Nonlinearity Mitigation in the Presence of Intercore-Crosstalk

Daniel J. Elson[1*], Benjamin J. Puttnam[2], Ruben S. Luis[2], Georg Rademacher[2], Eric Sillekens[1], Lidia Galdino[1], Domaniç Lavery[1], Yoshinari Awaji[2], Naoya Wada[2] and Polina Bayvel[1]

(1) Optical Networks Group, Department of Electronic and Electrical Engineering, UCL, London, UK
*(daniel.elson.13@ucl.ac.uk)
(2) National Institute of Communication Technology (NICT), 4-2-1, Nukui-Kitamachi, Koganei, Tokyo, 184-8795, Japan

Abstract *We experimentally investigated the performance of digital back-propagation (DBP) in the presence of intercore-crosstalk (IC-XT) in a homogeneous single-mode multi-core fibre. The DBP gain was reduced by 13.5% when the IC-XT increased from* -43.0 dB/100 km *to* -31.6 dB/100 km.

Introduction

Space-division-multiplexing (SDM) technologies have been widely proposed as a cost-effective solution to increase the transmission capacity of a single fibres by utilizing multiple cores or spatial-modes[1,2]. Single-mode multi-core fibres (MCFs) perhaps offer the simplestmigration path into SDM technology in the short term. Such fibres have been shown to support high spectral efficiency modulation formats without the complexity of high-order multiple input-multiple output (MIMO) based receivers[3] needed by multimode fibres. Impressive transmission experiments with MCFs have successfully demonstrated long-haul transmission, access metro distances and intra-data-center links, including, over 2 Pbit/s using a single-mode MCFs[3].

Over long transmission distances in single-mode single-core fibre the maximum achievable information rates are limited by nonlinear interference (NLI) noise. Well known NLI mitigation techniques include optical phase conjugation[4] and digital back-propagation[5] (DBP) at the receiver and/or transmitter. DBP acts as a solution that requires changing of the digital signal processing structure inside the transmitter or receiver. This has been used in record-breaking SMF transmission experiments and research into implementing DBP in field trials on transatlantic long-haul links are underway[6]. For MCF applications, the effects of nonlinearity on crosstalk have been investigated[7] but NLI mitigation has not been explored to date.

In this paper we experimentally evaluate the effect of intercore crosstalk (IC-XT) on the signal to noise ratio (SNR) in a 7 core MCF, together with the use of the receiver side DBP. The impact of NLI mitigation and IC-XT is investigated using a single dual polarisation (DP)-16-ary quadrature amplitude modulation (QAM) channel. To our knowledge, the first time DBP has been investigated in the presence of IC-XT. It is found that there is an SNR gain for all considered levels of IC-XT and that is acts in a similar way to additional ASE noise from transmission.

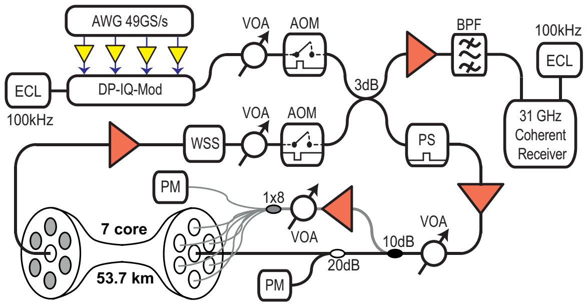

Fig. 1: Experimental setup.

Experimental Setup

An experimental strategy was devised to emulate different IC-XT values using the same fibre and the setup is shown in Fig. 1, and was based on a recirculating transmission loop[8]. The signal laser was a 100 kHz linewidth external cavity laser (ECL) at 1550.116 nm and was modulated in a dual parallel Mach-Zehnder modulator (DP-IQ-Mod). The modulator was driven by four independent arbitrary waveform generators (AWGs). Each AWG had an analogue bandwidth of 14 GHz and used a sampling rate of 49 GS/s. The generated signal was pre-equalized DP-16QAM at 24.5 GBd with a root-raised cosine pulse shape with a roll-off of 0.01. After modulation, an EDFA boosted the signal power before transmission over a 53.7 km 7-core MCF. The channel under test (CUT) used the central core of the MCF span.

Optical taps and variable optical attenuators (VOAs) were used to set and monitor the launch powers into the interfering cores. IC-XT was generated by using dummy channels taken from the loop output after each recirculation. The dummy channels were amplified and decorrelated with fibre patch cords before being re-injected into the outer cores of the fibre. Taking the dummy channels directly from the CUT as it

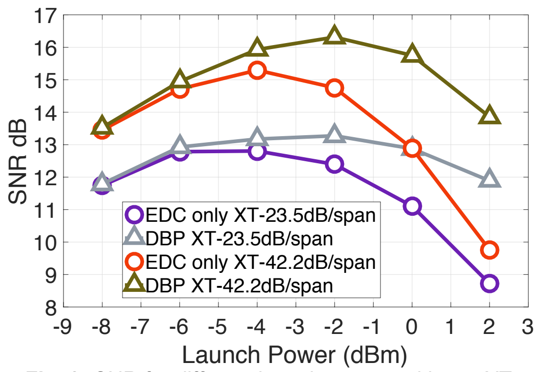

Fig. 2: SNR for different launch powers with two XT levels with and without DBP after 35 spans.

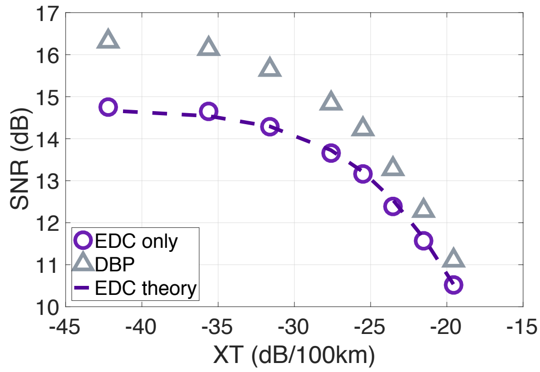

Fig. 3: SNR against XT with and without DBP after 35 spans at a launch power of -2 dBm.

propagated inside the loop ensured that the dummy channels had experienced transmission and noise degradation similar to the CUT, emulating a real MCF link. To investigate the impact of IC-XT, the signal launch powers were maintained at constant values between -8 and +2dBm while the dummy channel power was varied to achieve a range of XT/span values of -45.7 dB to -21.2 dB, equivalent to -43.0 dB/100 km and -18.5 dB/100 km.

The loop contained two EDFAs and 30 GHz bandpass filter set by a wavelength selective switch (WSS) to limit ASE. Acousto-optic modulators (AOMs) were used to control the recirculation time and the receiver was triggered for the required distance. The receiver path from the loop output contained an EDFA, a polarisation scrambler (PS) and a VOA for polarisation and power control. Signal detection was performed in a polarisation-diverse optical coherent receiver connected to a digital sampling oscilloscope with 31 GHz analog bandwidth operating at 80 GS/s. Offline processing was used to recover the signal. For the electronic dispersion compensation (EDC) case, the signal was resampled to 2 samples per symbol, followed by normalization and dispersion compensation. Polarisation de-multiplexing was performed using a MIMO structure whose equalisers were 33-tap filters updated using a decision-directed least-mean squares algorithm with carrier frequency offset and phase recovery performed in the equaliser loop. For the DBP case, the entire received signal was passed to the algorithm with 15 steps per span that was found to be optimum. For both cases the SNR was then calculated from the average of three waveforms, (each containing at least 250,000 symbols). The SNR was calculated as $\mathrm{SNR} = \frac{\mathbb{E}[|X|^2]}{\mathbb{E}[|Z|^2]}$ by assuming an additive white Gaussian channel $Y = X + Z$ with transmitted signal X, received signal Y and $Z \sim \mathcal{N}(0, \sigma^2)$ as the noise.

Results

Initially, the launch power was swept from -8 to 2 dBm for all crosstalk values and the SNR was measured. In Fig. 2, the SNR curves for IC-XT values of -23.5 dB/100 km and -42.2 dB/100 km with (triangle markers) and without DBP (circle markers) are shown. As can be expected for the EDC case increasing IC-XT reduces the received SNR regardless of launch power. The maximum achievable SNR at the optimum launch power of -4 dBm is reduced by 2.7 dB when increasing the IC-XT from -23.5 dB/100 km to -42.2 dB/100 km. When DBP is applied, the optimum launch power is increased to -2 dBm. The corresponding SNR gains with respect to the EDC case were 0.47 dB and 0.99 dB IC-XT values of -23.5 dB/100 km and -42.2 dB/100 km, respectively. This shows that DBP is still effective in removing NLI on MCF transmission in the presence of IC-XT. However, the achievable the DBP gain was clearly reduced with the increase of IC-XT.

The received SNR as a function of IC-XT is shown in Fig. 3 for a fixed launch power of -2 dBm at a distance of 1876 km. As is expected for electronic dispersion compensation (EDC) only case the SNR drops with higher IC-XT, matching our theoretical expectation[9,10]. The latter is based on assuming the SNR is described as,

$$\frac{1}{\mathrm{SNR_{EDC}}} = \frac{1}{\mathrm{SNR_{ASE}}} + \frac{1}{\mathrm{SNR_{NLI}}} + \frac{1}{\mathrm{SNR_{TR}}} + \frac{P_{XT}}{P_S},$$

where $\mathrm{SNR_{EDC}}$ is the received SNR, $\mathrm{SNR_{ASE}}$, $\mathrm{SNR_{NLI}}$ and $\mathrm{SNR_{TR}}$ as the SNR due to: ASE from optical amplifiers, nonlinear interference (NLI) noise (from the Kerr effect) and transceiver noise (the highest achievable SNR of the system in a back-to-back case). P_{XT} and P_S are the IC-XT and signal powers, respectively. When DBP is applied, the NLI is mitigated and therefore, the received SNR increases for all levels of IC-XT.

It is noted that the DBP case does not have a theory line, as the assumptions taken to produce

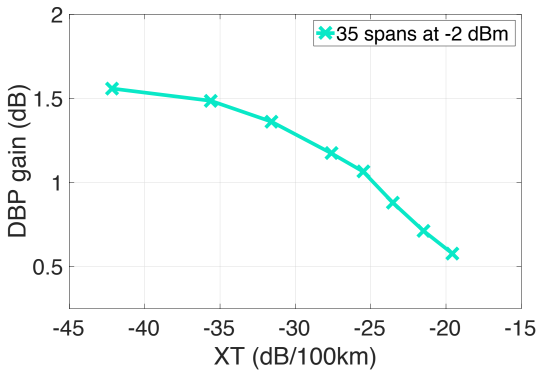

Fig. 4: DBP gain as a function of XT.

the EDC theory line are not valid for DBP. The exact theory is currently being developed but the amount of gain DBP provides, is known to be a function of the amount of signal-noise mixing[11]. As this is a stochastic component that cannot be mitigated, it is expected to decrease steadily with increasing IC-XT. The noise sources that contribute to signal-noise mixing are P_{XT}, ASE noise power or the ultimately limiting transceiver noise[8]. For larger IC-XT values there is more noise power present, that increases the amount of mixing noise power and hence reduces the achievable gain.

The measured back-to-back SNR of the system was 24.5 dB and with the transmission distance shown here of 1876 km, the received SNR is 15 dB. At this distance the effect of transceiver noise on DBP is reduced but as shown in[9], this is still significant as it is less than 16 dB away from the maximum back-to-back SNR. Hence, longer transmission distances are required until the received SNR reaches 8.5 dB, where the DBP gain would be limited by P_{ASE} and P_{XT}.

The gain in SNR from DBP as a function of IC-XT is shown in Fig. 4 at a constant launch power of -2 dBm. Here the effectiveness of DBP can be clearly seen to drop with increasing IC-XT. The step from minimum IC-XT of -42 dB/100 km to -35.66 dB/100 km the DBP gain drops by only 0.1 dB, a rate of 0.01 dB per dB. It is noted that with an IC-XT of -31.6 dB/100 km the case for equal power into all cores[10], DBP gain drops from 1.56 dB to 1.35 dB a reduction of only 13.5%. For IC-XT higher than this the DBP gain drops more significantly at a rate of 0.077 dB per dB. It is noted that in the case of full field DBP transceiver noise plays a significant part of the potential gain[9]. This has not been factored into the presented theory so does not attempt to include the phenomenon of transceiver noise on SNR. This is the subject of further work on modelling the SNR in the presence of IC-XT after DBP has been performed.

These results show that for long distance MCF transmission experiments that use nonlinear compensation techniques, reducing IC-XT can give a two-factor improvement in performance. SNR improves from better nonlinear compensation and improved OSNR.

Conclusion

For the first time we have shown that the use of DBP for NLI mitigation provides performance gain when used in a single-mode MCF transmission scenario. The gain is seen to drop with increasing IC-XT. For the case of equal launch power into all cores the DBP gain is seen to drop by just 13.5%. With lower IC-XT values DBP becomes limited by transceiver noise.

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References

[1] D. J. Richardson et. al., 'Space-division multiplexing in optical fibres,' Nat. Photonics 7 (5), pp. 354–362, (2013).

[2] G. M. Saridis et. al., 'Survey and evaluation of space division multiplexing: From technologies to optical networks,' IEEE Commun. Surv. Tutor. 17 (4), pp. 2136–56, (2015).

[3] B. J. Puttnam et. al., 'High Capacity Transmission Systems Using Homogeneous Multi-Core Fibers,' J. Light. Technol., Vol. 35, No. 6, pp. 1157–1167, (2015).

[4] I. Sackey et. al., 'Kerr Nonlinearity Mitigation: Mid-Link Spectral Inversion Versus Digital Backpropagation in 5×28-GBd PDM 16-QAM Signal Transmission,' J. Light. Technol., Vol. 33, No. 9, (2015).

[5] R. Maher et. al., 'Spectrally Shaped DP-16QAM Super-Channel Transmission with Multi-Channel Digital Back-Propagation,' Sci. Rep. 5, 8214, (2015).

[6] J. Cho et. al., 'Trans-Atlantic Field Trial Using Probabilistically Shaped 64-QAM at High Spectral Efficiencies and Single-Carrier Real-Time 250-Gb / s 16-QAM,' Proc. OFC Th5B.3, (2017).

[7] A Macho, et. al., 'Experimental evaluation of nonlinear crosstalk in multi-core fiber,' Opt. Express, Vol. 23, No. 14, (2015).

[8] B. J. Puttnam, et. al., 'Inter-core crosstalk spectrum and penalty measurements in 7- core fiber,' Proc. ECOC W.3.E.5, (2017).

[9] L. Galdino, et. al., 'On the limits of digital back-propagation in the presence of transceiver noise,' Opt. Express, vol. 25, no. 4, p. 4564, (2017).

[10] B. J. Puttnam, et. al., 'Impact of Intercore Crosstalk on the Transmission Distance of QAM Formats in Multicore Fibers,' IEEE Photon. Lett. Vol. 8, No. 2, (2016).

[11] D. Rafique et. al., 'Impact of signal-ASE four-wave mixing on the effectiveness of digital back-propagation in 112 Gb/s PM-QPSK systems,' Opt. Express 19, pp. 3449–3454, (2011).