Simplified Backpropagation Equalization in WDM Coherent Polarization Multiplexed Systems

L. M. Pessoa[1], H. M. Salgado[1] and I. Darwazeh[2]
[1] *INESC Porto, Faculdade de Engenharia, Universidade do Porto, Porto, Portugal*
[2] *Department of Electronic and Electrical Engineering, University College London, UK*
email: luis.pessoa@ieee.org, h.salgado@ieee.org, i.darwazeh@ee.ucl.ac.uk

ABSTRACT
The digital equalization of fibre impairments in coherent optical communications allows for ultimate limits of spectral efficiency to be achieved, while reducing the cost and complexity compared to optical based solutions. Digital backpropagation (BP) was proposed recently as a reduced complexity approach for jointly compensating linear and non-linear impairments in single polarization coherent optical systems. Furthermore, polarization division multiplexed quadrature phase-shift keying (PDM-QPSK) has emerged as a promising format to increase spectral efficiency. Here we assess the performance of the simplified backpropagation equalization in both single channel and multiple channel transmission in combination with polarization multiplexing for different dispersion map configurations. It is shown that polarization multiplexing induces a degradation in performance due to cross-phase modulation polarization scattering, the backpropagation algorithm still overperforming linear equalization.
Keywords: coherent systems, backpropagation, polarization multiplexed.

1. INTRODUCTION

A digital revolution has strongly impacted optical communications . Digital Signal Processing (DSP) techniques are gaining increasing importance as they allow for robust long-haul transmission with full compensation at the receiver. Furthermore, it has been reported that systems employing in-line dispersion compensating fiber (DCF), perform worse than those with only digital compensation [1]. The results presented in this paper will also support this fact.

The employment of advanced DSP functions implies that sufficient sampling rates are satisfied. However, the lack of suitable ADC-DAC technology has originated the need for reducing the symbol rate while increasing spectral efficiency, leading to the investigation of multilevel modulation formats in conjunction with polarization multiplexing.

The main nonlinear impairments limiting long haul WDM systems are the inter-channel effects, specifically cross-phase modulation (XPM) and four wave mixing (FWM) [2]. However, if sufficient channel spacing is allocated, these impairments are reduced and then the major impairments become intra-channel effects, namely self-phase modulation (SPM) and also a linear impairment, chromatic dispersion (CD). These nonlinear impairments stem from the Kerr effect, which accounts for the fiber refractive index change proportional to the optical power. XPM is a nonlinear phenomenon which occurs when two or more optical waves copropagate in the optical fiber due to the refractive index change induced by each wave, which in turn induces a nonlinear polarization-dependent phase shift on the other copropagating waves [3]. When the interaction takes place between intensity modulated waves, the nonlinear phase shift becomes time dependent leading to phase and polarization modulation of the other waves.

Backpropagation has been proposed as a universal technique for jointly compensating linear and nonlinear impairments for WDM systems using coherent detection, DSP and DCF, enabling higher launched power and longer transmission reach [4]. BP involves propagating the received signal through a backward channel (with opposite sign of nonlinearity and dispersion), using the iterative symmetric split-step Fourier method (SSFM) for solving the nonlinear Schrödinger equation (NLSE). Furthermore, in [1] a computationally simpler algorithm was proposed, using a non-iterative asymmetric SSFM and yet obtaining similar performance. The same work also reported that the best performance is obtained by omitting the use of DCF (with electronic dispersion compensation entirely at the receiver), and that three-times oversampling was required for good numerical accuracy.

In this paper we focus on this simplified approach, while considering polarization division multiplexing (PDM), for 10 GSymbols/s RZ-QPSK transmission in a 25×80 km spans of single mode fibre (SMF) and variable length of inline DCF. We also consider the cases of single polarization transmission and time interleaved (TI) PDM. This paper is organized as follows: in section 2 the system modeling is described, section 3 presents the simulation results as well its discussion, and finally the conclusions are given in section 4.

2. SYSTEM MODELING

The coupled nonlinear Schrödinger equations that describe the propagation in a linearly birefringent optical fibre

978-1-4244-4826-5/09/$25.00 ©2009 IEEE

are given by [5]:

$$\begin{aligned}\frac{\partial u_x}{\partial z}+\left\{\alpha_x+j\beta_{0x}+\beta_{1x}\frac{\partial}{\partial t}-\frac{j}{2}\beta_{2x}\frac{\partial^2}{\partial t^2}\right\}u_x+j\frac{\gamma}{3}\left(3|u_x|^2+2|u_y|^2\right)u_x=0\\ \frac{\partial u_y}{\partial z}+\left\{\alpha_y+j\beta_{0y}+\beta_{1y}\frac{\partial}{\partial t}-\frac{j}{2}\beta_{2y}\frac{\partial^2}{\partial t^2}\right\}u_y+j\frac{\gamma}{3}\left(3|u_y|^2+2|u_x|^2\right)u_y=0\end{aligned}, \quad (1)$$

where α, β_0, β_1 and β_2 account for the attenuation, birefringence, differential group delay and CD, respectively. The coefficient γ is the nonlinear coefficient of the fiber. Higher order nonlinear terms are omitted because we consider that the birefringent beat length (typically a few meters) is much shorter than the nonlinear length (hundreds of kilometers in this work), leading to rapidly oscillating terms that would cancel out. Therefore, in the work presented in this paper, we have set β_0 and β_1 to zero, because birefringence does not affect the nonlinear term [5] and polarization mode dispersion can be neglected at 10 Gsymbols/s [6], respectively. However, equation (1) shows that the signal carried on the orthogonal polarization makes a $2/3$ factor contribution to the nonlinear phase, compared to the signal propagating on that polarization, which means the polarization multiplexing operation may induce a significant penalty in the system performance.

The numerical implementation of equation (1) is achieved using the SSFM. After propagating through a small length of fiber h, the electric field is given by:

$$E(z+h,t)=\exp\left(\frac{h}{2}\hat{D}\right)\exp\left\{\int_z^{z+h}\hat{N}(z)dz\right\}\exp\left(\frac{h}{2}\hat{D}\right)E(z,t), \quad (2)$$

where $\hat{D}$ and $\hat{N}$ correspond to the linear and nonlinear terms of the NLSE. Since the nonlinear term is not known at $z+h$, it is found iteratively.

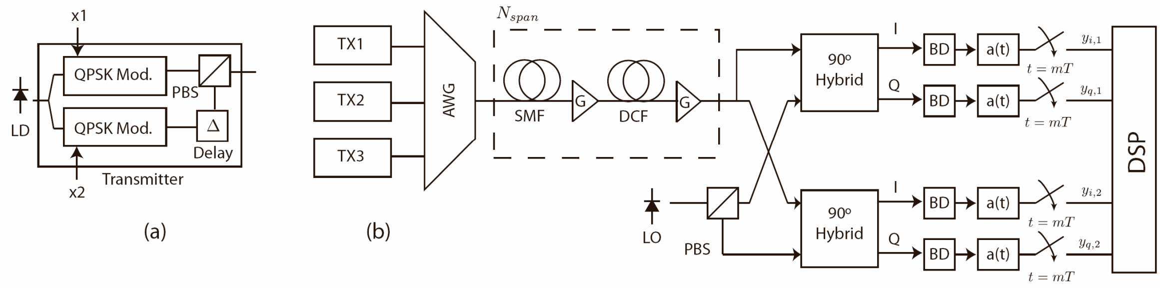


Figure 1. Block diagram of: a) PDM transmitter. b) WDM transmitter, transmission channel and digital coherent receiver.

The system model is shown in Fig. 1. The pulse shape was adjusted for 50% RZ. The transmitter includes a delay Δ which can be set to half the symbol period if time-interleaving between the two polarizations is desired. The oversampling rate m is set to 3 in our simulations according to [1]. The antialias filters were set as lowpass 5th order Butterworth with a bandwidth of 40% of the symbol rate. The DSP performs the functions of backpropagation and carrier phase estimation (CPE). However, for simplicity phase noise was not included in our simulations, therefore, CPE corresponds to a single phase rotation. A simple moving average filter with length 64 was used [7].

The simplified backpropagation algorithm consists of a backward fibre model that assumes the forward model is composed by a nonlinear section followed by a linear section in each span. This method is based on the heuristic that nonlinear effects are strongest at the beginning of a fiber section where signal power is highest [1].

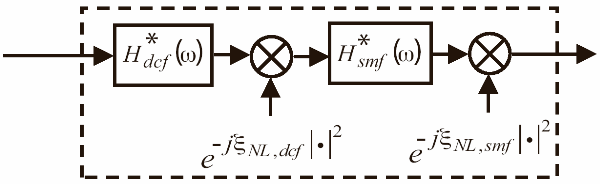


Figure 2. Mathematical model of backpropagation algorithm with span-length step size.

Figure 2 describes the mathematical modeling of the BP algorithm where:

$$\xi_{NL,smf} = \xi\gamma_{smf}L_{eff,smf}, \quad (3)$$

$$\xi_{NL,dcf} = \xi\gamma_{dcf}L_{eff,dcf}Ge^{-\alpha_{smf}L_{smf}}, \tag{4}$$

$H^*_{smf}(w)$ and $H^*_{dcf}(w)$ represent the conjugated of SMF and DCF chromatic dispersion transfer functions, respectively. L_{eff} is the nonlinear effective length [3]. According to [1] the factor ξ would need to be optimized according to several system parameters. However, in our simulations, optimal results were found in all cases for $\xi = 0.5$.

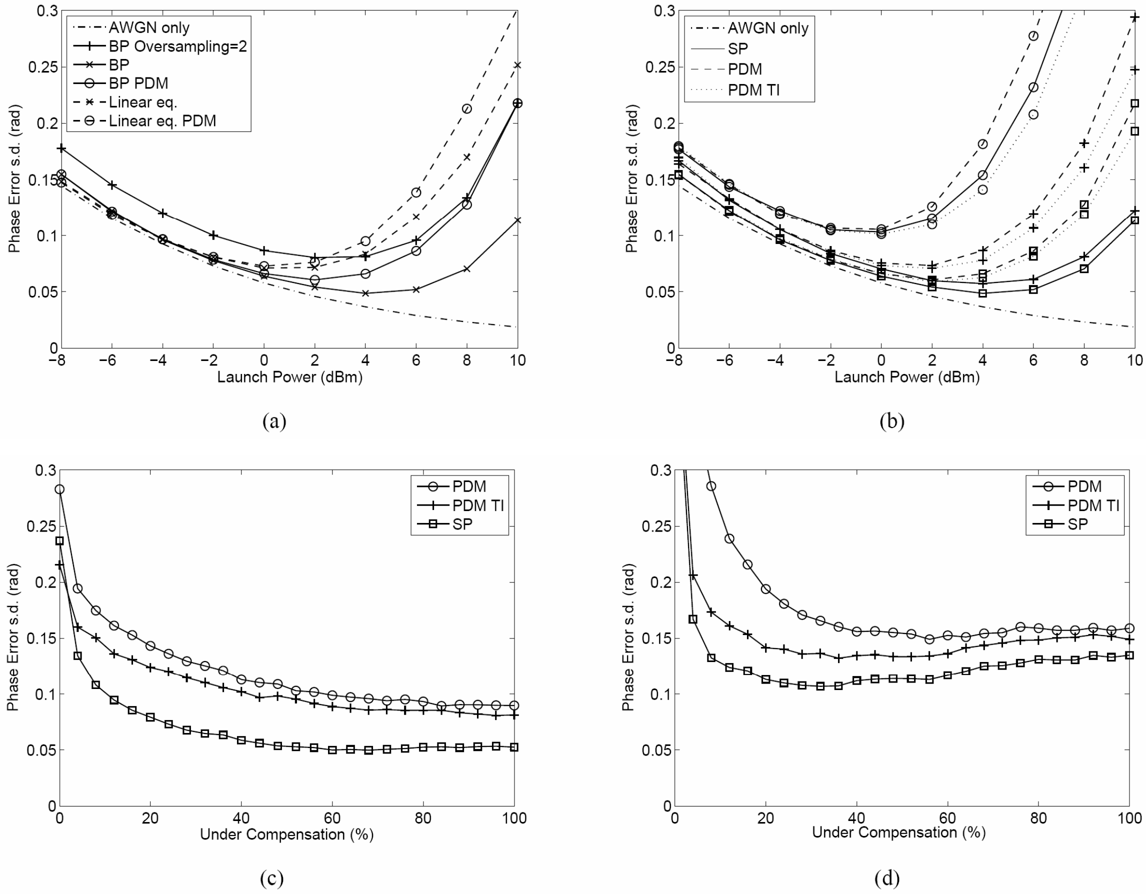


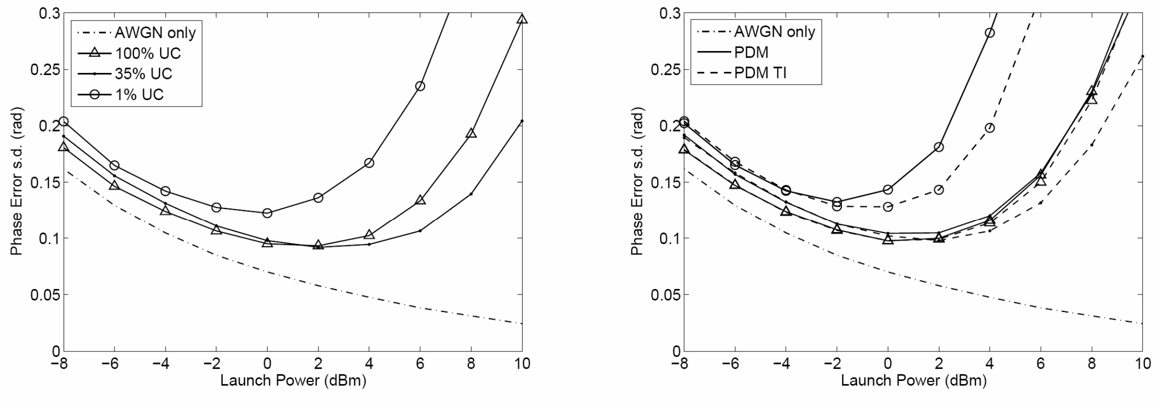
Figure 3: (a) Single Channel, 100% UC; (b) Single Channel Backpropagation,"∘", "+" and "□" refer to 1%, 35% and 100% UC, respectively; (c) Single Channel, Launch Power = 6 dBm; (d) 3 WDM Channels, Launch Power = 6 dBm.

3. RESULTS AND DISCUSSION

The transmission performance of the 10 GSymbols/s RZ-QPSK system is shown in Fig. 3a and Fig. 3b show how the phase error standard deviation of the constellation after detection varies with launch power. The "AWGN only" limit curve corresponds to the ideal case when all other impairments are turned off, and a matched filter is used at the receiver to compensate the transmitter pulse shape. In particular Fig. 3a shows that the BP algorithm with an oversampling rate of 2 is numerically insufficient. This is because of the nonlinear terms being of third order in the NLSE [1]. Therefore 3 times oversampling was used throughout the paper. The performance of the algorithm is also depicted for the case of PDM transmission. One can see that up to 0 dBm of launched power there is no observable difference to the single polarization case, whereas after this point the PDM result exhibits a penalty due to the nonlinear interaction between the two polarizations. The result of linear equalization is also shown for the cases of SP and PDM. It is clear that although linear equalization slightly overperforms BP for low launched powers (due to the pulse shape compensation given by the linear filter), it performs much worse when nonlinearity is present, for both SP and PDM formats. This means that not only SP but also PDM systems may benefit from the BP algorithm. In Fig. 3b the BP performance for several under-compensation (UC) scenarios was investigated, specifically, 1%, 35% and 100%. Furthermore, PDM with time-interleaving was also considered. This format was suggested in [9], [10] for RZ pulses in WDM transmission, because it helps reducing the nonlinear polarization scattering in dispersion-managed system, due to the state of polarization of the signal becoming data independent, causing alternate opposite nonlinear polarization rotations.

We have considered this TI format in our simulations, and for completeness, included it also for the single channel case where it still provides a slight improvement. A penalty in performance is apparent with increasing fiber compensation (decreasing UC).

Figures 3c and 3d plot the phase error as a function of undercompensation for both single and multiple channel cases, respectively. It is shown in the single channel case that the ideal level of under-compensation is 100%, which means that no DCF is used and complete compensation is done digitally in the receiver, independently of the system being SP or PDM. The same conclusion was found in [1] regarding the SP case, and [8] for the PDM case. However, when transmitting multiple channel the conclusions are different. The optimum under-compensation is approximately 35% in the SP case. Then, if PDM is used, the minimum value of phase error s.d. stays approximately constant between 40% and 100%. Furthermore, if PDM-TI is used, unlike the single channel case, a considerable difference to the PDM case is observed for low undercompensation levels, where it is clear that optimum value of undercompensation is again 35%, which means that better performance might be achieved if DCF is used. The result obtained for the case of the backpropagation algorithm is in agreement with [9] for the case of a linear equalized receiver. In Fig. 4 the performance of the WDM transmission system against launched power is assessed. In Fig. 4a the single polarization scenario is evaluated. It is shown that, as suggested by Fig. 3d the 35% under-compensation results starts over-performing the 100% UC result above +2 dBm of launched power, which means that for WDM SP, dispersion managed systems behave better than systems without dispersion management, a result supported in [10]. Additionally, one can see in Fig. 4b that the same conclusions apply to PDM-TI transmission. Furthermore, the time-interleaving does not provide any improvement in the 100% UC case as expected, since the pulses broaden rapidly in propagation [9]. In [10] it was suggested that it is the PDM that makes the dispersion managed system perform worse than the system without DCF. That is why the time-interleaved format inverts that behavior, since the nonlinear interaction between polarizations is significantly reduced. However, in contrast to multiple channel systems, in single channel transmission the non-dispersion managed configuration performs better than dispersion-managed. This is due to the fact that dispersion causes noise to walk off from the signal, and DCF induces higher nonlinearity than SMF [1]. This fact leads us to the conclusion that in multiple channel transmission with 100% UC, although the noise walks off from the channel it starts interfering with adjacent channels, and therefore dispersion compensation becomes preferable.



(a) (b)

Figure 4: (a) 3 WDM Channels, Single polarization only; (b) 3 WDM Channels, "∘", "·" and "Δ" refer to 1%, 35% and 100% UC.

4. CONCLUSIONS

The assessment of the simplified backpropagation algorithm was carried out for a polarization multiplexed system employing RZ-QPSK transmission. Both single and multiple channel configurations were evaluated with varying length of inline dispersion compensating fibre. The results are found to be in accordance with previously published results for linear equalization, confirming that backpropagation can be applied with benefit to polarization multiplexed systems.

ACKNOWLEDGEMENTS

This work was supported in part by "Fundação para a Ciência e Tecnologia" (FCT) under the programme POCTI/FEDER with grant REEQ/1272/EEI/2005 – Fibre Optic Supported Broadband Communication Networks. L. M. Pessoa acknowledges support from a PhD grant from FCT.

REFERENCES

[1] E. Ip, and J. M. Kahn, “Compensation of dispersion and nonlinear effects using digital backpropagation”, *Journal of Lightwave Technology*, vol. 26, no. 20, pp. 3416-3425, Oct. 2008.

[2] E. Ip, A. Lau, D. Barros and J. M. Kahn, “Coherent detection in optical fiber systems”, Optics Express, vol. 16, no. 2, pp. 753-791, Jan. 2008

[3] G. P. Agrawal, “*Nonlinear Fiber Optics*”, 3rd ed. London, U.K.: Academic, 2001.

[4] Xiaoxu Li *et al.*, “Electronic post-compensation of WDM transmission impairments using coherent detection and digital signal processing”, *Optics Express*, vol. 16 no. 2, 21 Jan. 2008.

[5] A. Carena *et al*., “A time-domain optical transmission system simulation package accounting for nonlinear and polarization-related effects in fiber,” *IEEE J. Sel. Areas Commun.* 15, 751, 1997.

[6] E. Ip and J. M. Kahn, “Digital equalization of chromatic dispersion and polarization mode dispersion”, *Journal of Lightwave Technology*, vol. 25, no. 8, pp. 2033-2043, Aug. 2007.

[7] M. Seimetz, “Laser linewidth limitations for optical systems with high-order modulation employing feed forward digital carrier phase estimation”, in *Proc. OFC/NFOEC 2008*.

[8] V. Curri, P. Poggiolini, A. Carena, and F. Forghieri, “Dispersion compensation and mitigation of nonlinear effects in 111-Gb/s WDM coherent PM-QPSK systems,” *IEEE Photonics Technology Letters*, vol. 20, no. 17, pp. 1473-1475, Sep. 2008.

[9] C. Xie, “WDM coherent PDM-QPSK systems with and without inline optical dispersion compensation”, *Optics Express*, vol. 17, no. 6, pp. 4815-4823, Mar. 2009.

[10] C. Xie, “Interchannel nonlinearities in coherent polarization-division-multiplexed quadrature-phase-shift-keying systems,” *Photonics Technology Letters*, vol. 21, no. 5, pp. 274-276 Mar. 2009.