

Polarization multiplexed 16QAM transmission employing modified digital back-propagation

Danish Rafique,^{1,*} Marco Mussolin,² Jonas Mårtensson,² Marco Forzati,² Johannes K. Fischer,³ Lutz Molle,³ Markus Nölle,³ Colja Schubert,³ and Andrew D. Ellis¹

¹ Photonics Systems Group, Tyndall National Institute and Department of Electrical Engineering/Physics, University College Cork, Dyke Parade, Prospect Row, Cork, Ireland.

² Acreo Netlab, Electrum 236, SE 16440, Kista, Sweden

³ Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute, Einsteinufer 37, D-10587 Berlin, Germany

*danish.rafique@tyndall.ie

Abstract: We experimentally demonstrate performance enhancements enabled by weighted digital back propagation method for 28 Gbaud PM-16QAM transmission systems, over a 250 km ultra-large area fibre, using only one back-propagation step for the entire link, enabling up to 3 dB improvement in power tolerance with respect to linear compensation only. We observe that this is roughly the same improvement that can be obtained with the conventional, computationally heavy, non-weighted digital back propagation compensation with one step per span. As a further benchmark, we analyze performance improvement as a function of number of steps, and show that the performance improvement saturates at approximately 20 steps per span, at which a 5 dB improvement in power tolerance is obtained with respect to linear compensation only. Furthermore, we show that coarse-step self-phase modulation compensation is inefficient in wavelength division multiplexed transmission.

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OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (190.4370) Nonlinear optics, fibers.

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1. Introduction

Exponentially growing global bandwidth demand is fueling the need to increase the capacity and spectral efficiency of the deployed wavelength-division multiplexed (WDM) optical networks [1]. In recent years, coherent detection and digital signal processing have become the most favourable technologies to enhance the available transport capacity in optical fibre [2]. For a further increase of channel capacity, a promising modulation format is polarization multiplexed 16-level quadrature amplitude modulation (PM-16QAM), which allows for a spectral efficiency of 4 bits/s/Hz, when transmitted at a symbol rate of 28/56 Gbaud over the 50/100 GHz channel grid [3]. Nevertheless, such an increase in transmission capacity emerges at the expense of increased susceptibility to linear and nonlinear fibre impairments. As linear compensation methods have matured in the past few years [2, 4, 5], research has intensified on nonlinear impairments compensation [6-8]. In particular, electronic signal processing using digital back-propagation (DBP) has been applied to the compensation of channel nonlinearities [7-11]. However, the complexity of DBP is currently exorbitant, due to significantly high number of processing steps required in such calculations. Simplified DBP algorithms have been proposed [12-14] and investigated for a 14 Gbaud PM-16QAM experimental transmissions [15].

In this contribution, we experimentally demonstrate the effectiveness of digital back-propagation in single-channel and WDM (eight channels) transmission of 28 PM-16QAM, over a 250 km straight-line fibre link consisting of ultra-large area fibre (ULAF). We report performance enhancements enabled by weighted digital back propagation (W-DBP) method, using only one back-propagation step for the entire link, enabling up to a 3 dB improvement in power tolerance with respect to linear compensation only. This is more or less the same improvement that can be obtained with the standard, computationally heavy, non-weighted digital back propagation (NW-DBP) employing one step per span. As an additional reference

point, we analyze the performance improvement based on the number of steps, and show that performance improvement is saturated at about 20 steps per segment, at which an improvement of 5 dB in the power tolerance is obtained with respect to compensation of linear impairments only. Furthermore, we show that self-phase modulation compensation is inefficient in WDM transmission. To the best of our knowledge this is the first experimental demonstration of 28 Gbaud PM-16QAM transmission employing DBP.

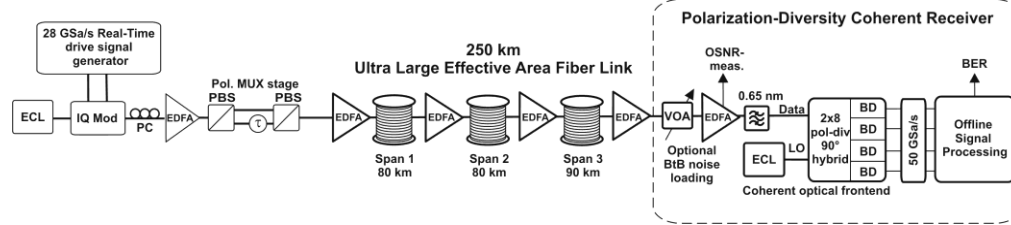


Fig. 1. Experimental setup for 224 Gb/s PM-16QAM transmission system with 3 total spans.

2. Experimental setup

2.1 Transmitter (single-channel)

The experimental setup is shown in Fig. 1. In-phase (I) and quadrature (Q) components of the electric field were modulated by an IQ modulator to generate 28 Gbaud 16QAM signals. The driving signals for the IQ modulators were generated by field programmable gate arrays (FPGAs) providing real time coding and bit mapping [16, 17]. The transmitted data is a de Bruijn binary sequence of length 2^{15} . A de-correlated polarization multiplexing stage was used to generate the 28 Gbaud PM 16QAM data signal. The link setup is shown in Fig. 1 (see [16, 17] for further details).

2.2 Transmitter (WDM)

Detailed experimental setup for 8×224 Gb/s PM-16QAM is reported in [16, 17], where the transmitter configuration shown in Fig. 1 is also used in the WDM experiments at 224 Gb/s.

2.3 Receiver and digital signal processing

At the receiver, an EDFA was used as preamplifier and a variable optical attenuator (VOA) allowed for variation in received OSNR for back-to-back measurements (when the signal was transmitted over the link, this stage was removed, and OSNR was varied by varying the power launched into the fibre). After passing through the amplifier and a 10 dB coupler (for OSNR evaluation), the signal was filtered by a 0.5 nm optical filter and boosted by a second EDFA.

The signals corresponding to I and Q components of the two orthogonal polarizations were digitized in batches of 10M samples by asynchronous sampling in a real-time oscilloscope and subsequently processed in a computer. The bandwidths and sampling rates of the employed oscilloscopes were 20GHz, 50GS/s. The post-processing included several blocks (see [18] for more details about some of the algorithms). First sampling skew and I/Q-phase offset was corrected before upsampling to approximately 2 samples/symbol. Then either linear chromatic dispersion (CD) compensation using a static frequency domain filter, or CD and nonlinear compensation using digital back-propagation (DBP) was performed before timing recovery and resampling again to a synchronous 2 samples/symbol. Polarization demultiplexing and equalization was performed using four adaptive filters in MIMO configuration with 27 taps each. Constant modulus algorithm (CMA) was used for initial convergence before estimating and removing initial carrier frequency offset and then switching to decision-directed adaptation combined with phase-noise tolerant decision-aided carrier phase estimation. Special care is taken when calculating the decision-directed least-mean square (LMS) error in

order to decouple filter tap updating from phase tracking. Finally, a number of symbols needed for convergence were discarded before mapping symbols, which were differentially coded, to bits and counting errors. About 5.5 million symbols in each polarization were used for the bit-error rate (BER) computation, which was eventually converted into Q-factor [19].

Nonlinear compensation was performed, using digital back-propagation based either on the standard split-step Fourier method (SSFM) [14] or on a variation of it, in which fewer back-propagation steps are used, and the nonlinear phase shift at a specific symbol is estimated on the basis not only of the intensity of the signal in that symbol, but also (through an appropriate linear filtering) of its neighbours, in order to take into account the fact that non-linear phase shift takes place at different positions over the link (specifically after each amplifier), at which the power profile is not constant, due to dispersion-induced pulses broadening [12-14]. We refer to this method as weighted digital back propagation (W-DBP) as opposed to the standard non-weighted digital back propagation (NW-DBP).

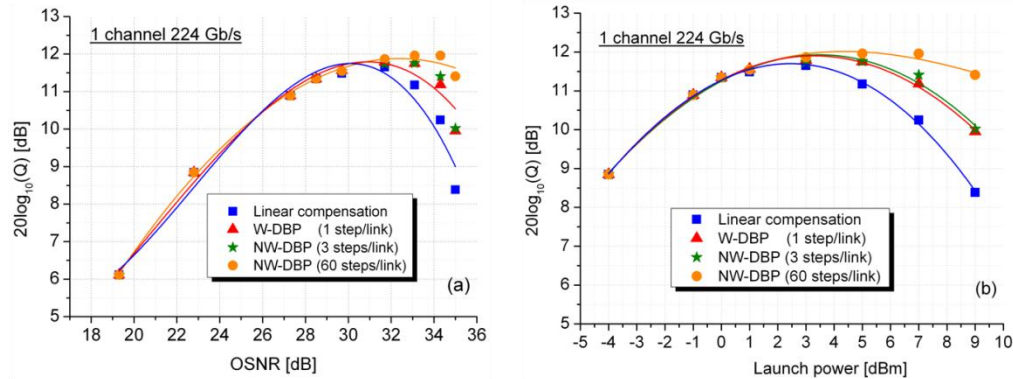


Fig. 2. (a) Q versus OSNR and, (b) versus launch power, for single-channel 28 Gbaud 16QAM transmission over 250 km ULAF with various digital compensation scenarios; different values of OSNR in the Fig. 2a were obtained by varying the launch power. Linear compensation (squares), weighted digital back-propagation (1 step per link, triangles), non-weighted digital back-propagation (3 steps per link, stars), non-weighted digital back-propagation (60 steps per link, circles).

3. Results and discussions

Fig. 2 depicts the Q -factor of the transmitted 28 Gbaud PM-16QAM signal (single-channel) as a function of received OSNR (Fig. 2a), for 250 km transmission, and as a function of launch power (Fig. 2b). The different curves refer to different electronic signal processing used at the receiver: with linear compensation (LC) only, with W-DBP (1 step for the whole link), and with NW-DBP (1 and 20 steps per span). At lower launch powers, where performance is limited by noise, Q increases with increasing launch power, and eventually reaches a maximum at an optimum launch power, above which it starts increasing again due to the accumulation of fibre nonlinearities. It can be seen that the Q curves for LC and DBP overlap in the noise-limited regime. However, the Q of the LC system reaches a maximum of ~ 11.5 at 3 dBm launch power (giving an OSNR of 31.7 dB), and then rapidly degrades due to intra-channel nonlinear effects. Such effects are alleviated by DBP techniques. Specifically, it can be seen that both NW-DBP with one step per span and W-DBP with one step for the whole link allows for a 3 dB increase of power tolerance (defined as the point at which Q reaches again the LC optimum of ~ 11.5 dB). This confirms that the computational burden of DBP can be greatly reduced using weighing, since only one extra FFT/IFFT stage is required in W-DBP with one step for the whole link (though an extra filtering stage with respect to only LC is needed, as well as one non-linear phase estimation stage), without compromising significantly performance improvement.

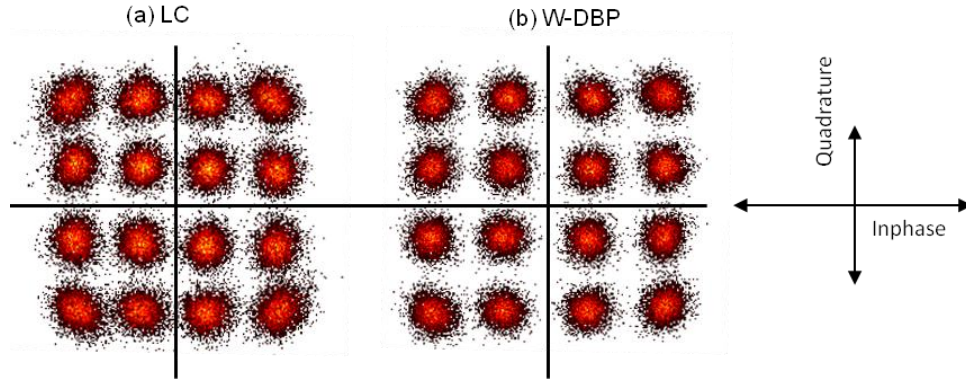


Fig. 3. Constellation diagrams with only (a) LC and, (b) W-DBP (1 step per link), at OSNR level of 35 dB (launch power of 9 dBm). Single channel transmission at 28 Gbaud.

The difference between LC and NW-DBP (20 steps per span) is qualitatively illustrated for 35 dB OSNR, in the constellation diagrams shown in Fig. 3. It is clear that when using LC (Fig. 3a) alone, the constellation diagrams are degraded. However, the use of DBP (Fig. 3b) enables almost noise-free identification of the mean location of individual symbols. Note that in both cases, the noise distribution looks symmetric (except for additional phase noise on outer symbols) and appear to follow bi-Gaussian distribution. We attribute the Gaussian noise distributions in this configuration to the short correlation length due to highly dispersive transmission, sufficiently randomizing the nonlinear interactions, in consistent with recently reported results [20]. In order to identify the maximum improvement achievable with DBP, we investigated the performance of NW-DBP algorithm, increasing the number of steps per span up to 50 as shown in Fig. 4. The scope of improvement with W-DBP is reduced for high number of steps, so it was not analyzed. It can be seen that Q increases as a function of required number of DBP steps up until 20 steps per span (giving a power tolerance improvement of 5 dB, Fig. 2), above which it saturates.

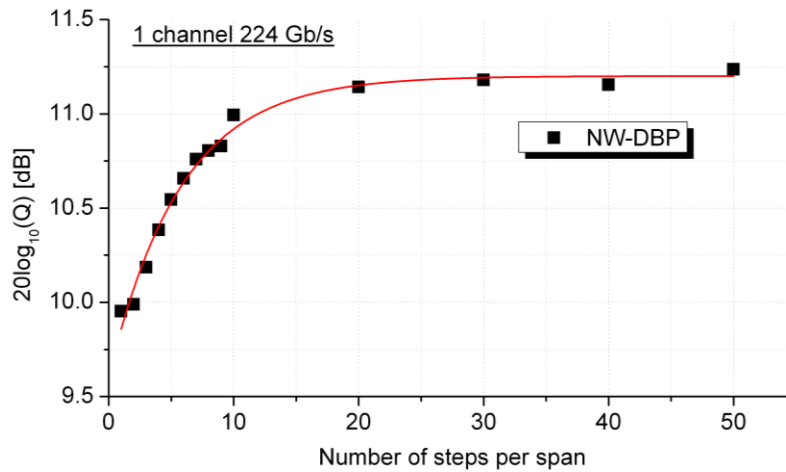


Fig. 4. Q versus steps per span (NW-DBP case). Single channel transmission at 28 Gbaud. OSNR level of 35 dB (launch power of 9 dBm)

Figure 5 shows the transmission performance as a function of launch power for WDM transmission employing 28 Gbaud PM-16QAM. It can be seen that intra-channel nonlinearity compensation is inefficient. This is because inter-channel effects are sufficiently strong to modify the optical fields in such a way that individual coarse-step channel compensation is

inept. Nonetheless, if DBP based on optimum step-size is employed, one may expect higher baud-rate systems to show improved performance, since relative impact of inter-channel nonlinearities reduces as the baud-rate increases [21].

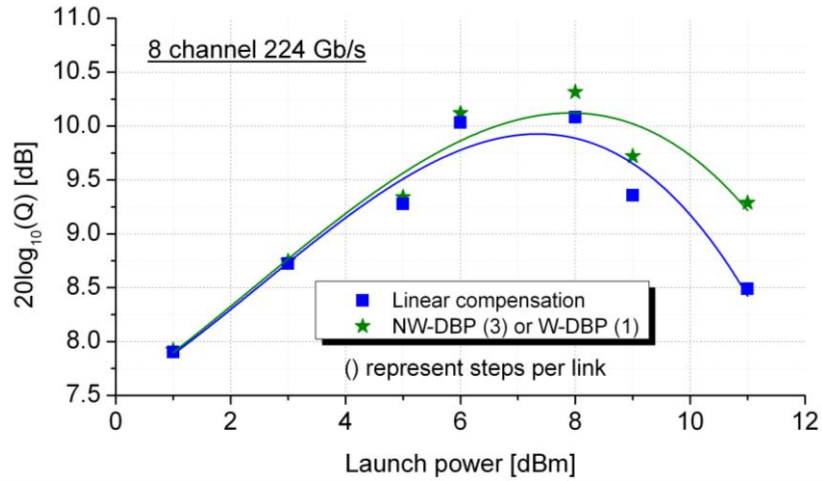


Fig. 5. Q versus launch power, for 8 channel 28 Gbaud transmission over 480 km SSMF transmission with LC (squares) and NW-DBP (3 steps per link).

4. Conclusions

We experimentally demonstrate the effectiveness of digital back propagation in coherently-detected 28 PM-16QAM system, over 250km of uncompensated link, and report up to 3 dB improvements in power tolerance compared to linear compensation. We show that the same improvement can be obtained using standard DBP with one step per span and with weighted DBP with one step for the whole link. This confirms that the computational burden of DBP can be greatly reduced using weighing, without compromising performance improvement significantly. We also investigated the maximum improvement achievable using non-weighted DBP with several steps per span and observed that performance improvement saturated at 20 steps per span, showing an improvement of 5 dB in launch power tolerance. We also show that in a WDM system, the coarse-step DBP approach has reduced effectiveness.

Acknowledgments

The work described in this paper was carried out with the support of the EUROFOS project, Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme, and Science Foundation Ireland under Grant 06/IN/1969. The ultra-large effective area fibres were kindly provided by OFS Labs.