

Digital Back-Propagation Performance in Wideband Optical Fibre Transmission Systems

Lidia Galdino⁽¹⁾, Gabriel Saavedra⁽¹⁾, Daniel Semrau⁽¹⁾, Daniel J. Elson⁽¹⁾, Domaniç Lavery⁽¹⁾, Mingming Tan⁽²⁾, Md Asif Iqbal⁽²⁾, Paul Harper⁽²⁾, Robert I. Killey⁽¹⁾, Polina Bayvel⁽¹⁾

⁽¹⁾ Optical Networks Group, Department of Electronic and Electrical Engineering, UCL, Torrington Place, London WC1E 7JE, UK. (l.galdino@ucl.ac.uk)

⁽²⁾ Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK.

Abstract *Single channel digital back-propagation (SC-DBP) performance with different transmission bandwidths is experimentally and theoretically investigated. The SC-DBP gain reduces with transmission bandwidth; from 1.2 b/sym for single channel to 0.2 b/sym for C-band transmission at 2000 km.*

Introduction

In transmission over a conventional optical fibre link, which is fundamentally nonlinear, the achievable SNR is limited by nonlinear distortion. Several digital techniques are available in the literature to mitigate fibre nonlinearity, among them - digital back-propagation (DBP)¹. Due to technological limitations of digital-to-analogue converters (DAC) and analogue-to-digital converters (ADC), practical implementation of wideband transmitter-side or receiver-side DBP using a single transceiver is currently challenging. For a single receiver, the highest bandwidth back-propagated that has been experimentally demonstrated is 120 GHz². Several reports on experimentally achievable gains for full-field DBP showed a doubling² and tripling³ of transmission distances. Additionally, the achievable gains of single channel DBP (SC-DBP) on fully loaded C- and L-band transmission systems have been studied, showing approximately 0.5 dB Q^2 -factor improvement⁴. The limits of SC-DBP as the transmission bandwidth increases have been only theoretically studied⁵.

In this work, we experimentally investigated the performance of SC-DBP over different propagated bandwidths. A theoretical performance analysis of the experiential transmission system, for both linear electronic chromatic dispersion compensation (EDC) only and DBP nonlinear compensation, has also been carried out, providing a deeper theoretical understanding of the experimental results. The GN-model⁹ and generalized expressions² to estimate the signal-to-noise ratio (SNR) in the presence of transceiver noise are used to estimate the DBP performance. The mutual information (MI) is used as the metric to quantify the DBP benefits on achievable

information rates. The channel under test is 40 GBd Nyquist-shaped dual polarization 64-ary quadrature amplitude modulation (DP-64QAM), analyzed for propagated bandwidths between 40 GHz and 4.1 THz, and over transmission distances of up to 2000 km.

Transmission system

The experimental setup used for transmission is shown in Fig. 1. Seven external cavity lasers (ECLs) with 100 kHz linewidth and 41 GHz frequency spacing were used as sources for four odd- and three even-indexed subcarriers. Each set of sources was modulated using an IQ modulator, with drive signals generated with root raised cosine (RRC) filters with 0.1% roll-off factor followed by 92 GS/s DACs, to obtain spectrally-shaped 40 GBd 64-QAM signals. The odd and even channels were decorrelated with a 15 ns delay and combined before being polarisation-multiplexed (PolMux) to form a 7x40 GBd DP-64QAM superchannel. The superchannel signal was subsequently combined with spectrally-shaped amplified spontaneous emission (SS-ASE) noise, used to emulate additional interfering channels^{6,7}, allowing a range of transmission bandwidths to be investigated. The inset in Fig. 1 illustrates the 7 subcarriers plus the SS-ASE, covering 4.1 THz of transmission bandwidth.

For transmission, a recirculating fibre loop was used comprising a polarization scrambler (PS), a single span of 101 km Corning® Vascade® EX2000 with a total loss of 16.2 dB, an EDFA, a wavelength selective switch (WSS) for adjustable gain flattening, and a second EDFA to overcome the loss of loop components.

At the receiver the optical signal was amplified and band-pass filtered at 1550 nm. A separate ECL was used as the local oscillator, and de-

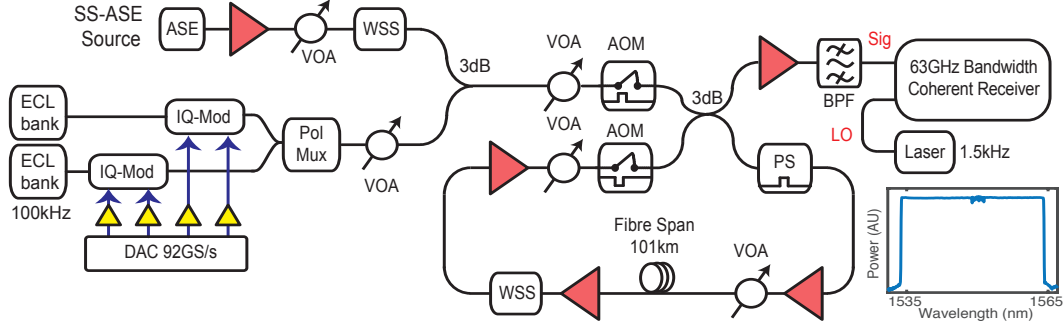


Fig. 1: Experimental configuration.

tection was carried out in a digital coherent receiver followed by digital signal processing (DSP) as in^{2,8}. SNR and mutual information (MI) were used as the performance metrics for this system.

The SNR was evaluated as the ratio between the variance of the transmitted symbols $\mathbb{E}[|X|^2]$ and the variance of the noise σ^2 , where $\sigma^2 = \mathbb{E}[|X - Y|^2]$ and Y represents the received symbols. The MI was estimated from the received data via Monte Carlo integration and provides an upper bound on the performance for any coded system based on DP-64QAM⁸. In the experimental testbed used, the maximum SNR of 21 dB with a MI of 11.8 b/sym for single channel and 11.3 b/sym at an SNR of 19 dB for WDM.

In the theoretical analysis, a generalized formula to estimate the SNR for EDC and DBP that accounts for the transceiver noise and, in particular, the interactions between the signal and the co-propagating transceiver noise was used as described in². Therefore, a transceiver limited SNR of 21 dB and 19 dB measured in the experimental testbed was considered in the analytical model for. The NLI coefficient was calculated using the GN model as detailed in⁹. The ASE noise power generated by the EDFA that compensates for the re-circulating loop loss components was also taken in to account on the analytical model.

Results

Single channel transmission

The DBP performance after transmission of a single 40 GBd DP-64QAM channel was first assessed to identify the upper bounds of the achievable DBP gains in the system under test. The performance improvements obtained by carrying out full-field DBP were then compared with the performance of single channel DBP over different transmitted bandwidths, of up to 4 THz.

Figure 2 illustrates the MI (at optimum signal launch power) as a function of distance for single channel transmission. The experimental measurements recorded that the MI after transmission

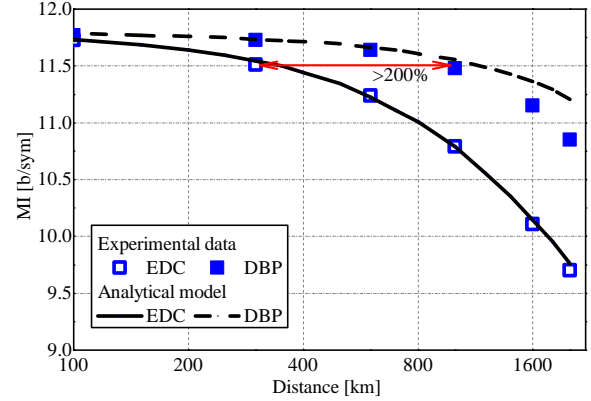


Fig. 2: Single channel transmission: MI vs. distance.

over 100 km using EDC only was 11.7 b/sym, reduced to 10.8 b/sym at 1000 km and further reduced to 9.7 b/sym at 2000 km. When DBP was applied, the MI gain over the values obtained with EDC only increased with distance. For a fixed MI of 11.5 b/sym, EDC only allowed a transmission distance of 300 km, while DBP achieved a reach of 1000 km, a more than tripling of the transmission distance. Additionally, a gain in MI of 1.2 b/sym by applying DBP was experimentally demonstrated at a transmission distance of 2000 km. These are the highest gains in distance and/or MI that have been reported, to the best of our knowledge. A good agreement between the theoretical model and experimental data was found; at longer distances, the small discrepancy between the theoretical model and experimental results may be due to stochastic effects, such as polarization mode dispersion as described in².

It is important to note that the MI gain increases with the transmission distance; at a distance of 100 km the gain was 0.05 b/sym, increasing to 0.8 b/sym at 1000 km and 1.2 b/sym at 2000 km. As illustrated in Fig. 2, at short transmission distances, the transceiver limited SNR is the predominant source of noise in the system. Thus, systems with finite SNR generally yield limited DBP performance over short transmission distances, where the link SNR is relatively high com-

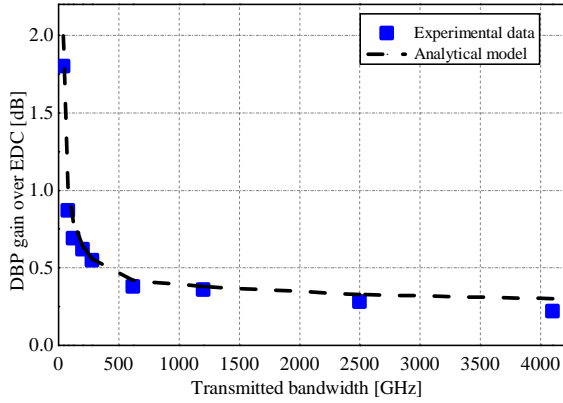


Fig. 3: SC-DBP gain over EDC at 1010 km for different transmitted bandwidths.

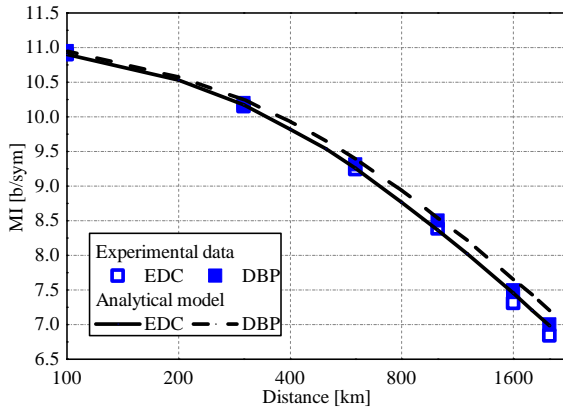


Fig. 4: 4.1 THz transmission: MI vs. distance.

pared to transceiver noise sources. For longer distances, the system performance is dominated by accumulation of ASE and by nonlinear effects, which are compensated by applying DBP.

Multi-channel transmission system

The next step was to investigate the performance of SC-DBP over different transmission bandwidths. As shown in Fig. 3, the SC-DBP gain over EDC was quantified for the propagated bandwidths of 40, 80, 120, 200, 280, 620, 1200, 2500 and 4100 GHz, after transmission over 1010 km. A decrease in the gain offered by SC-DBP as the propagated bandwidth was increased can be observed. This reduction in SNR gain is due to the accumulation of NLI according to a logarithmic law for increasing bandwidth, as described in⁷. The experimental results show a SNR gain of 1.8 dB for single channel transmission being reduced to 0.7 dB for a 120 GHz propagated bandwidth, and further reduced to 0.4 and 0.25 dB for propagated bandwidths of 1.2 and 4.1 THz, respectively. These results are in line with the theoretical study from⁵.

To analyze the performance of SC-DBP in a fully loaded C-band system, Fig. 4 illustrates the MI (at optimum launch power) as a function of

distance for a 4.1 THz propagated bandwidth. A marginal gain from SC-DBP over EDC can be observed; only 0.2 b/sym gain after a 2000 km transmission distance. Despite this marginal gain, the MI gain relative to EDC only is also increased for longer transmission distances; from 0.03 b/sym over 100 km to 0.2 b/sym over 2000 km.

Conclusion

SC-DBP performance was experimentally and theoretically studied for long haul transmission systems with signal propagated bandwidth to up to 4.1 THz. It was observed that the SC-DBP gain monotonically decreased with increasing propagated bandwidth. Although this effect was previously predicted theoretically, this is the first explicit and detailed experimental assessment of this, and it is in line with the GN-model predictions.

Acknowledgment

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