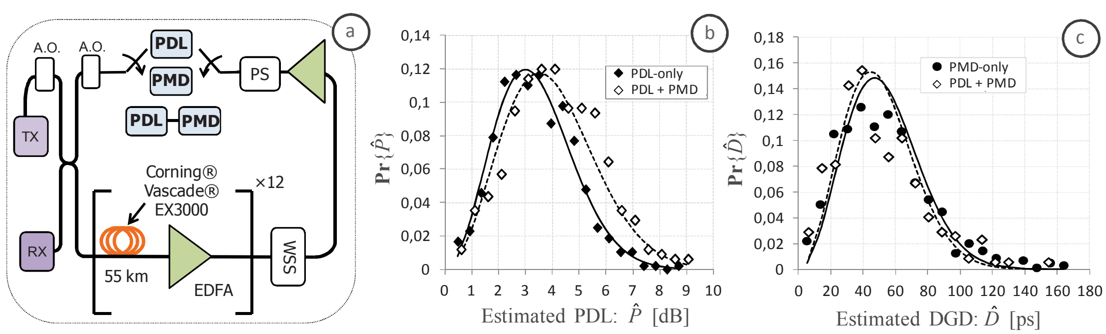

Fig. 1: a) Recirculation loop, WSS: wavelength selective switch, PS: loop-synchronous polarization scrambler, A.O.: acousto-optic switch, EDFA: Erbium-doped fiber amplifier. PMD: polarization mode dispersion element, PDL: polarization dependent loss element. b) Probability distribution of the estimated PDL. C) Probability distribution of the estimated differential group delay (DGD), markers: experiments, lines: Maxwellian fit.

ISBN 978-3-8007-4274-5

receiver, the channel under test was filtered and detected with a standard coherent receiver with a 33 GHz real-time scope working at 80 GSamples/s. Sampled waveforms were processed off-line by standard DSP blocks, including chromatic dispersion compensation, polarization de-multiplexing with 35-taps constant modulus algorithm and carrier phase estimation.

When needed, a 1.6 dB PDL and/or a 20 ps PMD elements were inserted at the end of the loop. A low speed polarization scrambler was placed just before the PDL/PMD elements in order to randomize the states of polarization at each round-trip. Therefore, the relative orientation of the channels and the PDL/PMD elements polarization axes were changed at each round-trip, such that after 10 loops (6600 km) the setup realized a ten-section PDL/PMD emulator with average PDL ~5 dB and average DGD ~63 ps.

NLC was optionally applied to the received waveforms. Three alternatives for NLC were considered: FDBP with 1 step per span (stps), FDBP with 0.25 stps, and PNLC.

Results

The characterization of the nonlinear gain provided by the FDBP and PNLC was done in four different cases: *1) No PDL - No PMD, 2) PMD only, 3) PDL only,* and *4) PDL + PMD.*

For each case, 600 waveforms were recorded and processed offline. The PDL and PMD values were estimated based on the equalizer frequency response methods by the following formulae[8,9]:

$$\hat{D} = 2\sqrt{det\left(\frac{1}{2\pi}\frac{d\mathbf{U}(f)}{df}\right)}\Bigg|_{f=0} \quad (1)$$

$$\hat{P} = \left|10log_{10}(\lambda_1(f)/\lambda_2(f))\right|_{f=0} \quad (2)$$

Where $\hat{D}$ is the estimated DGD, $\hat{P}$ is the estimated PDL, f is frequency, $\det(\cdot)$ is the determinant function, $\boldsymbol{U}(f) = \boldsymbol{W}(f)/\det(\boldsymbol{W}(f))$, $\boldsymbol{W}(f) = [W_{i,j}(f)]_{i,j=1,2}$ with $W_{i,j}(f)$ being the butterfly filter equalizers' frequency responses, and λ_1 and λ_2 are the eigenvalues of $\boldsymbol{W}(f)$.

Fig. 1b shows the probability ($\mathbf{Pr}$) distribution of the estimated PDL for the *PDL-only* and *PDL+PMD* cases. They follow Maxwellian distributions with mean value of ~4 dB, which is 1 dB lower than the theoretical expected ten-section mean PDL of ~5 dB (=1.6dB×√10). We believe this offset is due to the fact that the PDL estimation $\hat{P}$ from Eq.(2) underestimates the true value, as the equalizer response depends on the OSNR[8]. Further investigation is required. Fig. 1c shows the probability distribution of the estimated DGD for the *PMD-only* and *PDL+PMD* cases, which also follow Maxwellian distributions with mean 55 ps, in good agreement with the theoretical mean value of ~63 ps (= 20 ps×√10).

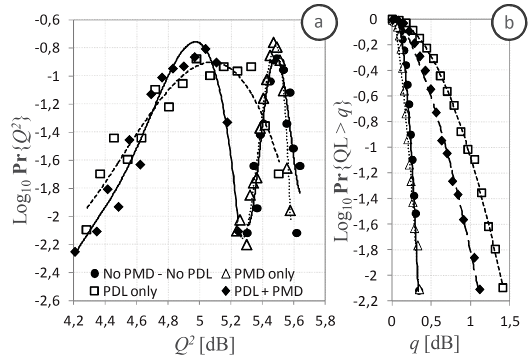

Fig. 2: Uncompensated Q^2*-factor* (a) probability density and (b) Q^2*-factor* loss (QL) probability for each study case.

The system is first characterized without NLC. Optical power was set to 18 dBm which corresponds to the optimum Q^2 when nonlinear compensation is applied (nonlinear threshold+1) as shown in [Ref. 5]. For each of the four cases, Fig. 2a shows the Q^2 probability density, while Fig. 2b shows the probability of the Q^2 loss (QL) defined as $QL = Q^2_{max} - Q^2$ [dB]. We observe that system performance is unaffected in case of *PMD-only*, as in[5,10]. On the other hand, in case of *PDL-only* the mean Q^2 decreases by ~0.5 dB, while the maximum observable QL is increased by ~1.4 dB. Adding PMD to PDL helps to decrease QL by 0.3 dB compared to the *PDL-only* case, while the mean value is unchanged[11].

Nonlinear compensation is achieved by FDBP 1 stps, FDBP 0.25 stps, and by PNLC. Algorithms coefficients (for FDBP: κ and B in Eq.(1) of Ref.2, for PNLC: ρ in Eq.(2) of Ref.4) have been optimized to achieve maximum gain for each received waveform. In the case of PNLC a 300x300 look-up table was used as no further gain was found for larger LUT sizes.

For the four different study cases, Fig. 3 shows the probability density of the NLC gain (G_{NLC}) on top, and the probability of the G_{NLC} loss (GL) on bottom, defined as $GL = G_{NLC\text{-}max} - G_{NLC}$ [dB], that is, G_{NLC} degradation with respect to the best observed NLC gain. Fig. 3a corresponds to the *No PDL-No PMD* case. FDBP 1 stps and 0.25 stps achieve mean gains of 0.95 dB and 0.85 dB respectively, while PNLC achieves 0.8 dB. The maximum observable GL is 0.1 dB for PNLC and FDBP 0.25 stps, while for FDBP 1 stps it is slightly increased to 0.15 dB.

Fig. 3b corresponds to the case of *PMD-only,* maximum GL is basically unchanged for both cases of FDBP, while for PNLC is increased by a factor 2. Fig. 3b bottom includes also the GL probability of the old waveforms of the experiments in [Ref.5] (blank markers), which

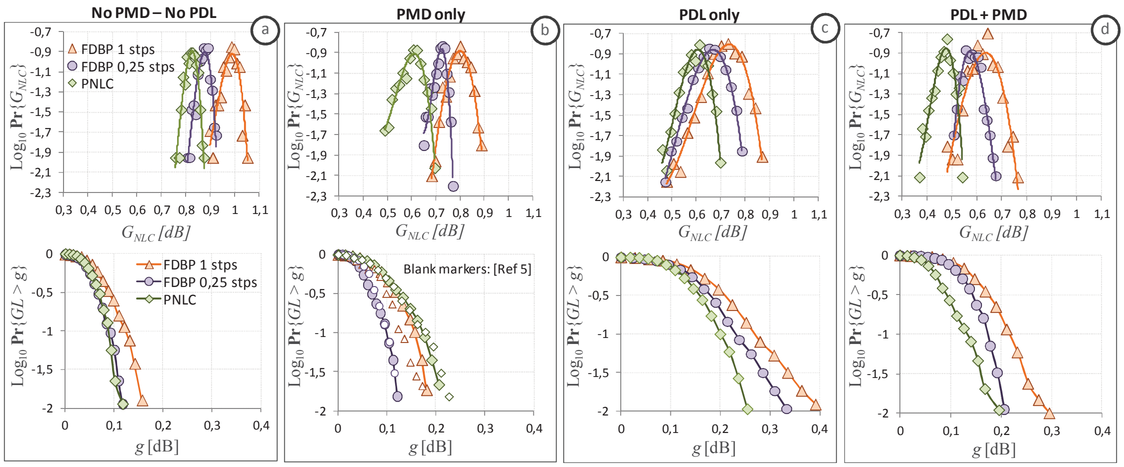

Fig. 3: Nonlinear gain (G_{NLC}) probability distribution and nonlinear gain loss (GL) for a) No PDL nor PMD, b) PMD-only, c) PDL-only, and d) PDL + PMD.

show the same trend as the new experiments.

Removing the PMD element and introducing PDL into the link (Fig. 3c) shows no further decrease on the mean G_{NLC} for all algorithms types. However GL is greatly increased, being FDBP the most affected one with values ~3x higher than when no PDL/PMD is perturbing the system. On the contrary, PNLC shows to be more robust with only ~2 x GL increases.

Finally, when both PDL and PMD are added into the link (Fig. 3d) the mean G_{NLC} is further decreased by ~0.1 dB for all algorithms, while the maximum observable GL is reduced by ~0.1 dB compared to the *PDL-only* case.

Results presented in Fig. 3 show that PNLC seems to be more sensitive to PMD than FDBP, as PNLC GL is increased by 0.1 dB while for FDBP it is not affected. On the contrary, PNLC is more robust than FDBP to PDL, as GL is increased by ~0.15 dB in comparison to 0.25 dB for FDBP. Furthermore, in the presence of both PDL and PMD, while the overall GL is reduced, PNLC is still more robust than FDBP.

Even with the high values of introduced PMD and PDL, maximum observable GL for PNLC is kept below 0.25 dB, which it is only 0.15 dB higher than when neither PDL nor PMD are present in the link, showing the robustness of PNLC to PMD and PDL impairments.

Conclusions

We have experimentally studied the impact of PDL and PMD on the performance of filtered digital backpropagation (FDBP) and perturbative nonlinear compensation algorithms (PNLC). We have shown that PDL values as large as 9 dB and PMD values as large 5 times the symbol duration lead to a maximum observable degradation of only 0.15 dB in PNLC gain fluctuations. While PNLC is more sensitive to PMD than FDBP, it is more robust to PDL. More theoretical work is required to fully understand the trends.

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ISBN 978-3-8007-4274-5