MITSUBISHI ELECTRIC RESEARCH LABORATORIES
http://www.merl.com

Reach Enhancement of 100%for a DP-64QAM Super Channel using MC-DBP with an ISD of 9b/s/Hz

Maher, R.; Lavery, D.; Millar, D.S.; Alvarado, A.; Parsons, K.; Bayvel, P.

TR2015-015 March 2015

Abstract

A digital coherent super-receiver enables the reception and demodulation of a 7x10GBd DP-64QAM Nyquist spaced super-channel. Multi-channel DBP provides a 100% improvement in reach from 640km to 1280km of SSMF, with an ISD of 9.15b/s/Hz.

Optical Fiber Communication Conference and Exposition (OFC)

Reach Enhancement of 100% for a DP-64QAM Super-Channel using MC-DBP

Robert Maher[1,*], Domaniç Lavery[1], David Millar[2], Alex Alvarado[1], Kieran Parsons[2], Robert Killey[1], and Polina Bayvel[1]

[1]*Optical Networks Group, University College London, Torrington Place, London WC1E 7J3, U.K.*
[2]*Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA 02139, USA*
**r.maher@ucl.ac.uk*

Abstract: A digital coherent super-receiver enables the reception and demodulation of a 7x10GBd DP-64QAM Nyquist spaced super-channel. Multi-channel DBP provides a 100% improvement in reach from 640km to 1280km of SSMF, with an ISD of 9.15b/s/Hz.

OCIS codes: (060.1660) Coherent communications; (060.4080) Modulation.

1. Introduction

The achievable transmission capacity of conventional optical fibre communication systems is currently limited by non-linear distortions due to the Kerr effect. Digital back propagation (DBP) is a fibre nonlinearity mitigation technique that has previously been employed to compensate signal distortions caused by self phase modulation (SPM) on a single optical channel [1]. This technique can be extended by receiving multiple optical channels using a high bandwidth receiver for simultaneous processing and enables the mitigation of nonlinear distortions due to both SPM and cross phase modulation (XPM). Multi-channel DBP (MC-DBP) was previously demonstrated using a spectrally sliced coherent receiver to achieve an optimal Q^2-factor gain of 1dB by back propagating a 5-channel 30GBd DP-16QAM super-channel [2]. A single coherent super-receiver was demonstrated by Tanimura et al. [3] to back propagate a 4-channel 28GBd OFDM super-channel and an enhanced Q^2-factor margin was achieved at a fixed distance of 1000km.

We have previously demonstrated the transmission performance of a DP-16QAM super-channel, after propagating over 1940km of SSMF [4]. MC-DBP provided a 62% increase in transmission reach, with an information spectral density (ISD) of 7.47b/s/Hz. In this paper, we demonstrate the performance of a Nyquist spaced DP-64QAM super-channel. The entire DP-64QAM signal with seven 10GBd sub-channels is simultaneously received using a digital coherent super-receiver and the performance of each sub-channel is analysed after transmission over 1280km of SSMF, with and without MC-DBP. An irregular repeat-accumulate (IRA) low-density parity-check (LDPC) based soft decision forward error correction (SD-FEC) scheme is also implemented offline, where the code rate (R) is optimised for each sub-channel.

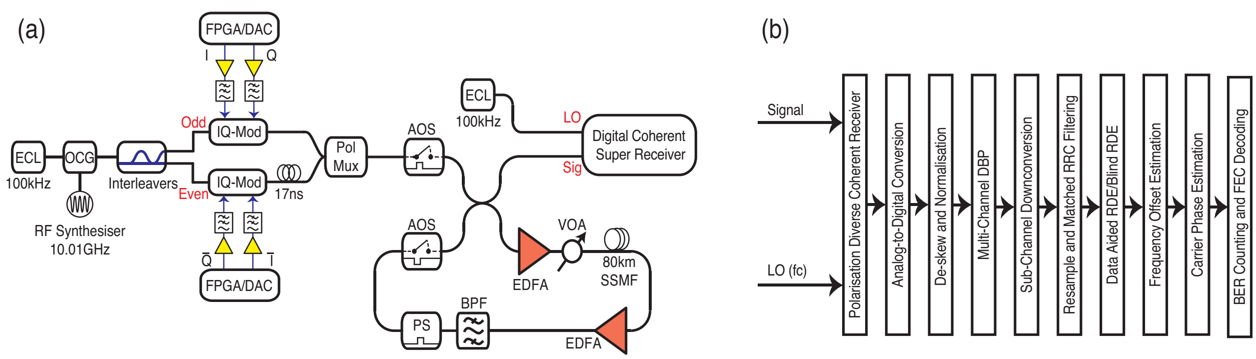

Fig. 1. (a) DP-64QAM super-channel experimental setup. AOS: acousto-optic switch, PS: polarisation scrambler, VOA: variable optical attenuator, BFP: band pass filter, EDFA: erbium doped fiber amplifier. (b) Receiver DSP functions.

2. Nyquist Spaced DP-64QAM Experimental Setup

The 7x10GBd DP-64QAM super-channel transmission system is illustrated in Fig. 1(a). A 100kHz external cavity laser (ECL) was passed through an optical comb generator (OCG) to obtain seven frequency locked comb lines with a channel spacing of 10.01GHz. The eight-level drive signals required for 64QAM were generated offline in Matlab and were digitally filtered using a root raised cosine (RRC) filter with a roll-off factor of 0.1%. The resulting in-phase (I) and quadrature (Q) signals were loaded onto a pair of field-programmable gate arrays (FPGAs) and output using two digital-to-analogue converters (DACs) operating at 20GSa/s (2Sa/sym). The odd and even sub-channels were independently modulated using two complex IQ modulators, which were subsequently decorrelated before being combined and polarisation multiplexed to form a Nyquist spaced DP-64QAM super-channel. The loop configuration was similar to that presented in [4] and included a single 80km span of standard single mode fibre (SSMF). The polarisation diverse coherent receiver had an electrical bandwidth (BW) of 70GHz and used a second 100kHz ECL as a local oscillator (LO). The frequency (f_c) of the LO was set to coincide with the central sub-channel of the DP-64QAM super-channel and the received signals were captured using a 160GSa/s real-time sampling oscilloscope with 63GHz analogue electrical BW.

The key receiver DSP blocks are illustrated in Fig. 1(b). All seven channels were simultaneously received using the digital coherent super-receiver. The skew associated with the coherent receiver and the variation in the photodiode responsivities was initially corrected before the entire super-channel was simultaneously back propagated. The number of steps per span was 20, with a symmetric split step for chromatic dispersion compensation. After MC-DBP, each channel was individually down converted to baseband and processed separately. This ensured that the coherent receiver was operated as a true super-receiver, thus demonstrating the capability of the reception and demodulation of optical super-channels. Each channel was resampled to 2Sa/sym before matched RRC filtering. A data aided radially directed equaliser (RDE) was used to equalise the signal and to undo polarisation rotations experienced during transmission. Finally, the frequency offset was removed before blind carrier phase estimation.

The proposed forward error correction (FEC) scheme is a concatenation of an outer hard decision (HD) staircase code (SCC) and an inner IRA LDPC code. The inner LDPC code was implemented offline in Matlab and 8 code rates ranging from 1/2 to 9/10 were considered. These mother codes are those from the DVB-S2 standard and were punctured via pseudorandom puncturing patterns in order to obtain a larger family of code rates. This enabled the FEC overhead (OH) to be tailored to each of the received DP-64QAM sub-channels. An outer SCC code with a rate, R = 16/17 (6.25% OH) was assumed [5], as this code produces a post-FEC bit error rate (BER) of 10^{-15} for a post-LDPC BER of $4.7{\cdot}10^{-3}$. If the hard-decisions from the LDPC decoder were below the threshold for the SCC ($4.7{\cdot}10^{-3}$), a post-FEC BER of 10^{-15} was assumed to have been achieved.

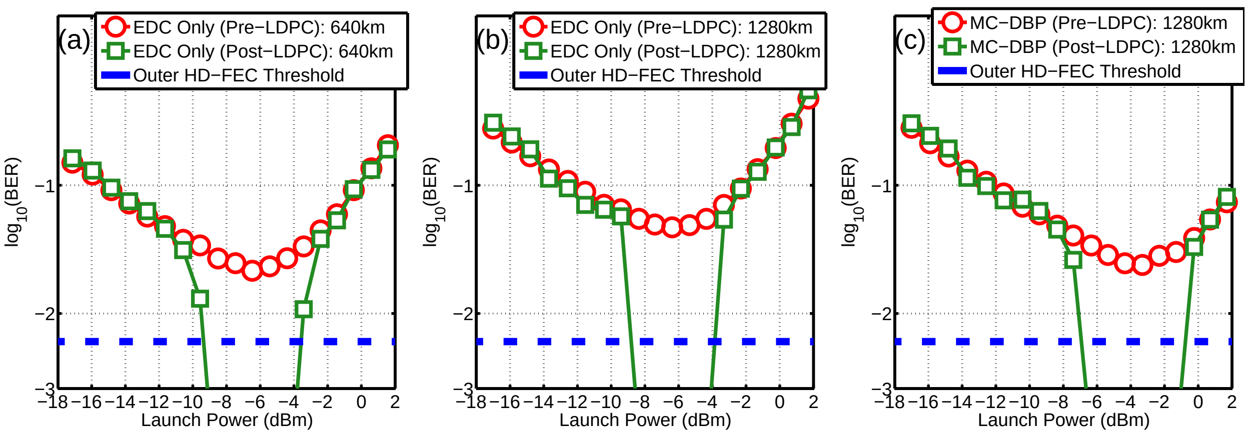

Fig. 2. Pre- and post-LDPC BER as functions of launch power for the central sub-channel. (a) EDC only after 640km of SSMF (R = 5/6), (b) EDC only after 1280km of SSMF (R = 3/4) and (c) MC-DBP after 1280km of SSMF (R = 5/6).

3. Results and Discussion

The pre- and post-LDPC BER as functions of launch power for the central sub-channel are displayed in Fig. 2. After 640km transmission over SSMF and with electronic dispersion compensation (EDC) only, the pre-LDPC BER reduced as the launch power increased from −18dBm to −8dBm, as seen in Fig. 2(a). The minimum BER was achieved at an optimum launch power of −6.5dBm, after which the pre-LDPC BER began to increase with higher launch power due to signal distortions arising from fibre non-linearity. The corresponding post-LDPC BER, using a LDPC code with R=5/6 (20% OH), is also shown in Fig. 2(a). This reduced the BER below the threshold for the outer HD-FEC code and also provided a launch power margin of ∼6dB (at the HD-FEC threshold). When the transmission distance was increased to 1280km (Fig. 2(b)), the pre-LDPC BER at the optimum launch power increased from $2.6{\cdot}10^{-2}$ to $5.6{\cdot}10^{-2}$. Therefore, a LDPC code with R=3/4 (33.33% OH) was required to maintain a consistent launch power margin at the HD-FEC threshold. However, when MC-DBP was employed in the receiver DSP, the optimum launch power increased by 3dB to −3.5dBm and there was a corresponding decrease in the pre-LDPC BER to $2.9{\cdot}10^{-2}$, as shown in Fig. 2(c). This enabled a reduction in the required OH for the SD-FEC decoder to 20%, which was identical to that used for the EDC only case after 640km transmission. Therefore, this provided the same ISD of 9.5b/s/Hz (including HD-FEC OH) for the central sub-channel but, significantly, at double the transmission distance.

Fig. 3(a) illustrates the mutual information (MI) for all seven sub-channels of the DP-64QAM signal after transmission over 1280km of SSMF. 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-64QAM. When only chromatic dispersion compensation was employed in the receiver DSP, a maximum MI of 9.76b/s/Hz was achieved for sub-channel -1. The MI varied by $\sim$0.2b/s/Hz over the central three channels, but reduced significantly towards the edge channels. This deterioration in performance is attributed to the frequency dependent effective number of bits in the receiver analog-to-digital converters and caused the MI to reduce to 8.42b/s/Hz for sub-channel -3. Therefore, the edge channels of the DP-64QAM signal significantly impaired the mean MI of the entire super-channel. Multi-channel DBP increased the MI of each sub-channel by $\sim$1b/s/Hz and provided a mean MI for the DP-64QAM super-channel of 10.12b/s/Hz.

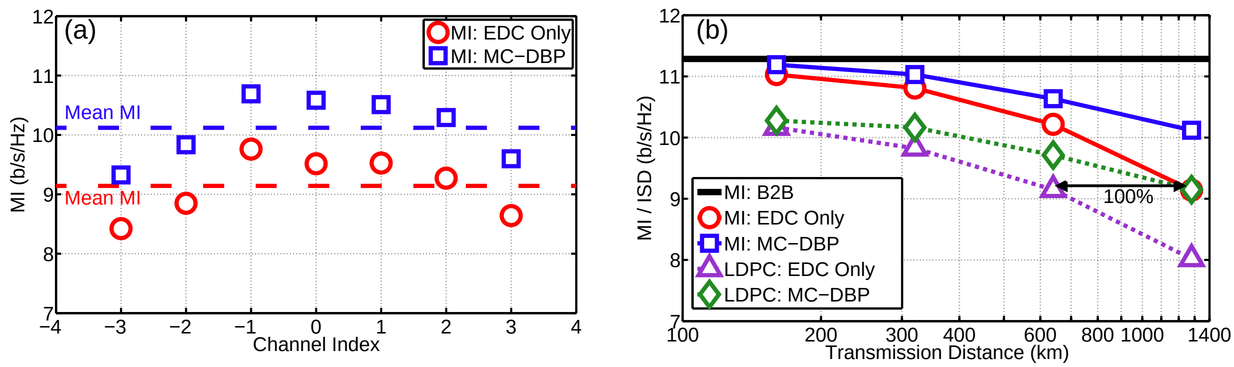

Fig. 3. (a) MI for each sub-channel with and without MC-DBP after transmission over 1280km of SSMF. (b) Mean ISD of the 7 sub-channel DP-64QAM signal, estimated using Monte Carlo integration and also for our implemented LDPC decoder.

The average MI for all seven sub-channels, as a function of transmission distance, is displayed in Fig. 3(b). The back-to-back (B2B) mean MI of the DP-64QAM super-channel was 11.3b/s/Hz and provided the maximum achievable ISD of the system. After transmission over 160km of SSMF and with only EDC (circles), the MI reduced to 11b/s/Hz, which decreased further to 9.15b/s/Hz at the maximum transmission distance of 1280km. When MC-DBP was also utilised in the receiver DSP (squares), the MI increased for all recorded transmission distances. A marginal improvement in MI was achieved at a transmission distance of 160km, however at the maximum reach, there was a 1b/s/Hz increase in the MI relative to the EDC only case. The ISD at the maximum transmission distance of the coded DP-64QAM super-channel system, achieved with a post-LDPC BER below $4.7 \cdot 10^{-3}$, is also displayed in Fig. 3(b). A constant 1b/s/Hz penalty in the achievable ISD was incurred using the LDPC decoder at all transmission distances. For EDC only (triangles), the achieved ISD followed the same trend as the estimated MI, reducing from 10.16b/s/Hz at a transmission distance of 160km to 8b/s/Hz at 1280km. Again, MC-DBP (diamonds) provided a gain in ISD of 1b/s/Hz at the maximum reach. However, for a fixed mean ISD of 9.15b/s/Hz, EDC only achieved a transmission distance of 640km, while MC-DBP achieved a reach of 1280km. This represents a 100% reach enhancement due to MC-DBP and is in excellent agreement with the central sub-channel performance shown in Fig. 2.

4. Conclusion

A high bandwidth digital coherent super-receiver enabled the simultaneous reception and subsequent multi-channel DBP of a Nyquist spaced DP-64QAM super-channel with a mean ISD of 9.15b/s/Hz and a net bit rate of 640Gb/s. MC-DBP was used to mitigate signal distortions arising from both SPM and XPM and provided a transmission reach enhancement of 100% relative to when only EDC was used in the receiver DSP.

The support under the UK EPSRC Programme Grant UNLOC (UNLocking the capacity of Optical Communications) EP/J017582/1 is gratefully acknowledged.

References

1. E. Ip and J.M. Kahn, J. Lightwav. Technol. **26**, pp. 3416-3425 (2008).
2. N.K. Fontaine et al., European Conference on Optical Communications (ECOC), Mo.3.D.5 (2013).
3. T. Tanimura et al., Optical Fiber Communications conference (OFC), Tu3A.1 (2014).
4. R. Maher et al., European Conference on Optical Communications (ECOC), P.5.10 (2014).
5. L.M. Zhang and F.R. Kschischang, J. Lightwav. Technol. **32**, pp. 1999-2002 (2014).