Unrepeatered Nyquist PDM-16QAM Transmission over 364 km using Raman Amplification and Multi-Channel DBP

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Received Month X, XXXX; revised Month X, XXXX; accepted Month X, XXXX; posted Month X, XXXX (Doc. ID XXXXX); published Month X, XXXX

Transmission of a net 467 Gb/s PDM-16QAM Nyquist-spaced superchannel is reported with an intra-superchannel net spectral efficiency (SE) of 6.6 (b/s)/Hz, over 364 km SMF-28 ULL ultra-low loss optical fiber, enabled by bi-directional second order Raman amplification and digital nonlinearity compensation. Multi-channel digital back-propagation (MC-DBP) was applied to compensate for nonlinear interference; an improvement of 2 dB in Q^2-factor was achieved when 70 GHz DBP bandwidth was applied, allowing an increase in span length of 37 km.

 OCIS Codes: (060.1660) Coherent communications; (060.2330) Fiber optic communications.

Increasing both the length and transmission capacity in point-to-point unrepeatered links is attractive for achieving cost-effective transmission solutions to satisfy growing capacity demands. This is especially valuable for subsea systems, connecting islands and the mainland, as no in-line elements are required.

The capacity can be increased by using complex modulation formats with higher cardinality or by reducing the frequency spacing between WDM channels, while simultaneously employing advanced amplification techniques, hybrid fiber spans or some form of optical fiber nonlinearity compensation to maintain the transmission distance.

Enormous progress in unrepeatered transmission based on polarization division multiplexed quadrature phase shift keying (PDM-QPSK) modulation has been reported [1,2]. The longest unrepeatered distance of 557 km was achieved for a single 28 GBd PDM-QPSK channel [1], and required complex and sophisticated amplification schemes, such as remote optical amplifiers (ROPA). In order to increase the information per symbol, recent efforts have been directed towards demonstrating higher order modulation formats in unrepeatered systems [3-7]. However such modulation formats require higher optical-signal-to-noise ratios (OSNR), reducing the transmission distances which can be achieved. A dual-carrier (2 x 28 GBd) 448 Gb/s PDM 16-*ary* quadrature amplitude modulation (QAM) channel was transmitted over 401 km [4]. Recently, transmission of 40 x 28 GBd PDM-16QAM channels were transmitted over 304 km (achieved using

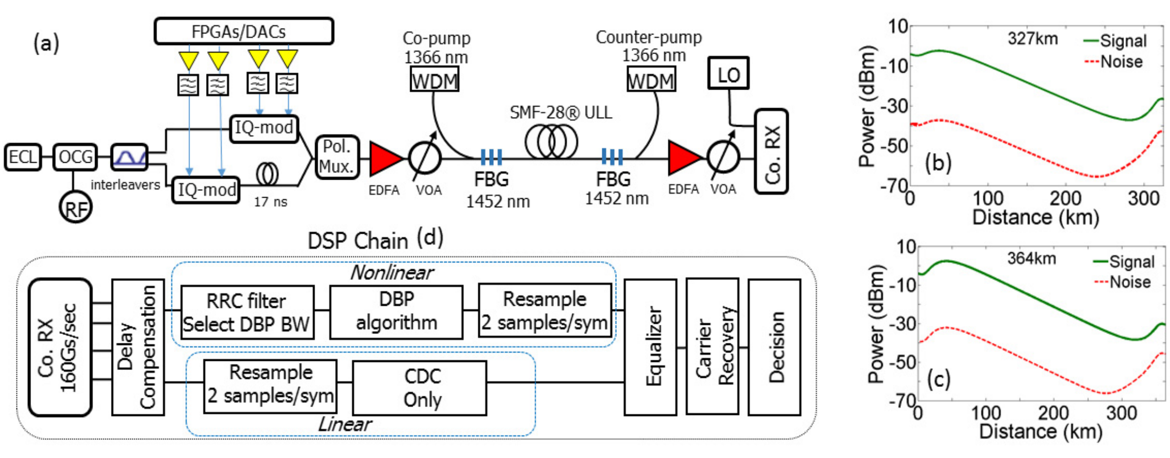

Fig. 1: (a) 7-sub-channel PDM-16QAM WDM Nyquist-spaced unrepeatered Raman amplified transmission system, (b) Simulated signal and noise power distribution in 327 km and (c) 364 km link. The simulated signal power distributions were used for the power evolution in the DBP algorithm. (d) DSP chain.

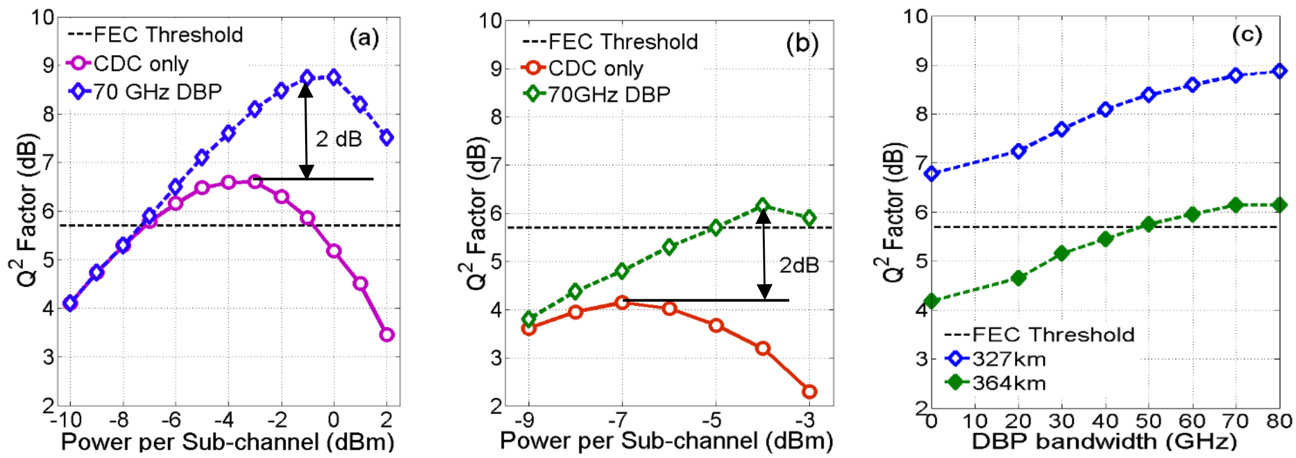

Fig. 2: Performance of unrepeatered transmission over (a) 327 km, (b) 364 km and (c) impact of DBP bandwidth.

Raman amplification and large effective area fiber) [6] and over 363 km, by adding ROPAs [7]. In all the above, a minimum 50 GHz spacing between the channels was considered. The first and only unrepeatered PDM-16QAM system using Nyquist spacing between the channels was reported in [4].

In this paper we report the unrepeatered transmission of a gross 560 Gb/s (7 x 10 GBd PDM-16QAM) Nyquist-spaced superchannel over 364 km Corning® SMF-28® ULL fiber using bi-directional second order Raman amplification and multi-channel digital back propagation (MC-DBP) [8]. This is the first time that the DBP algorithm has been applied in a forward and backward Raman pump transmission system.

Multichannel DBP has recently been considered for multi-span (repeatered) systems [4,8-10], where the overall computational complexity is equal to or greater than that considered in this work. This is because at least several steps per span are required to ensure accurate nonlinearity mitigation, with multiple spans required for such links.

The experimental configuration used in this work is shown in Fig. 1(a). A 100 kHz linewidth external cavity laser, wavelength 1550 nm, was input to an optical comb generator (OCG), consisting of a Mach-Zehnder modulator overdriven with a 10.01 GHz sinusoidal signal generating 7 evenly-spaced, frequency-locked comb lines. The frequency comb was subsequently separated into odd and even carriers using cascaded optical interleavers. Two IQ modulators were then used to modulate the odd and even carriers. Four de-correlated bit sequences of length 2^{15} were mapped to 16QAM symbols, sampled at 2 Sa/sym. The signals were digitally filtered using root-raised-cosine filters with 0.1% roll-off[1]. The resulting pulse shaped in-phase (I) and quadrature (Q) signals were loaded onto two digital-to-analog convertors (DACs) operating at 20 GSa/s. Each DAC output was connected to two cascaded electrical low pass filters (7.5 GHz bandwidth) to remove the signal images. The odd and even channels were optically decorrelated (by 17 ns), using a length of fiber (3.4 m) before being combined and passed through a polarization multiplexing emulation stage (Pol. Mux.) with 50 ns delay between X and Y polarizations. This results in 7 Nyquist-spaced 10 GBd PDM-16QAM sub-channels, forming a superchannel at the output of the polarization multiplexer with 7.99 (bit/s)/Hz gross spectral efficiency.

The fiber span was comprised of SMF-28 ULL ultra-low-loss fiber with an attenuation of 0.165 dB/km (including splice losses), <17 ps/nm/km dispersion and $83\ \mu m^2$ effective area. The signal power launched into the optical fiber was set using an EDFA followed by a variable optical attenuator (VOA). Ultra-long Raman fibre laser (URFL) amplification[2] at 1366 nm was used as bi-directional pumps [12]. It relies on a scheme that uses fibre Bragg grating (FBG) centered at 1452 nm to form an ultra-long laser cavity in the transmission fiber, allowing to achieve second-cascade pumping of the signal with a single pump wavelength, reducing signal power excursion and providing signal amplification in the C-band [12]. The insertion loss from WDM couplers and FBGs was 1.8 dB

The simulated signal and noise power distributions over 327 km and 364 km span lengths are shown in Fig. 1(b) and Fig. 1(c), respectively. The optimum forward and backward pump powers were 30.7 dBm and 31.6 dBm at 327 km, and 31.1 dBm and 31.4 dBm at 364 km, providing 36.3 dB and

[1] In [11] we demonstrated that a roll-off parameter of 0.1% and 128 filter taps was sufficient to incur a linear crosstalk induced OSNR penalty of less than 1 dB.

[2] Contrary to conventional 2^{nd} order Raman amplification, in URFL the spectral gain profile can be modified, and enhanced, without the need from additional pumping sources

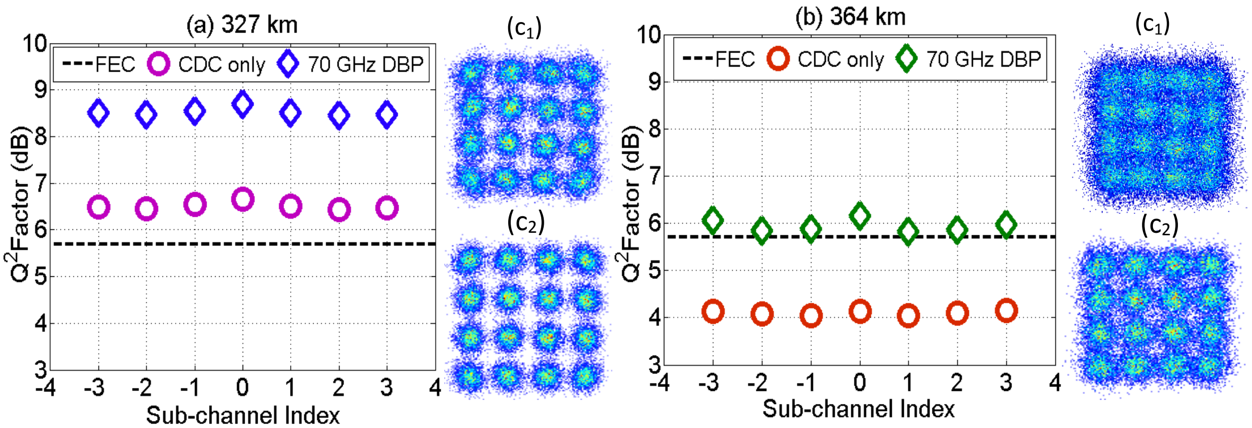

Fig. 3: Received Q^2-factor for all seven channels after (a) 327 km and (b) 364km Inset (C_1) and (C_2) illustrate the received 16QAM constellations at the optimum launch power for CDC only and MC-DBP, respectively.

41.6 dB distributed Raman ON/OFF gain, respectively. The total link loss including WDMs, FBGs, and splices for optical fiber lengths of 327 km and 364 km were 54.8 dB and 61.3 dB, respectively.

The received optical signal was pre-amplified using an EDFA (noise figure 5 dB) and received using a balanced phase and polarization diverse coherent receiver (ECL local oscillator with a 100 kHz linewidth). The output from the photodetectors (70 GHz electrical bandwidth) was sampled at 160 GSa/s using real time digital sampling oscilloscopes with 63 GHz analog electrical bandwidth.

The offline, linear, digital signal processing (DSP) initially resampled the received signals to 2 Sa/symbol prior to ideal chromatic dispersion compensation and frequency domain RRC matched filtering. The signal was equalized using a 41-tap (T/2 spaced) radially directed equalizer (RDE) followed by fourth power frequency offset estimation and decision directed carrier phase estimation [13]. For the cases in which fiber nonlinearity compensation was considered, the DBP was applied before the linear DSP, as indicated in Fig. 1(d). An ideal 'brick wall' filter was used to select the DBP bandwidth before the DBP algorithm was applied. The algorithm was carried out by solving the Manakov equation using the split-step Fourier method.

In contrast to an EDFA-based system, where the power profile can be easily predicted in advance (exponential decrease), in a forward and backward Raman pumped amplification system, the signal power profile, shown in Fig. 1(b) and (c), requires a more complex calculation to obtain the correct power evolution at each step of the DBP algorithm. This calculation was performed as described in [14]. In this work, 160 steps were used for the DBP algorithm to ensure that the nonlinearity compensation was close to optimum, however, it may be possible to significantly reduce the number of DBP steps, while maintaining transmission performance [8]. After DBP, the complex signals were resampled to 2 Sa/symbol and processed as in the linear case. The 7-sub-channel Nyquist-spaced transmitter exhibited a back-to-back implementation penalty of 1.1 dB relative to the theoretical SNR limit; achieved at a BER of 2.7×10^{-2}, and requiring an OSNR of 12.1 dB. This BER has been shown to be corrected to below 10^{-15} using a soft decision forward error correcting code (FEC), requiring 20% overhead (OH) [15]. In [16] is indicating that for high code rates the measuring pre-FEC BER is enough to predict post-FEC BER when the modulation format is changed in a nonlinear channel.

The experimental transmission performance based on the central sub-channel BER after 327 km and 364 km is illustrated in Fig. 2. The performance was analyzed for two DSP scenarios: (i) with only chromatic dispersion compensation (CDC) and (ii) MC-DBP, in which the entire 70 GHz bandwidth of the superchannel was back propagated. The transmission performance improved linearly with power until the nonlinear interference became significant with respect to the amplifier noise. The superchannel transmission performance over 327 km with only linear DSP, at the optimum launch power (-4 dBm per sub-channel), exceeded the assumed FEC threshold (5.7 dB Q^2-factor), with a net SE of 6.6 (b/s)/Hz (given by the useful information rate excluding error correction codes divided by the occupied bandwidth in hertz). Applying MC-DBP, the optimum Q^2-factor was improved by 2 dB, to 8.8 dB. The experimentally measured Q^2-factor over 364 km is shown in Fig. 2(b). At this transmission distance, linear CDC compensation achieves 4.1 dB Q^2-factor at the optimum launch power (-7 dBm per sub-channel). The MC-DBP results in an additional 2 dB improvement over the linear compensation case, enabling transmission over a distance of 364 km.

The impact of varying the bandwidth of the component of the superchannel which was digitally back propagated, from 0 to 80 GHz, where 0 GHz implies CDC only, is presented in Fig. 2(c). As the Kerr nonlinearity leads to spectral broadening, due to the generation of additional frequency components outside the original 70 GHz signal bandwidth, the DBP bandwidth was extended to 80 GHz in an effort to compensate for those frequency components. Note that, there are diminishing returns when extending the DBP bandwidth beyond the signal bandwidth, however, in this work, the limited receiver bandwidth necessarily limited our exploration of this regime. Experimentally, as expected, system performance improved with an increase in DBP bandwidth. In contrast to single sub-channel DBP, digitizing the full optical bandwidth enabled compensation of nonlinear distortions resulting from both self-phase modulation (SPM) and cross-phase modulation (XPM). Although MC-DBP has provided an improvement in performance there are challenges associated with this technique, in terms of complexity. In [8] was demonstrated the DBP performance as function of the MC-DBP bandwidth and the number of DBP steps per fiber span.

The Q^2-factor values were measured for all sub-channels, applying both CDC only and MC-DBP, for transmission distances of 327 km and 364 km, and are shown in Fig. 3. Optically shifting the LO (to explore the limits of this technique), only a small Q^2-factor variation among the sub-channels of the superchannel was observed, with an average Q^2-factor of 6.5 dB after 327 km (4.1 dB after 364 km). Applying MC- DBP provided a 2 dB Q^2-factor gain for all sub-channels, increasing the average Q^2-factor to 8.5 dB and 6.1 dB after 327 km and 364 km, respectively. We also tried to digitally down convert all the sub-channels when the LO was tuned to the central sub-channel. However, the performance of the outer sub-channels was slightly degraded due to the limited effective number of bits in the analog-to-digital converters (ADCs) used in this work. As an example, in transmission over 364 km, when applying 70 GHz MC-DBP the performance of the two outers sub-channels was degraded by 0.2 dB for each sub-channel.

In conclusion, transmission with a net intra-superchannel SE of 6.6 (bit/s)/Hz was demonstrated in unrepeatered systems over 364 km of SMF-28 ULL fiber, using bi-directional second order Raman amplification and MC-DBP. This result was achieved without the use of ROPAs, however we note that the described nonlinearity compensation technique could, in principle, be used to further extend the reach of systems incorporating ROPAs. The use of MC-DBP, improved the performance in Q^2-factor by 2 dB, enabling an increase of 37 km in the span length and permitted transmission over the same distance as in ref. [7], which required a ROPA and 3rd order Raman pumping.

The authors thank Corning Inc. for supplying the SMF-28 ULL fiber. The support under the UK EPSRC Programme Grant UNLOC (UNLocking the capacity of Optical Communications) EP/J017582/1 and CNPQ-Brazil (for Dr. L. Galdino) is gratefully acknowledged.

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