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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

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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.

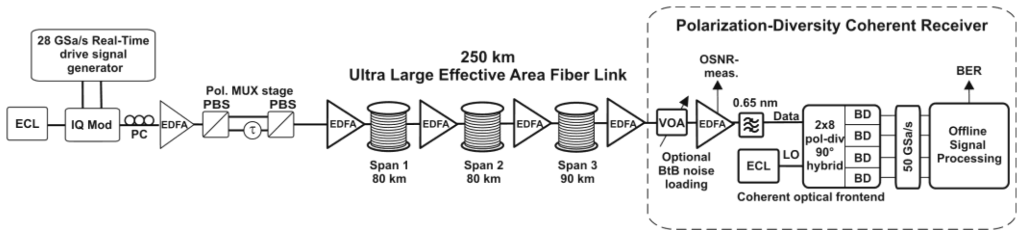

Fig. 1. Experimental setup for 224 Gb/s PM-16QAM transmission system with 3 total spans.

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

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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].

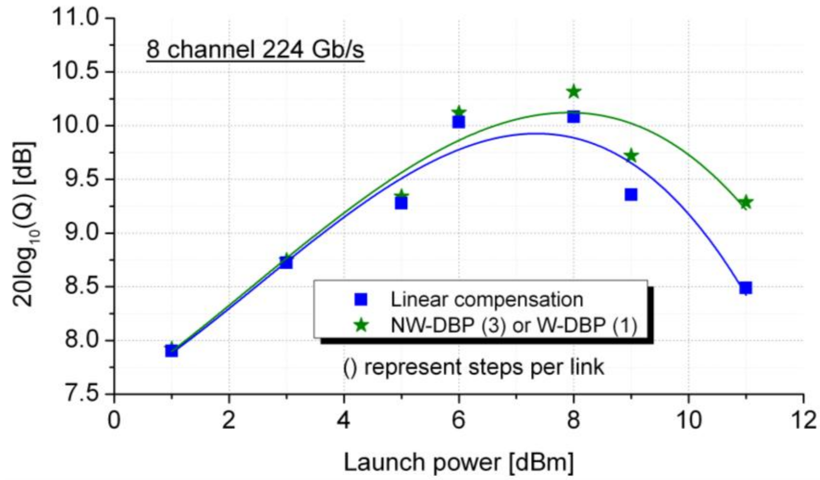

Fig. 5. Q versus launch power, for 8 channel 28 Gbaud transmission over 480 km SSMF transmission with LC (squares) and NW-DBP (3 steps per link).

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.

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