Unrepeatered Transmission over 253.4 km Ultra Low Loss Fibre Achieving 6.95 (b/s)/Hz SE using EDFA-only Pre-amplifier

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Abstract *A 560 Gb/s (7x80 Gb/s Nyquist spaced PDM-16QAM) superchannel achieving 6.95 (b/s)/Hz spectral efficiency is transmitted over 253.4 km SMF-28® ULL fibre using only EDFA pre-amplification and full-field digital back-propagation, corresponding to a record SE-distance product of 1761.1 b/s/Hz·km.*

Introduction

Achieving a longer span length for a given transmitted capacity is key for unrepeatered inter-city transmission systems and unrepeatered subsea systems, such as island arcs. Unrepeatered links provide a cost-efficient solution as no in-line active elements are required.

Enormous progress in unrepeatered transmission was recently reported in a demonstration based on polarization division-multiplexed quadrature phase shift keying (PDM-QPSK) modulation with a 50GHz wavelength division multiplexing (WDM) grid[1]. Transmission of 4 x PDM-QPSK channels, with a gross SE of 1 (b/s)/Hz enhanced ROPA and Raman amplification over an unrepeatered 523 km of ultra large effective area A_{eff} (112 μm²) and low-loss fibre (0.161 dB/km) was reported[2]. However, transmission systems with a high spectral efficiency (SE) are required in order to satisfy increasing capacity demands on the optical network. For this reason, transmission of PDM 16-*ary* quadrature amplitude modulation (QAM) with a net SE of 3.12 (b/s)/Hz over 304 km has also been demonstrated[3]. This was enabled by Raman amplification, hybrid fibre spans (large-Aeff (152 and 110 μm²) and low-loss fibre (~0.158 dB/km)) and single channel digital back-propagation (DBP).

In this paper we experimentally investigate transmission of a 560 Gb/s (7 x 80 Gb/s PDM-16QAM) Nyquist-spaced superchannel, achieving a net SE of 6.95 (b/s)/Hz over 253.4 km of ultra-low loss Corning® SMF-28® ULL fibre with A_{eff} of 83 μm² using only EDFA receiver pre-amplification. It is, to the best of our knowledge, the highest SE-distance product (1761.1 b/s/Hz·km) reported to date. The transmission distance of 253.4 km was achieved through the application of full superchannel field (7-WDM channels) DBP[4], which mitigates nonlinear distortions resulting from self-phase modulation (SPM), inter-carrier cross-phase modulation (XPM), and other deterministic nonlinearities.

Nyquist WDM PDM-16QAM Unrepeatered Transmission Setup

The experimental configuration of the 7-channel 10GBd PDM-16QAM unrepeatered transmission system is illustrated in Fig. 1. An external cavity laser (ECL) with 100kHz linewidth was passed through an optical comb generator (OCG), consisting of a Mach-Zehnder modulator (MZM) followed by a phase modulator, both overdriven with a 10.01GHz sinusoidal signal. This generated 7 evenly-spaced, frequency-locked comb lines that were subsequently separated into odd and even carriers using three cascaded Kylia micro-interferometer (MINT) interleavers. The odd and even carriers were modulated using two distinct IQ modulators. Four mutually decorrelated

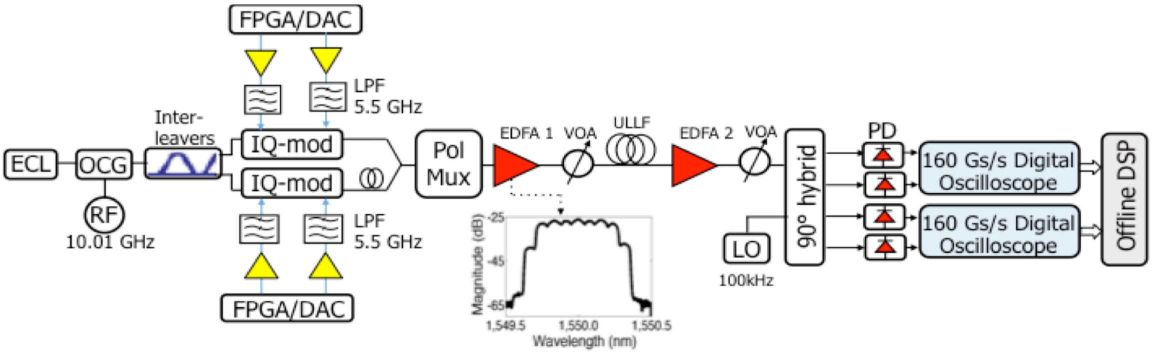

Fig. 1: Superchannel unrepeatered transmission setup.

pseudo random bit sequences (PRBS) of length 2^{15}-1 were digitally generated and mapped to 16QAM symbols, sampled at 2 samples/symbol. The signals were subsequently filtered using a truncated root-raised-cosine (RRC) filter with a roll-off of 0.1%. The resulting pulse shaped in-phase (I) and quadrature (Q) signals were used to drive a digital-to-analog convertors (DACs) operating at 20GS/s. An 8th-order analog electrical low pass filter (LPF) with a cut-off frequency of 5.5GHz was used to remove the images. The odd and even channels were optically de-correlated (17 ns) before being combined and passed through a polarization multiplexing emulation stage, where the signal was split and delayed before recombination in orthogonal polarizations stated. This formed a 560 Gb/s superchannel (7x10GBd PDM-16QAM). The channel spacing for the wavelength division multiplexed signals was equal to the symbol rate plus 0.1%[*], achieving a gross SE of 7.99 (bit/s)/Hz. Assuming a 15% overhead of the Soft-Decision Forward Error Correction (SD-FEC) code[6] which is able to correct a bit-error-rate (BER) of 1.9×10^{-2}, the net SE was 6.95 (b/s)/Hz, the highest reported in an unrepeatered transmission system.

For the back-to-back analysis, the signal was passed directly to the coherent receiver. For the transmission experiments, the output of polarizations multiplexing was connected to an erbium doped fibre amplifier (EDFA 1) with a noise figure of 4.5dB and a variable optical attenuator (VOA) to adjust the input power to the ULL fibre. The received signal and local oscillator laser (ECL with 100kHz linewidth) were combined using a Kylia 90° optical hybrid (CH28) and balanced photodetectors with 70GHz electrical bandwidth. The signal and LO power at the photodetectors were -6 and +1 dBm, respectively. The received signals were digitized using two synchronized 160Gsamples/s real time sampling oscilloscopes with 63GHz analog bandwidth.

The offline linear digital signal processing (DSP) initially resampled the received signals to two samples per symbol prior to ideal chromatic dispersion compensation and frequency domain RRC matched filtering. The signal was equalized using a 21-tap (T/2 spaced) radially directed equaliser (RDE) followed by fourth power frequency offset estimation and decision directed carrier phase estimation (64 symbol sliding window)[7]. Bit error rate (BER) estimation was performed on the central WDM channel and the Q^2 factor was calculated from the BER.

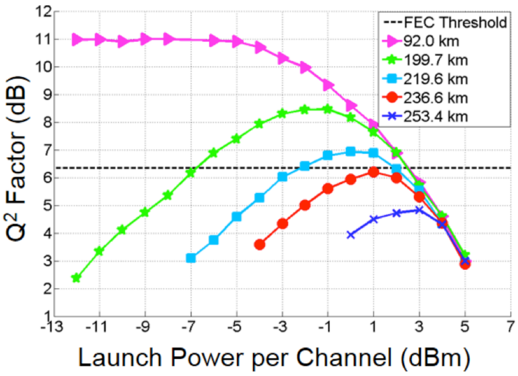

Fig. 2 Q^2 factor of PDM-16QAM Nyquist-WDM signals vs launch power per channel for different span lengths.

The nonlinear DBP DSP was applied before the linear DSP. Initially, the signal was sampled at 160 Gsample/sec. An ideal sinc filter was used to select the DBP bandwidth and then the DBP algorithm[4] was applied.

The optical power spectrum of PDM-16QAM superchannel at Nyquist spacing with a roll-off of 0.1% is also illustranted inset Fig. 1. The spectrum was measured by connecting the monitor port of EDFA 1, with an output power of 0 dBm, to an optical spectrum analyzer with 0.01 nm resolution. The seven WDM channels exhibited a power variation < 1dB and the unused comb lines were supressed by ~14dB.

Results and Discussions

All measurements were taken for the central channel of the comb, located at 1550 nm. The superchannel back-to-back implementation penalty of 1.3 dB relative to the theoretical SNR limit was achieved at a BER of 1.9×10^{-2}, which corresponds to a soft decision FEC requiring 15% overhead[6].

The performance of the PDM-16QAM superchannel unrepeatered transmission over different span lengths is presented in Fig. 2. The Q-factor measurement for each span length was performed by varying the signal launch power. The sensitivity was limited by the shot noise at the receiver for low launch powers. The shot noise limit for 10 GBd PDM-16QAM at a BER of 1.9×10^{-2} is -43.3 dBm. The 4.5 dB noise figure of the pre-amplifier combined with a 1.3 dB implementation penalty, limited the sensitivity to -40.0 dBm. The transmission penalty, the optimum launch power and the amount of nonlinear noise increased for long span lengths. The span lengths of 92.0, 199.7 and 219.6 km exceeded the FEC threshold (6.3dB Q^2 factor), however, due the increase of nonlinearity, it was not possible to reach the FEC threshold for 236.6 and 253.4 km. To improve the performance of the system, full field digital back-propagation was applied to mitigate for both intrachannel

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[*] An artificial performance enhancement is observed when using an odd/even channel modulation scheme, while operating with a channel spacing equal to the symbol rate[5]. Experimentally, we determined that a small shift in channel espacing (10MHz) was sufficient to negate this unrealistic performance improvement, data. It was confirmed using simulations with de-correlated data.

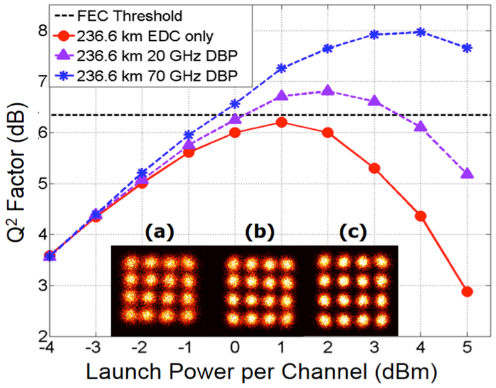

Fig. 3: Performance of PDM-16QAM Nyquist-WDM signals over 236.6 km span length transmission.

and interchannel nonlinear distiortions within the superchannel. The transmission over 236.6 and 253.4 km applying only electronic dispersion compensation (EDC), single channel and full superchannel field back-propagation is presented in Fig. 3 and 4 respectively. The constellation diagrams for (a) EDC only, (b) single channel DBP (central channel with 20 GHz DBP bandwidth), and (c) full superchannel field DBP compensation at the optimum launch power for each case are also illustrated in Figs. 3 and 4 (inset). For both 236.6 km and 253.4 km span lengths, the optimum Q^2 factor was improved by 0.7 dB when applying only the central channel DBP (20 GHz bandwidth), and 1.8 dB for full field (70 GHz bandwidth) DBP. For each power setting, the number of steps per span (*Np*) and the nonlinear coefficient parameters (γ) of the DBP algorithm were optimized. The optimum γ was 2.5 $(W.km)^{-1}$ for 20 GHz DBP bandwidth and 1.1 $(W.km)^{-1}$ for the full superchannel bandwidth. *Np* saturated at 40 steps for all cases.

A recent experimental investigation of single span transmission[3] demonstrated a 0.5 dB Q-factor gain when using single channel DBP, which is in agreement with the 0.7 dB gain seen in this work. From Fig. 3 and 4 it can be seen that the gain can be further increased to 1.8 dB when applying full-field DBP. This demonstrates both the efficacy and applicability of full-field DBP in single span transmission systems

Fig. 5 shows the superchannel power spectral density of the coherently detected signal after 253.4 km unrepeatered transmission with 5 dBm launch power (signal sampled at 160 Gsample/sec) and different bandwidths selected for DBP. The digital sampling oscilloscope and the coherent receiver provided sufficient electrical bandwidth to capture the entire superchannel.

Conclusions

In this paper we have demonstrated 7-channel Nyquist spaced PDM-16QAM unrepeatered transmission over 253.4 km of SMF-28 ULL fibre using only EDFA pre-amplification and full superchannel field digital back-propagation. This result represents a net SE of 6.95 (b/s)/Hz; the highest SE and the highest SE-distance product (1761.1 b/s/Hz·km) in a unrepeatered transmission system reported to date.

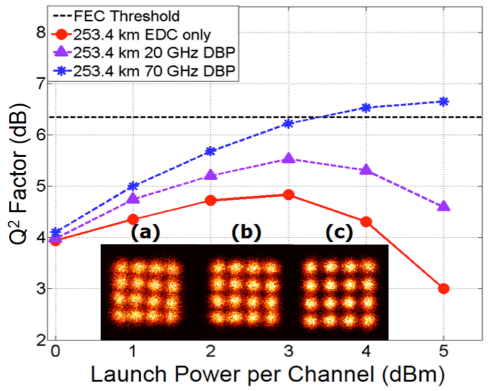

Fig. 4: Performance of PDM-16QAM Nyquist-WDM signals over 253.4 km span length transmission.

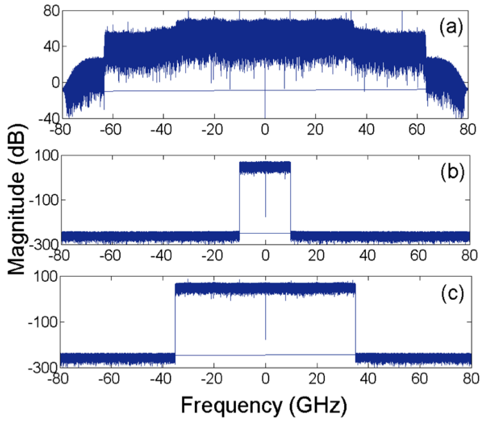

Fig. 5: a) Seven channel Nyquist-WDM coherently detected signal, (b) 20 GHz DBP bandwidth filter, and (c) 70 GHz DBP bandwidth filter.

Acknowledgements

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