Algorithms and Reach Enhancement for Ultra High Bandwidth Transceivers

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Abstract: The simultaneous reception of a DP-256QAM super-channel with an achievable information rate of 1.32Tb/s is demonstrated using a high bandwidth optical transceiver. An SNR improvement of 1dB is also demonstrated using MC-DBP after 2000km transmission.

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

1. Introduction

Coded modulation, which is a combination of non-binary modulation and forward error correction (FEC), is predominantly coupled with spectral shaping and is the primary methodology used to increase the information rates of optical communications links. For a capacity-achieving code and zero-guard band transmission, the spectral efficiency (SE) of an optical carrier can only be improved by increasing the order of the modulation format, which inherently requires a corresponding increase in the signal-to-noise ratio (SNR). The upper limit on the SNR of coherent optical transmission systems is currently limited by the inherent performance constraints of practical transceiver subsystems. For a finite SNR, the challenge is to optimally encode each optical carrier to maximise SE at the output of the transmitter and thus, subsequently maintain this information rate over the greatest possible transmission distance, which typically requires the mitigation of fibre non-linearity. There have been many techniques employed to mitigate fibre non-linear distortion, such as digital back-propagation (DBP) [1], optical phase conjugation [2], Volterra series non-linear electronic equalisation [3, 4], maximum likelihood sequence estimation [5–7] and the non-linear Fourier transform [8]. Recently, the advent of high bandwidth (BW) digital coherent receivers has enabled the mitigation of both inter- and intra-channel non-linearity using multi-channel DBP (MC-DBP) [9–12], with transmission reach enhancements of up to 100% demonstrated [13].

This paper highlights some of the practical limitations of current state-of-the-art digital coherent transceivers and the gain in transmission reach achieved using MC-DBP for the dual polarisation (DP) 256-quadrature amplitude modulation (QAM) format.

2. DP-256QAM WDM Transmission System

The experimental setup used in this work is illustrated in Fig. 1. An external cavity laser (ECL) with a linewidth of 1.1 kHz was passed through an optical comb generator (OCG) that provided 15 frequency and phase locked comb lines with a 3 dB variation in power uniformity. The multi-level drive signals required for the 256QAM format were generated offline and spectrally shaped using a root raised cosine (RRC) filter with a roll-off factor of 1%, before being upsampled to 4 Sa/sym. The in-phase (I) and quadrature (Q) components were loaded onto a pair of digital-to-analogue convertors (DAC) operating at a sample rate of 32 GSa/s. The comb lines were split into odd and even sub-carriers using cascaded de-interleavers before being bulk modulated using two IQ modulators and polarisation multiplexed (Pol. Mux.) to form a 15 sub-carrier 8 GBd DP-256QAM super-channel. For back-to-back (B2B) measurements, the output of the pol. mux. was passed directly into the signal port of the high BW digital coherent receiver, which consisted of a 90° optical hybrid, 70 GHz balanced photodiodes and a real time sampling oscilloscope with a sample rate of 160 GSa/s and an electrical BW of 63 GHz. A second ECL was used as a local oscillator (LO) and an amplified spontaneous emission (ASE) noise source was used to vary the received SNR. The offline DSP implementation was identical to that described in the Methods section of [12]. A recirculating fibre loop was employed for transmission experiments and consisted of a single 100 km span of Corning® Vascade® EX2000 fibre, two EDFAs, a band pass filter (BPF) for ASE rejection, a loop synchronous polarisation scrambler (PS) and two acousto-optic switches (AOS). The ASE noise loading stage was removed for the transmission experiments and the performance of the system was analysed by estimating the mutual information (MI) as a function of carrier launch power. The launch power was set by adjusting the variable optical attenuator (VOA), positioned directly before the fibre span.

Fig. 2 (a) illustrates the experimentally measured B2B MI, calculated over both polarisations, as a function of the received SNR for the central sub-carrier from the DP-256QAM wavelength division multiplexed (WDM) signal. The received SNR was ideally estimated over both polarisations in the receiver DSP through: SNR $= \sigma_x^2/\sigma_z^2$, where σ_x^2 is

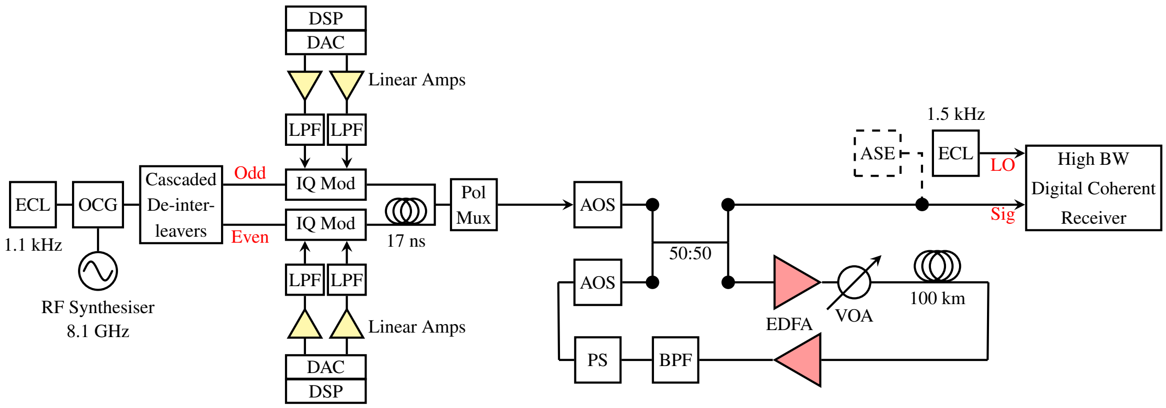

Fig. 1: Experimental setup for the 15 sub-carrier DP-256QAM super-channel transmission system. (LPF: low pass filter)

the average received signal power and σ_z^2 is the noise power. From Fig. 2 (a), it is observed that the MI was 2 b/sym at an SNR of 0 dB and increased to 8 b/sym at an SNR of 12.5 dB, before reaching a maximum of 12.9 b/sym at a received SNR of 20.7 dB. The maximum MI of 12.9 b/sym is below the theoretical maximum for the DP-256QAM format, which is 16 b/sym ($2 \cdot \log_2(256)$). This was due to a saturation in the received SNR, which was dominated by the performance limitations of the state-of-the-art transceiver subsystems used in this work. As the power of the noise loading stage was reduced to zero, or removed completely, the maximum recorded SNR remained saturated at 20.7 dB. The key components that limited the B2B SNR performance of the transceiver were the DAC (effective number of bits (ENOB): ~4 bits at 5 GHz), the linear electrical amplifiers in the transmitter (noise figure: 6 dB) and the ADCs (ENOB: ~4.8 bits). These components provided a maximum SNR of ~26 dB, which was further degraded due to the non ideal blind DSP implementation (~1 dB penalty) and the OCG and de-interleaver stages (~3 dB penalty).

Fig. 2 (b) illustrates the B2B MI of all 15 sub-carriers without noise loading, which were simultaneously received and individually downconverted to baseband in the digital domain before passing through the remaining DSP functions. The MI for the central carrier was 12.9 b/sym, which decreased towards the outer sub-carriers, with an identical MI of 9.9 b/sym achieved for sub-carriers ±7. The roll-off in MI towards the high frequency sub-carriers was due to the inherent frequency dependent ENOB of the receiver ADCs. The worst performance was observed for sub-carrier +4, which was simultaneously degraded due to a lower ENOB at the ADC interleaving frequency (32 GHz) and the sub-optimal power uniformity across the comb. The average MI of the DP-256QAM super-channel was 11 b/sym, which indicates that the largest possible information rate that could be achieved with this digital coherent transceiver is 1.32 Tb/s, with an average SE of 10.9 b/s/Hz. Once this level of performance has been realised in a B2B scenario, the key challenge is to maintain this throughput over an appreciable transmission distance. One concept that provides a significant reach enhancement for high throughput optical communications systems is MC-DBP.

3. DP-256QAM Super-Channel Transmission with MC-DBP

The transmission performance of the DP-256QAM super-channel was analysed after transmission over 2000 km of fibre. Fig. 3 illustrates the experimentally measured MI of the central sub-carrier as a function of launch power. When only electronic dispersion compensation (EDC) was applied within the digital coherent receiver, the MI increased

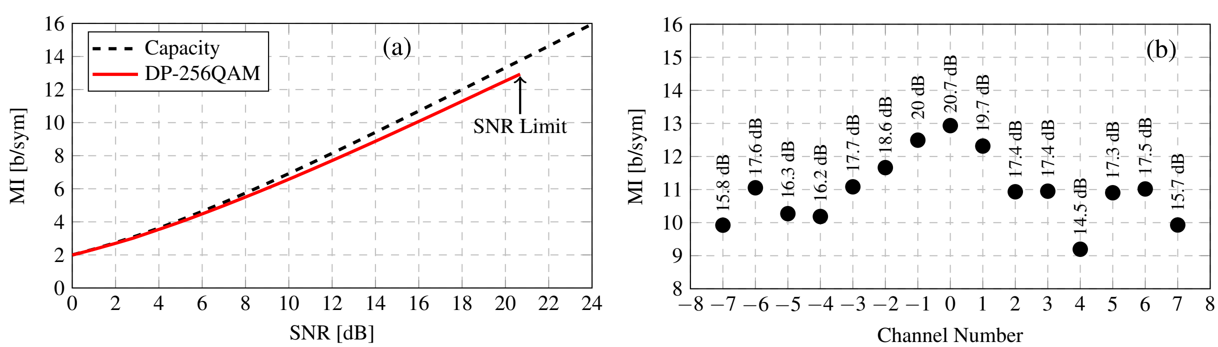

Fig. 2: (a) Experimentally measured B2B MI (measured over two polarisations) as a function of SNR for the central sub-carrier of the DP-256QAM super-channel and (b) corresponding MI (and received SNR) for each DP-256QAM sub-carrier without noise loading.

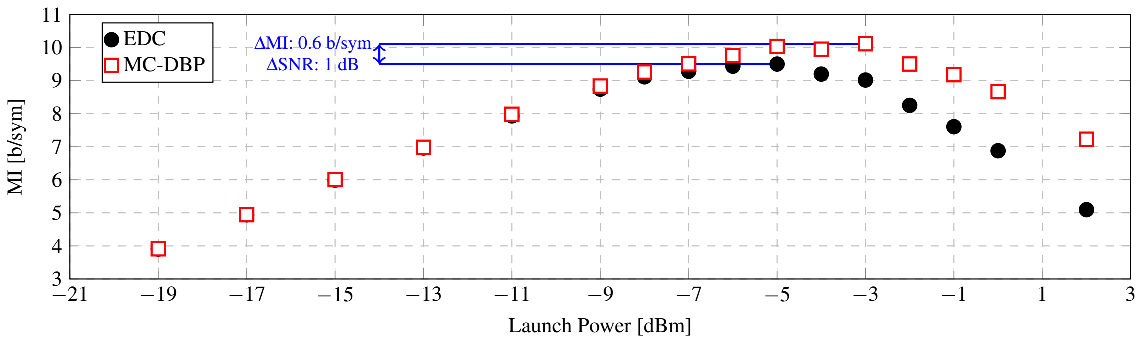

Fig. 3: MI of the central sub-carrier as a function of launch power, for EDC only and with MC-DBP, after 2000 km transmission.

linearly with power from 3.9 b/sym at a launch power of -19 dBm, to 7.9 b/sym at a power of -11 dBm. At the optimum launch power of -5 dBm, a MI of 9.5 b/sym was achieved, while the measured SNR was $\sim$15 dB. For higher launch powers, the MI degraded sharply due to the increased influence of fibre non-linearity. The implementation of MC-DBP, where all 15 sub-carriers were digitally back-propagated, provided no performance improvement in the linear transmission regime, as expected. However, in the non-linear regime, the optimum launch power was increased by 2 dB to -3 dBm and the MI also exhibited a corresponding increase of 0.6 b/sym (from 9.5 b/sym to 10.1 b/sym). This translates to a 1 dB increase in the received SNR at the optimum launch power relative to the EDC only scenario. This improvement in SNR due to MC-DBP can be used to either increase the overall throughput of the system for a fixed transmission distance or alternatively, to increase the reach of the system for a fixed throughout. For this experimental transmission test-bed, a 1 dB increase in SNR provided an enhanced reach of $\sim$700 km, which corresponds to a 35% increase in transmission distance.

The finite SNR of a coherent optical transceiver is an inherent property that cannot be compensated and currently represents a significant obstacle to increasing the throughput of lightwave communications systems. Future increases in throughput are reliant on the continual development of DACs, ADCs, implementable capacity approaching FEC codes and adequate mitigation of transmission impairments, all of which will be of paramount importance if optical fibre communications are to keep pace with the projected growth in global data traffic.

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