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Multi-Channel DBP for Reach Enhancement of High Capacity M-QAM Super-Channels

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Abstract: The combination of joint DSP and wideband digital coherent receivers are explored for the mitigation of nonlinear optical transmission impairments. Application in M-QAM super-channel transmission systems lead to increases in achievable reach and ISD.

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

1. Introduction

Increasing the throughput (net bit rate) of optical networks is vital in order to satisfy the continuing demand for information. Greater fibre throughput can be achieved by reducing the guard band between wavelength division multiplexed (WDM) channels to the Nyquist frequency and through the optimisation of both the modulation format and the code rate of the forward error correction (FEC) scheme. However, aggressive non-ideal digital filtering and zero guard band transmission significantly reduces the tolerance of optical systems to intersymbol interference (ISI) and inter-channel interference (ICI), while employing higher order modulation formats increases the sensitivity of the system to laser phase noise. Multi-channel receivers have been proposed to enable the implementation of joint signal processing of optical super-channels, as this provides information across multiple optical sub-carriers that can be exploited to mitigate ISI [1], ICI [1, 2] and laser phase noise [3]. In addition to linear channel impairment mitigation, both frequency stitched coherent receivers [4] and wide bandwidth digital coherent receivers [5–7] have been recently proposed for fibre nonlinearity compensation.

Multi-channel digital back-propagation (MC-DBP) provides the ability to mitigate fibre nonlinearities arising from both self phase modulation (SPM) and cross phase modulation (XPM). MC-DBP typically increases the information spectral density (ISD) of an optical super-channel through a reduction in the required FEC overhead [8, 9]. Alternatively, for a fixed ISD, MC-DBP can dramatically increase the maximum reach of super-channel transmission systems [10]. In this paper, we will discuss some of the challenges associated with wide bandwidth receivers for systems based on M-ary quadrature amplitude modulation (M-QAM) and the reach enhancement achieved for a dual-polarisation (DP) 64QAM super-channel that exhibits a raw bit rate of 840Gb/s.

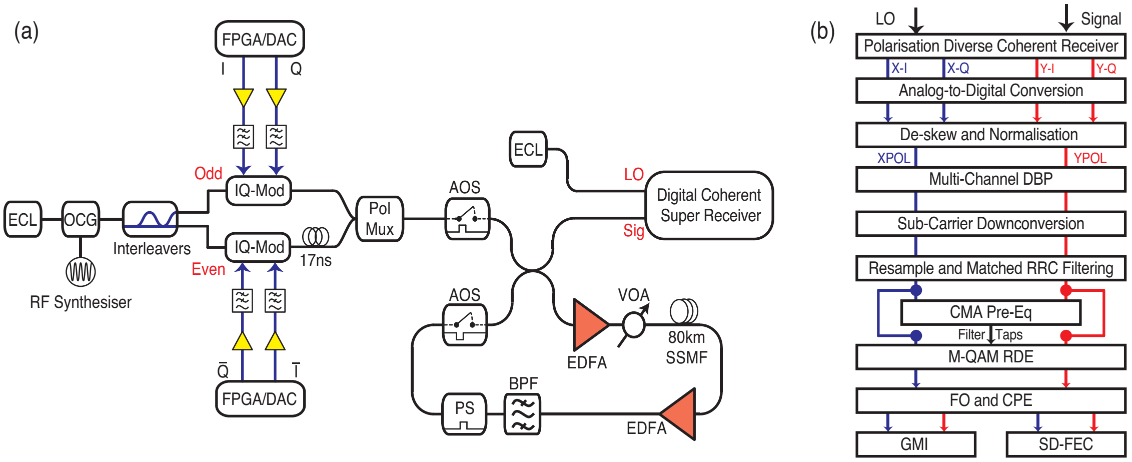

Fig. 1. (a) Experimental setup (AOS: acousto-optic switch, PS: polarisation scrambler, BPF: band-pass filter, EDFA: erbium doped fibre amplifier, SSMF: standard single mode fibre). (b) Receiver DSP functions.

2. Nyquist Spaced M-QAM Experimental Setup

The DP-M-QAM transmission system is illustrated in Fig. 1(a). For super-channel transmission, a 1.1kHz linewidth 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 multi-level drive signals required for M-QAM, where $M \in \{4, 16, 64\}$, 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 output using two digital-to-analogue converters (DACs) operating at 20GSa/s (2Sa/sym). The modulated odd and even sub-carriers were decorrelated before being combined and polarisation multiplexed to form a Nyquist spaced DP-M-QAM super-channel, consisting of seven 10GBd sub-carriers. A standard loop configuration consisting of a single 80km span of SMF was used for transmission experiments. The polarisation diverse coherent receiver had an electrical bandwidth (BW) of 70GHz and used a second 1.5kHz linewidth ECL as a local oscillator (LO). The frequency of the LO was set to coincide with the central sub-carrier of the M-QAM super-channel and the received signals were captured using a 160GSa/s real-time sampling oscilloscope with 63GHz analogue electrical BW. For single channel experiments, the OCG stage was by-passed and the DACs operated at a sample rate of 32GSa/s (4Sa/sym), thus providing a symbol rate of 8GBd.

The key receiver DSP blocks are illustrated in Fig. 1(b). Due to the large BW of the coherent receiver, the complete super-channel was simultaneously detected and sampled using the 160GSa/s analog-to-digital convertors (ADC). Therefore, the entire super-channel was back-propagated using 20 steps per span and a symmetric split step for chromatic dispersion compensation (CDC). After MC-DBP, each channel was digitally downconverted to baseband and processed separately. This ensured that the coherent receiver operated as a true super-receiver and provided the capability for joint DSP.[1] Each channel was resampled to 2Sa/sym before matched RRC filtering. A 51-tap radially directed equaliser (RDE) was used to equalise the signal and to undo polarisation rotations experienced during transmission, with a constant modulus algorithm (CMA) equaliser used for pre-convergence. The frequency offset was subsequently removed before blind carrier phase estimation was performed. Finally, the generalised mutual information (GMI) [11] was calculated and the ISD was obtained from the output of the soft decision FEC (SD-FEC) decoder (as in [10, Fig. 8]).

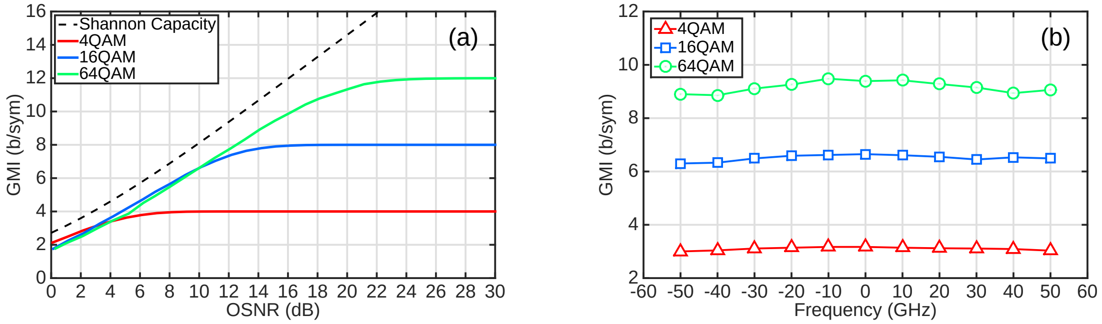

Fig. 2. (a) B2B GMI as a function of received OSNR for a single Nyquist shaped DP-M-QAM optical carrier. (b) GMI as a function of intermediate frequency offset within the high bandwidth digital coherent receiver.

3. Results and Discussion

The performance of the wide bandwidth super-receiver was initially experimentally characterised in a back-to-back (B2B) configuration using a single optical carrier and is illustrated in Fig. 2. The GMI, measured over both signal polarisations, as a function of the received optical signal to noise ratio (OSNR), is shown in Fig. 2(a). For the coded system based on DP-4QAM, the GMI increased from 2.14b/sym at an OSNR of 0dB to the maximum GMI of 4b/sym at an OSNR of 10dB. An important aspect of the GMI curves, is the crossing points between modulation formats, as this indicates the optimum modulation order for a given OSNR. For example, at an OSNR of 3dB, greater ISD was achieved using the DP-16QAM format and a low code rate, as apposed to employing DP-4QAM and a high code rate. A corresponding crossing point occured between DP-16QAM and DP-64QAM at an OSNR of 10dB and a GMI of 6.6b/sym. This characterisation provides an indication of the optimum modulation format and FEC overhead for each sub-carrier that constitutes a super-channel, based on the OSNR achieved at the receiver.

The single channel performance in Fig. 2(a) was verified when the frequency offset between the source laser and the LO was $\sim$0GHz. However, in a super-channel transmission system where the full bandwidth of the receiver is required to simultaneously detect multiple channels, the performance of the receiver at large frequency offsets becomes critical for high cardinality modulation formats. Fig. 2(b) illustrates the GMI as a function of frequency offset for all three modulation formats at OSNRs of 3dB, 10dB and 16dB, for 4, 16 and 64QAM respectively. For DP-4QAM, a very small variation in GMI of 0.17b/sym was incurred across the entire frequency range. This variation increased to

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[1] The Multi-Channel DBP and Sub-Carrier Downconversion DSP blocks were by-passed for single channel back-to-back experiments.

0.35b/sym for DP-16QAM and was a maximum at 0.62b/sym for the DP-64QAM format. The reason for an increased performance degradation as a function of the modulation order was due to the frequency dependent effective number of bits (ENOB) of the receiver ADCs. The ENOB varied from 5bits at a frequency of 0GHz to 4bits at an offset frequency of 60GHz. Although, the reduction in ENOB was only 1bit over the entire BW, such a variation can be critical for higher order formats, such as 64QAM, which require greater resolution to achieve the maximum per-channel ISD.

To analyse the performance of the wide BW receiver, super-channel transmission experiments were carried out. The ISD of each super-channel sub-carrier was calculated after transmission over 1280km of SMF and is illustrated in Fig. 3(a). When only CDC was employed in the receiver DSP, a constant ISD of 8.47b/s/Hz was achieved for the central three sub-carriers. However, the performance of the super-channel degraded sharply towards the outer sub-carriers, with the minimum ISD of 6.77b/s/Hz being achieved for sub-carrier -3. This degradation in performance was due to both the frequency dependent ENOB of the receiver (as seen in Fig. 2(b)) and a varying OSNR across the super-channel. When MC-DBP was performed, there was a reduction in the received BER of each sub-carrier, which enabled a corresponding increase in the code rate of the SD-FEC implementation. Therefore the mean ISD across the entire super-channel increased from 7.9b/s/Hz (CDC only) to 8.97b/s/Hz when MC-DBP was employed. This represents an increase in ISD of ∼1b/s/Hz for a DP-64QAM system using MC-DBP and provided an overall throughput of 628Gb/s.

In order to verify the increase in transmission reach afforded by MC-DBP, the mean ISD of the DP-64QAM super-channel was recorded as a function of transmission distance and is illustrated in Fig. 3(b). When only CDC was performed in the receiver DSP, a mean ISD of 10b/s/Hz was achieved after a transmission distance of 160km, which reduced to 8b/s/Hz at the maximum transmission distance of 1280km. However, when MC-DBP was implemented, an ISD of 9.15b/s/Hz was achieved after transmission over 1280km, which represents a 100% increase in reach relative to when only CDC was employed (ISD of 9.15b/s/Hz after 640km).

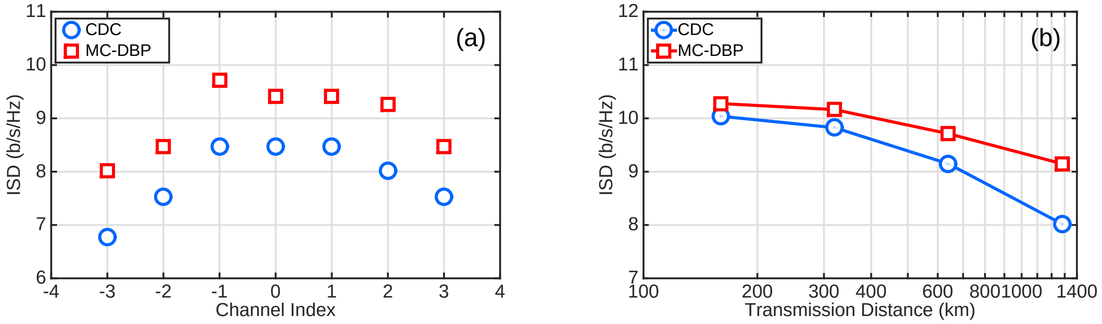

Fig. 3. (a) ISD of each 10GBd DP-64QAM sub-carrier, with and without MC-DBP. (b) Mean super-channel ISD as a function of transmission distance, with and without MC-DBP.

4. Conclusion

Wide bandwidth coherent receivers offer the potential to simultaneously detect multiple optical carriers for joint processing in order to compensate various transmission impairments. MC-DBP mitigates nonlinear distortion arising from both SPM and XPM, thus effectively enabling a reduction in the mean FEC overhead of an optical super-channel. This provides either an increase in ISD of ∼1b/s/Hz or alternatively, a significant enhancement in transmission reach for a fixed ISD. However, it is important to note, that the frequency dependent ENOB of the high speed ADCs in the receiver pose a significant obstacle to the processing of higher order modulation formats and may require optimal loading of each sub-carrier in terms of modulation format and code rate, in order to achieve an acceptable post-FEC BER.

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