Unrepeated Transmission over 253.4 km Ultra Low Loss Fiber Achieving 6.95 b/s/Hz SE using only EDFA Pre-amplification

Lidia Galdino [(1)], Gabriele Liga[(1)], Domaniç Lavery[(1)], Robert Maher [(1)], Tianhua Xu [(1)], Masaki Sato[(1,2)], Robert I. Killey [(1)], Seb J. Savory[(1)] Benn C. Thomsen[(1)] and Polina Bayvel[(1)]

[(1)] Optical Networks Group, University College London, Torrington Place, London WC1E 7JE, United Kingdom (l.galdino@ee.ucl.ac.uk)
[(2)] NEC Corporation, Abiko, Japan

Abstract *A 560 Gb/s (7x80 Gb/s Nyquist spaced PDM-16QAM) superchannel achieving 6.95 b/s/Hz spectral efficiency (SE) is transmitted over 253.4 km ULLF using only EDFA pre-amplification and full field nonlinear backpropagation, corresponding to a record SE-distance product of 17611.3 b/s/Hz·km.*

Introduction

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

Enormous progress in unrepeated transmission was recently made 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 four PDM-QPSK channels, with a net SE of 1 b/s/Hz enhanced ROPA and Raman amplification over an unrepeated 523 km (557 km single channel) of ultra large effective area A_{eff} (112 μm²) and low loss fiber 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 4.18 b/s/Hz, and Raman amplification over 240 km of large-A_{eff} (133 μm²) has also been demonstrated.

In this paper we experimentally investigate transmission of a 560 Gb/s (7 x 80 Gb/s PDM-16QAM) superchannel at Nyquist spacing achieving a net SE of 6.95 b/s/Hz over 253.4 km of ultra-low loss Corning SMF-28 fiber (ULLF) 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 (17611.3 b/s/Hz·km) reported so far and the longest single span used for transmitting a PDM-16QAM signal. The transmission distance of 253.4 km was achieved through the application of full field digital back-propagation (DBP)[4], which mitigates nonlinear distortions resulting from self-phase modulation (SPM), (inter-carrier) cross-phase modulation (XPM), and other deterministic nonlinearities.

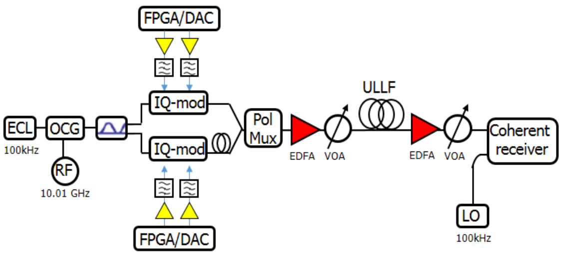

Fig. 1: Superchannel unrepeated transmission setup

Nyquist WDM PDM-16QAM Unrepeated Transmission Setup

The experimental configuration of the 7-channel 10GBd PDM-16QAM unrepeated 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* sinusoid. 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 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 convertor (DAC) operating at 20GS/s. An 8th order analog electrical low pass filter (LPF) with a cut-off

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*It is known that 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 spacing (10MHz) was sufficient to negate this unrealistic performance improvement, which was confirmed using simulations that incorporated full de-correlated data.

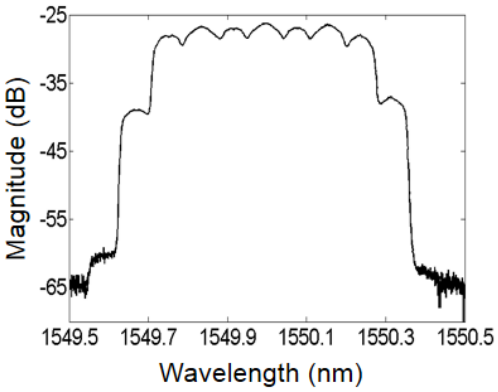

Fig. 2: : Optical power spectrum (0.01nm resolution) of the PDM-16QAM superchannel.

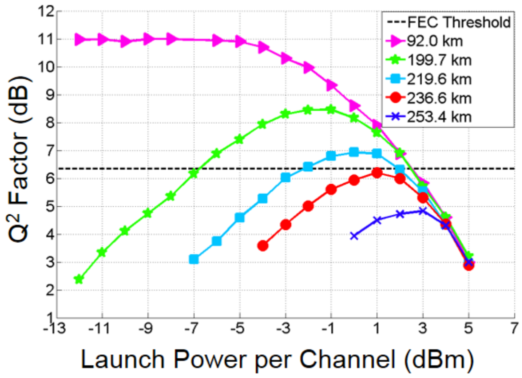

Fig. 3: Q^2 factor of PDM-16QAM Nyquist-WDM signals as a function of launch power per channel over different span lengths transmission.

frequency of 5.5GHz was used to remove the alias. 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 polarization 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 b/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 $1.9\text{x}10^{-2}$. The net SE was 6.95 b/s/Hz, the highest reported in an unrepeated transmission system.

For back-to-back analysis, the signal was attenuated before being passed directly to the coherent receiver. For transmission experiments, the signal was connected to an erbium doped fiber amplifier (EDFA) with a noise figure of 4.5dB and a variable optical attenuator (VOA) to adjust the input power to the coherent receiver. The signal and local oscillator laser (ECL with 100kHz linewidth) were combined using a Kylia 90˚ optical hybrid (CH28) and balanced photodetectors with 70 GHz electrical bandwidth. The signal and LO power at the photodetectors were -6 and +2 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.

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

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 of1.3 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[4]. The optical power spectrum of the PDM-16QAM superchannel at Nyquist spacing with a roll-off of 0.1% is illustrated in Fig. 2. The seven WDM channels exhibited a power variation < 1dB and the unused comb lines were supressed by ~14dB.

The performance of the PDM-16QAM superchannel unrepeated transmission over different span lengths is presented in Fig. 3. 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 and the optimum launch power increased for long span lengths. The span lengths of 92.0, 199.7 and 219.6 km exceeded the FEC threshold (6.34dB Q^2 factor), however it was not possible to reach the threshold for 236.6 and 253.4 km with only linear DSP.

To improve the performance of the system, full field digital back propagation was applied to mitigate nonlinear distortions caused by SPM, XPM (with respect to the central channel) and others deterministic nonlinearities. The transmission over 236.6 and 253.4 km applying only electronic dispersion compensation (EDC), single channel and full field back propagation is

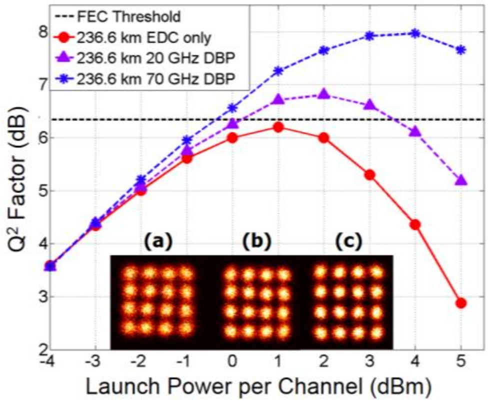

Fig. 4: Performance of PDM-16QAM Nyquist-WDM signals over 236.6 km span length transmission

presented in Fig. 4 and 5 respectively. The constellation diagrams for (a) EDC only, (b) single channel DBP (central channel with 20 GHz DBP bandwidth), and (c) full field DBP compensation at the optimum launch power for each case are also illustrated in Figs. 4 and 5 (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 instance, considering the 253.4 km span length transmission case, the best Q^2 factor was improved from 4.8 dB to 5.5 dB when just the central channel was back propagated and 6.6 dB when the full field was back propagated; a Q^2 factor above the FEC threshold. 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.

Fig. 6 shows the superchannel power spectral density of the coherently detected signal after 253.4 km unrepeated transmission with a 5 dBm launch power (signal sampled at 160 Gsample/sec) with 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 WDM Nyquist spaced PDM-16QAM unrepeated transmission over 253.4 km of ULLF using only EDFA pre-amplification achieving a net SE of 6.95 b/s/Hz; the highest SE and the highest SE-distance product (1761.1 b/s/Hz·km) reported so far in a unrepeated transmission system. This

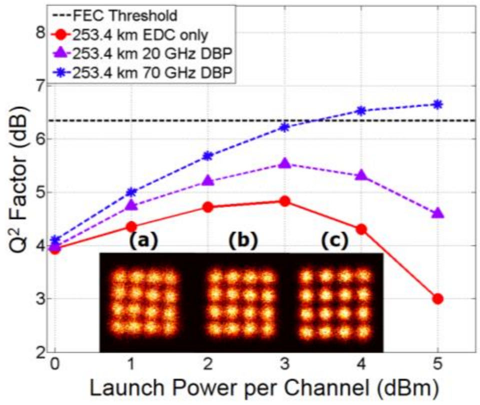

Fig. 5: Performance of PDM-16QAM Nyquist-WDM signals over 254.3 km span length transmission.

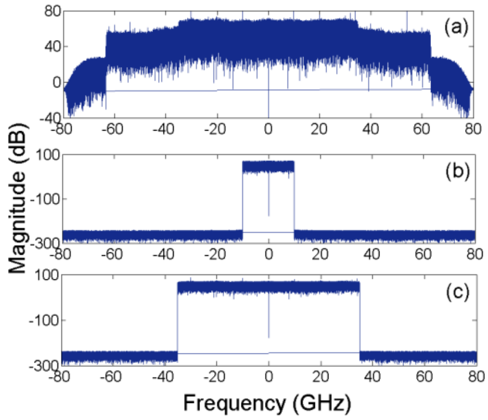

Fig. 6: a) Seven channel Nyquist-WDM coherently detected signal, (b) 20 GHz DBP bandwidth filter, and (c) 70 GHz DBP bandwidth filter.

esult was enabled by the use of multichannel nonlinear digital backpropagation.

Acknowledgements

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