

Single-Step Digital Backpropagation for O-band Coherent Transmission Systems

Romulo Aparecido^(1,*), Jiaqian Yang⁽¹⁾, Ronit Sohanpal⁽¹⁾, Zelin Gan⁽¹⁾, Eric Sillekens⁽¹⁾, John D. Downie⁽²⁾, Lidia Galdino⁽²⁾, Vitaly Mikhailov⁽³⁾, Daniel Elson⁽⁴⁾, Yuta Wakayama⁽⁴⁾, David DiGiovanni⁽³⁾, Jiawei Luo⁽³⁾, Robert I Killey⁽¹⁾, and Polina Bayvel⁽¹⁾

⁽¹⁾ Optical Networks Group, UCL (University College London), London, UK.

*romulo.aparecido.22@ucl.ac.uk

⁽²⁾ Corning Research and Development Corporation, Corning, NY 14831, USA

⁽³⁾ Lightera Labs, Somerset, NJ 08873, USA

⁽⁴⁾ KDDI Research, Inc., 2-1-15 Ohara, Fujimino 356-8502, Japan

Abstract We demonstrate digital backpropagation-based compensation of fibre nonlinearities in the near-zero dispersion regime of the O-band. Single-step DBP effectively mitigates self-phase modulation, achieving SNR gains of up to 1.6 dB for 50 Gbaud PDM-256QAM transmission over a 2-span 151 km SMF-28 ULL fibre link. ©2025 The Author(s)

Introduction

Optical networks are central to the global digital communications infrastructure^{[1],[2]} with cloud services and AI applications driving capacity demands of inter-/intra-data centre networks. To meet this growth, research has focused on accessing the available fibre bandwidth beyond C-band^[3]. The O-band, centred at 1310 nm, offers a number of benefits: it has a large bandwidth (17.5 THz) relative to the C-band; the low dispersion of standard single-mode fibre across the O-band avoids the need for large dispersion compensating filters; and it is located, spectrally, well away from the C-band, avoiding interchannel stimulated Raman scattering (ISRS) between the bands in the case of O+C-band transmission^[4]. Recent developments in bismuth-doped fibre amplifiers (BDFAs) make it possible to use a single amplifier to cover the bandwidth of the O-band^{[5],[6]}, eliminating the need for multiple parallel amplifiers and associated WDM filters, used to split and combine the different bands. However, O-band transmission also comes with some drawbacks: signals experience higher

attenuation, approximately 0.3 dB/km, due to increased Rayleigh scattering in silica, whereas C-band signals typically experience attenuation of between 0.15 dB/km and 0.2 dB/km. Additionally, the larger nonlinear coefficient and near-zero dispersion of standard single-mode fibre in the O-band result in greater nonlinear distortions, limiting throughput. In^[7], 144 coherent channels were transmitted with wavelengths ranging from 1283 nm to 1334 nm, achieving over 40 Tb/s over 45 km. A considerable performance reduction of up to 6 dB for higher signal launch power was observed in the signal-to-noise ratio (SNR) around zero dispersion wavelengths due to fibre nonlinearity.

Digital nonlinearity compensation techniques have been successfully implemented for coherent systems operating in the C-band, ranging from Volterra filters^[8], machine learning algorithms^[9], and digital backpropagation (DBP)^[10]. In the DBP algorithm, the signal is digitally back-propagated over a virtual link, where the nonlinear Schrödinger equation (NLSE) is solved in reversed steps and with inverted parameters, allowing

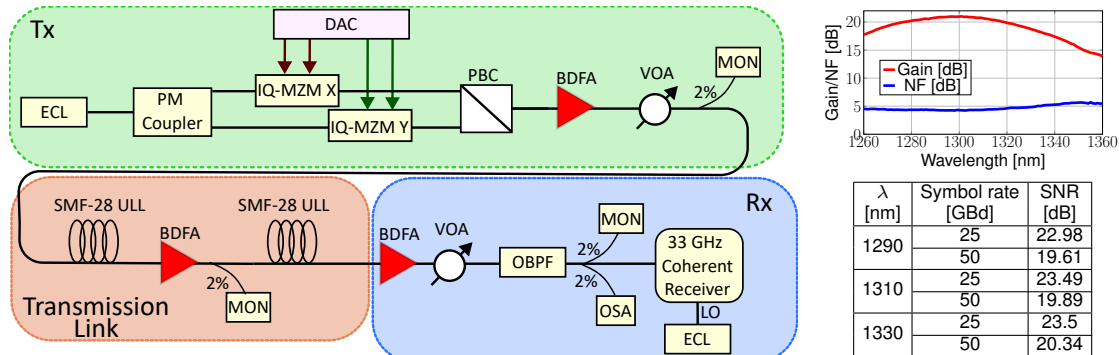


Fig. 1: O-band experimental transmission setup with measured B2B SNR values. The inset shows the gain and noise figure (NF) as a function of the wavelength for an input of 0 dBm. External cavity laser (ECL), polarisation maintaining (PM), in-phase-quadrature Mach-Zehnder modulator (IQ-MZM), polarisation-beam combiner (PBC), bismuth-doped fibre amplifier (BDFA), variable optical attenuator (VOA), optical bandpass filter (OBPF), power monitor (MON), local oscillator (LO).

full compensation of the linear and nonlinear deterministic effects. This technique, although very powerful, can present a high computational complexity as it requires two fast Fourier transform operations per step and multiple steps per span^[11]. However, the low chromatic dispersion in the O-band has the advantage of allowing a significant reduction in complexity of the DBP digital signal processing (DSP), since a smaller number of steps is required to solve the NLSE with sufficient accuracy to mitigate the nonlinearities.

In this paper we investigate the application of DBP for nonlinearity compensation in the transmission of dual-polarisation QAM signals with coherent detection in the O-band. Our experiments with 25- and 50-GBd signal transmission over a 2-span, 151-km long Corning® SMF-28® ULL G.654.C-compliant fibre link with chromatic dispersion of up to 2.5 ps/(nm·km) show that one-step DBP provides significant self-phase modulation (SPM) compensation.

Experimental Setup

Figure 1 shows the experimental transmission setup. Light from a <10 kHz linewidth ECL was first split by a PM 3-dB coupler and independently modulated by 23-GHz bandwidth IQ-MZMs to generate 25-GBd or 50-GBd 256QAM signals, shaped with a 1%-roll-off root-raised cosine filter. The QAM signals were generated offline, applying linear digital pre-distortion^[12], and the modulators were driven by a 92-GS/s arbitrary waveform generator with an ENOB of 5-bits. The signals were re-combined with a polarisation beam combiner to form a dual-polarisation QAM signal. A BDFA was used as a booster amplifier, followed by a VOA to control the launched optical power (LOP).

The BDFA comprised a 200-metre bismuth-doped fibre (BDF), backward-pumped by a 1150 nm beam, offering >20-dB gain with a 5-dB NF with a design similar to that presented in^[13]. The gain and NF versus wavelength for an input power of 0 dBm are shown in Fig. 1. The signals were transmitted over a 151-km link, comprising 2 spans of 75.5-km of SMF-28 ULL fibre with an attenuation of 0.283 dB/km at 1310 nm and a mid-link BDFA. Although SMF-28 ULL fibre may have a cutoff wavelength up to 1520 nm (note that G.654.E specification allows up to 1530 nm), negligible penalty due to multipath interference is expected in the O-band^[14].

After transmission, the fibre attenuation was compensated by a third BDFA. A second VOA controlled the power into the receiver, followed by an optical bandpass filter to remove the out-of-band amplified spontaneous emission generated by the BDFAs. Power monitors were used before the transmission block, between the two spans,

and at the receiver to assist in controlling the launched and received power, the latter being maintained at 2 dBm.

The coherent receiver consisted of a 90°-hybrid, four 70-GHz balanced photodetectors, and a 33-GHz digital sampling oscilloscope with 8-bit ADCs. The lower oscilloscope bandwidth (compared to the photodetectors) was due to practical limitations, as a single oscilloscope was used to simultaneously capture all four tributaries. A <10 kHz linewidth O-band ECL was used as a local oscillator (LO). Following detection, pilot-based DSP was used with a pilot sequence length of 2^{10} and a pilot insertion rate of 1/32^[15]. EDC or DBP was subsequently applied, with EDC compensating for residual chromatic dispersion, and DBP addressing both dispersion and nonlinear effects. Transmission performance was evaluated at three wavelengths: 1290 nm, 1310 nm, and 1330 nm. An initial launch power versus SNR sweep was performed using EDC to determine the optimal launch power. DBP was then applied at this power, sweeping the dispersion and nonlinear coefficient (γ_{DBP}) used in the algorithm to determine the values that maximise the SNR gain relative to EDC. The optimal chromatic dispersion values at 1290 nm, 1310 nm, and 1330 nm employed in the DBP were found to be -2.5, 0.01, and 2.2 ps/(nm·km), respectively. The DBP was implemented following the Wiener-Hammerstein (WH) model^[16], illustrated in Fig. 3, where a fraction κ of the link accumulated dispersion is first compensated, followed by nonlinearity compensation (a signal-power-dependent phase shift), and finally the remaining $(1 - \kappa)$ portion of the dispersion is compensated in the final stage. This single step combines the individual lengths and LOPs to account for both spans. The SNR was defined as $\text{SNR} = \mathbb{E}[|X|^2]/\mathbb{E}[|X - Y|^2]$, where X and Y are the transmitted and received signals, respectively.

O-band Transmission Results

The back-to-back (B2B) SNR values were measured for 25 GBd and 50 GBd at 1290 nm, 1310 nm, and 1330 nm for the PDM-256QAM modulation format, and the results are shown in the table in Fig 1. Each B2B SNR value is the average over 100 recorded traces. The SNR after transmission was measured over a range of launched optical powers after EDC and DBP for PDM-256QAM signals at both 25 GBd and 50 GBd, and the results are shown in Fig. 2, for the 1290 nm, 1310 nm, and 1330 nm wavelengths, respectively. Note that, since the BDFA gain was lower than the loss of the first fibre span, the launch power into the second span was lower than that into the first span, with both sets of powers

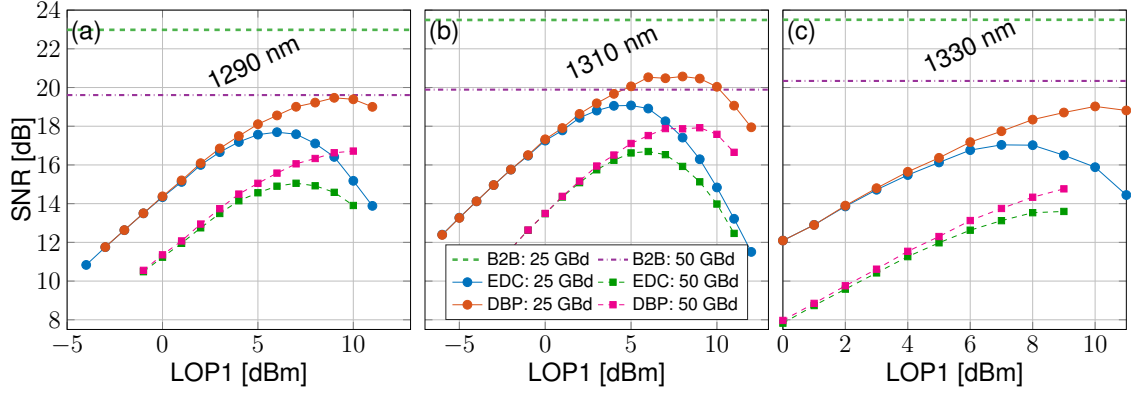


Fig. 2: SNR versus first span launch optical power (LOP1) after 256QAM signals transmission over two spans, comparing EDC and DBP with single step at 25 GBd and 50 GBd for (a) 1290 nm, (b) 1310 nm, and (c) 1330 nm.

shown in Table 1.

Tab. 1: Launch powers into the first span (LOP1) and the second span (LOP2) at the three different wavelengths.

LOP1 [dBm]	1290 [nm]	1310 [nm]	1330 [nm]
-9	-1.94	-0.33	-2.75
-6	-1.73	0	-2.56
-3	-1.3	0.36	-2.3
0	-0.8	0.96	-1.94
3	0.2	1.93	-1.42
6	1.6	3.3	-0.6
9	3.42	5	0.7

Transmission performance was assessed by computing the SNR as the average over 50 recorded traces. At 1290 nm, the SNR gain from DBP was approximately 1.8 dB at 25 GBd, measured at the optimal LOP, which resulted in the highest SNR. However, at 50 GBd, the system was limited to a greater extent by the transceiver noise, and the DBP gain was reduced to around 1.6 dB. For 1330 nm, an SNR gain of 2.0 dB was observed for the 25 GBd case, while for 50 GBd the available LOP was insufficient to assess the SNR at the optimal power; nonetheless, at 9 dBm, a gain of approximately 1.1 dB was measured by applying DBP. At 1310 nm, where the chromatic dispersion is near zero, a gain of 1.6 dB was observed for 25 GBd symbol rate, while for 50 GBd, 1.2 dB SNR gain was demonstrated. In terms of achievable information rate (AIR)^[17], calculated from the generalised mutual information, increases of 11.3%, 7.6%, and 7.7% were achieved for 50 GBd signals at 1290 nm, 1310 nm, and 1330 nm, respectively, with AIRs improving from 440 Gb/s, 494 Gb/s, and 396 Gb/s to 496 Gb/s, 535 Gb/s, and 430 Gb/s, respectively.

All nonlinearity-compensated signals shown in Fig. 2 were measured using a WH split of $\kappa = 0.5$. The resulting DBP SNR gain, relative to EDC, is presented in Fig. 3 for a range of WH split from 0 to 1. The variation in split ratio had a negligible impact on performance, indicating that dispersion can be fully compensated either before or after the nonlinearity compensation. This finding significantly simplifies the implementation, as it halves the number of FFT operations required.

In the case of wavelength division multiplexed transmission, additional interchannel nonlinear effects, such as cross-phase modulation and four-wave mixing, would lower the optimal launch powers per channel and hence would affect the SNR gains achievable with the use of single channel DBP. The low dispersion in the O-band leads to these interchannel effects being greater than in the C-band, and an assessment of this will be the subject of future experimental investigation.

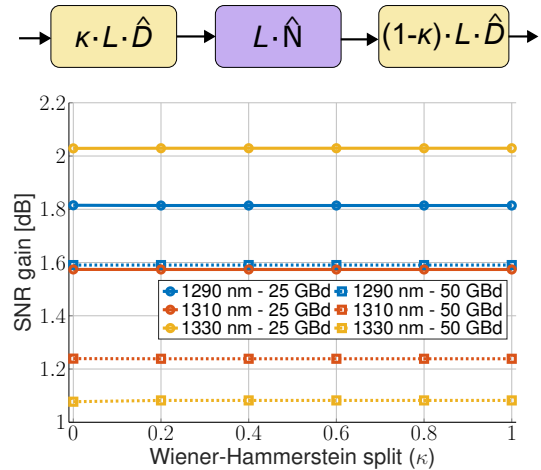


Fig. 3: Top figure: Wiener-Hammerstein model diagram. Bottom figure: SNR gain from DBP over EDC as a function of the WH split at the optimal DBP LOP.

Conclusions

To the best of our knowledge, this work represents one of the first demonstrations of digital backpropagation for nonlinearity mitigation in the O-band and near-zero dispersion regime. The low chromatic dispersion in the O-band increases the practical feasibility of DBP, as it allows the use of a single step. Low-complexity nonlinearity compensation based on a single-step DBP was demonstrated in PDM-256QAM signal transmission over a 151 km ULL G.654.C-compliant fibre link, leading to an SNR gain of up to 1.6 dB and a corresponding 11.3% increase in the achievable information rate at 50 Gbaud.

Acknowledgements

This work was supported by EPSRC Grant EP/R035342/1 Transforming Networks - building an intelligent optical infrastructure (TRANSNET), EP/W015714/1 Extremely Wideband Optical Fibre Communication Systems (EWOC), and EP/V007734/1 EPSRC Strategic equipment grant.

Romulo Aparecido is supported by a UCL Research Excellence Scholarship, and Polina Bayvel, by a Royal Society Research Professorship.

References

- [1] P. J. Winzer, D. T. Neilson, and A. R. Chraplyvy, "Fiber-optic transmission and networking: The previous 20 and the next 20 years [invited]", *Optics Express*, vol. 26, no. 18, pp. 24 190–24 239, 2018. DOI: 10.1364/OE.26.024190.
- [2] P. Bayvel, R. Maher, T. Xu, *et al.*, "Maximizing the optical network capacity", *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 374, no. 2075, p. 20 140 440, 2016. DOI: 10.1098/rsta.2014.0440.
- [3] E. Agrell, M. Karlsson, F. Poletti, *et al.*, "Roadmap on optical communications", *Journal of Optics*, vol. 26, no. 9, 093001, p. 093 001, Sep. 2024. DOI: 10.1088/2040-8986/ad261f.
- [4] M. Jarmolovičius, D. Semrau, H. Buglia, *et al.*, "Optimising O-to-U band transmission using fast ISRS Gaussian noise numerical integral model", *Journal of Lightwave Technology*, vol. 42, no. 20, pp. 7095–7103, 2024. DOI: 10.1109/JLT.2024.3417696.
- [5] V. Mikhailov, M. A. Melkumov, D. Inniss, *et al.*, "Simple broadband bismuth doped fiber amplifier (BDFA) to extend O-band transmission reach and capacity", in *2019 Optical Fiber Communications Conference and Exhibition (OFC)*, 2019, M1J.4. DOI: 10.1364/OFC.2019.M1J.4.
- [6] V. Mikhailov, J. Luo, D. Inniss, *et al.*, "Amplified transmission beyond C- and L- bands: Bismuth doped fiber amplifier for O-band transmission", *Journal of Lightwave Technology*, vol. 40, no. 10, pp. 3255–3262, 2022. DOI: 10.1109/JLT.2022.3169172.
- [7] D. J. Elson, Y. Wakayama, V. Mikhailov, *et al.*, "9.6-THz single fibre amplifier O-band coherent DWDM transmission", in *2023 Optical Fiber Communications Conference and Exhibition (OFC)*, 2023, Th4B.4. DOI: 10.1364/OFC.2023.Th4B.4.
- [8] G. Saavedra, G. Liga, and P. Bayvel, "Volterra-assisted optical phase conjugation: A hybrid optical-digital scheme for fiber nonlinearity compensation", *Journal of Lightwave Technology*, vol. 37, no. 10, pp. 2467–2479, 2019. DOI: 10.1109/JLT.2019.2907821.
- [9] R. A. de Paula, L. Marim, R. A. Penchel, *et al.*, "Mitigation of nonlinear phase noise in single-channel coherent 16-QAM systems employing logistic regression", *Optical and Quantum Electronics*, vol. 53, no. 9, p. 508, 2021. DOI: 10.1007/s11082-021-03149-7.
- [10] E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation", *Journal of Lightwave Technology*, vol. 26, no. 20, pp. 3416–3425, 2008. DOI: 10.1109/JLT.2008.927791.
- [11] G. Liga, T. Xu, A. Alvarado, R. I. Killey, and P. Bayvel, "On the performance of multichannel digital backpropagation in high-capacity long-haul optical transmission", *Opt. Express*, vol. 22, no. 24, pp. 30 053–30 062, 2014. DOI: 10.1364/OE.22.030053.
- [12] B. Geiger, E. Sillekens, F. Ferreira, R. Killey, L. Galdino, and P. Bayvel, "On the performance limits of high-speed transmission using a single wideband coherent receiver", *Journal of Lightwave Technology*, vol. 41, no. 12, pp. 3816–3824, 2023. DOI: 10.1109/JLT.2023.3277624.
- [13] V. Mikhailov, Y. Sun, J. Luo, *et al.*, "1255–1355 nm (17.6 THz) bandwidth O-band BDFA pumped using uncooled multimode 915 nm laser diode via YDF conversion stage", *Journal of Lightwave Technology*, vol. 42, no. 4, pp. 1265–1271, 2024. DOI: 10.1109/JLT.2023.3331325.
- [14] J. D. Downie, P. Sterlingov, J. Hurley, H. D. Pedro, X. Chen, and D. Seddon, "O-band transmission over high-cutoff G.654.C fiber", in *2023 Optical Fiber Communications Conference and Exhibition (OFC)*, 2023, Th3F.7. DOI: 10.1364/OFC.2023.Th3F.7.
- [15] Y. Wakayama, T. Gerard, E. Sillekens, *et al.*, "2048-QAM transmission at 15 GBd over 100 km using geometric constellation shaping", *Optics Express*, vol. 29, no. 12, pp. 18 743–18 759, 2021. DOI: 10.1364/OE.423361.
- [16] D. S. Millar, S. Makovejs, C. Behrens, *et al.*, "Mitigation of fiber nonlinearity using a digital coherent receiver", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 16, no. 5, pp. 1217–1226, 2010. DOI: 10.1109/JSTQE.2010.2047247.
- [17] A. Alvarado, T. Fehenberger, B. Chen, and F. M. J. Willems, "Achievable information rates for fiber optics: Applications and computations", *Journal of Lightwave Technology*, vol. 36, no. 2, pp. 424–439, 2018. DOI: 10.1109/JLT.2017.2786351.