Unrepeatered 64QAM over SMF-28 using Raman Amplification and Digital Backpropagation

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Abstract: Unrepeatered transmission over SMF-28 fibre is investigated using Raman based amplification. Experiments and simulations demonstrate a transmission up to 200 km (41 dB) span length using 28Gbaud 64 QAM modulation employing digital back propagation in DSP.
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1. Introduction

In fibre optic communications, quadrature amplitude modulation (QAM) with coherent detection is widely deployed due to its good balance between robustness against optical signal to noise ratio (OSNR) degradation and spectral efficiency. To maximise the transmission distance, it is necessary to maintain an acceptable OSNR through the system, which is critical while using high order modulation formats. Distributed Raman amplification[1] (DRA) reduces signal decay in the fibre span leading to a higher OSNR which can allow longer reach in long-haul transmission[2,3] or longer total distance in unrepeatered systems[4,5]. Ultra-long Raman fibre laser (URFL)[6] based amplification can further reduce the signal power variation in the fibre and has proved advantageous in comparison with EDFA only based systems[7]. In this paper, we experimentally investigate the performances of a single channel 28GBaud 64-QAM transmission with coherent detection over different Raman amplification schemes. The results show the benefits of employing digital back propagation (DBP) in an unrepeatered SMF-28 span without remote optically-pumped amplifier (ROPA), large effective or ultra-low loss fibre. With the reference to J. C. S. S. Januário et al.[8] where authors presented unrepeatered transmission up to 370 km using combination of low loss fibers, forward and backward ROPA combined with amplification map optimization, theoretically, we could extend our achievable distance from 200 km (41 dB) up to to 242 km employing only low-loss fibre (0.169 db/km)[8] without forward and backward ROPA using simple design of Raman amplifiers. These are first order counter-pumped, hybrid dual order (both first and second order) and URFL based amplification with 2nd order counter pumping.

2. Experimental setup

Figure 1 represents the experimental setup for a 28 Gbaud Nyquist-shaped optical 64-QAM signal. The transmitter consists of two synchronized 50 GSa/s arbitrary waveform generator (AWG), optical IQ modulator and an external cavity laser (ECL) laser having less than 100 kHz linewidth (LW). A pseudo-random bit sequence with a word length of 2^{15}-1 (PRBS15) is generated and Gray mapped to generate a 28Gbaud 64QAM signal followed by Nyquist pulse shaping having a 0.15 roll off factor. The sequence is then resampled to match the sampling rate of the AWGs. At the output of IQ modulator optical signal is amplified using an erbium doped amplifier (EDFA). Then signal is fed into preamplifier and band-pass filtered followed by the coherent receiver with an integrated local oscillator laser having less than 100 kHz LW. A digital storage oscilloscope (DSO, 80 GSa/s, 33 GHz) is used to convert the signal into digital domain with offline demodulation.

The transmission fibre used in the experiment was standard SMF-28 with approximately 0.2 dB/km loss. The measured loss in 160 km (4×40 km), 200 km (5×40 km) and 240 km (6×40 km) link including splices was 33.6 dB, 41 dB and 52.7 dB, respectively. The loss from forward and backward WDM was 0.6 dB and 0.8 dB, respectively. In unrepeatered 160 km and 200 km transmissions, a first order distributed backward pumped (BP) Raman laser based amplification with pump centred at 1455 nm was sufficient to achieve the BER below the soft FEC. However, given the strong OSNR constraints of the system at higher distance links, in a 240 km experiment we used second order hybrid dual/URFL bidirectional Raman pumping scheme with the highly depolarised forward and backward pumps centered at 1366 nm. The Random distributed feedback (rDFB) lasing in the forward direction was formed due to reflected Stokes-shifted light by a high reflectivity (95%) FBG centred at 1455 nm with a 0.5 nm bandwidth. The backward pumping was formed by two Raman pumps at 1366 nm and 1455 nm. To combine and demultiplex

Raman pumps and the signal, we used 1×3 WDM couplers in the beginning and at the end of the span. In all setups, there was an EDFA implemented before and after the transmission line.

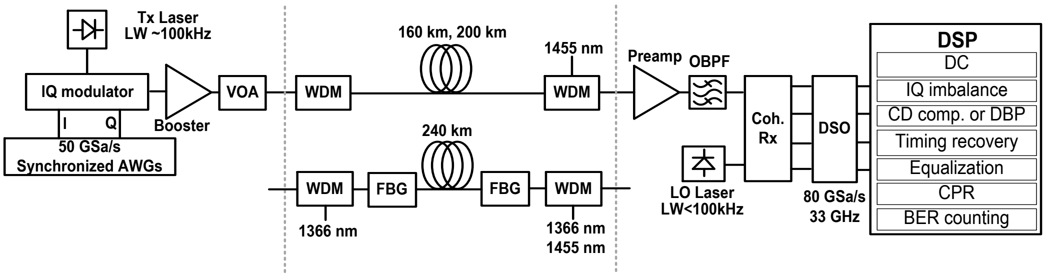

Fig. 1. Schematic design of 64 QAM experiment setup with distributed Raman amplifiers

Digital post-processing includes DBP realized by fixed step algorithm[9] followed by resampling to 1 samples per symbol. A multi-modulus algorithm (MMA) equalizer is applied to compensate for linear polarization effects and finally a filtered blind phase search (F-BPS)[10] for carrier frequency and phase recovery followed by error counting.

2. Transmission results and discussions

The constrains due to hardware limitations, the error free back to back performance of the 64 QAM transmitter was not possible. The optimal performance versus OSNR is shown in Fig. 2.

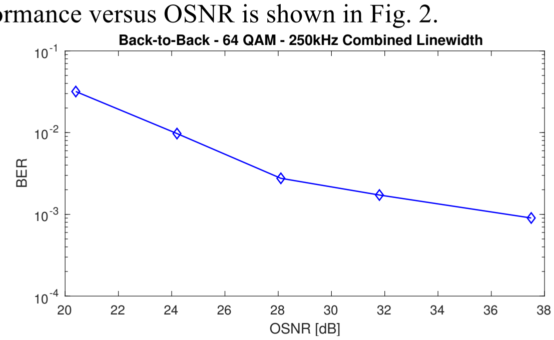

Fig. 2. BER back to back performance of a 64 QAM transmitter versus different OSNR.

The bit error rate (BER) results using first order backward Raman amplification with different input powers (I/P) over 160 km and 200 km fibre are shown in Fig. 3. In both experiments, the best BER result improvement using DBP are for the highest input powers due to higher nonlinear penalties in the beginning of the span. We may notice that there is no significant difference in the DBP improvement using higher backward Raman pump powers, which indicates that the BER improvement was noise limited. The maximum span length in the unrepeatered transmission experiment with average BER (based on 10 consecutive measurements) below the soft FEC limit ($1.9 \times 10{-}2$) was 200 km as shown in Fig. 3.

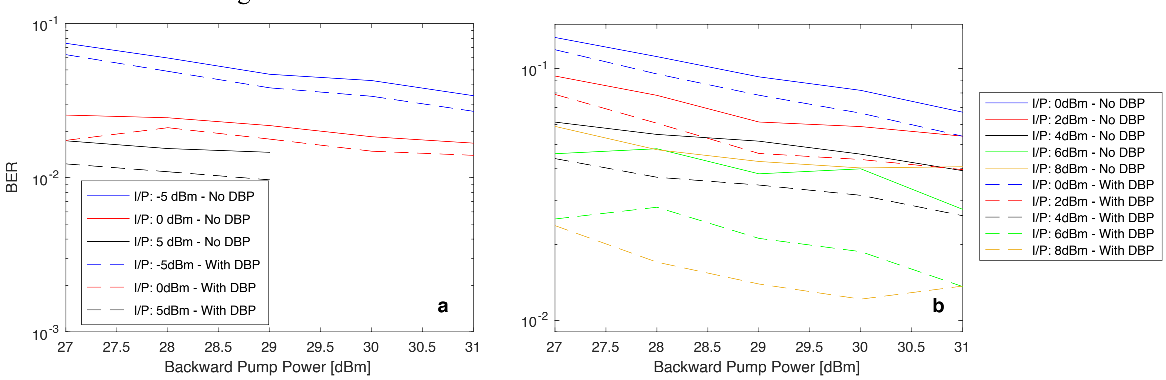

Fig. 3. BER vs BP powers for different input powers (I/P) in 160 km (a) and 200 km (b) experiment with (dashed) and without (solid) DBP.

Although higher order amplification is proven[3-5] to be superior in long-haul and unrepeatered transmissions, we could not achieve the BER performance that was below FEC in a 240 km experiment using second order

bidirectional Raman pumping. Based on previous unrepeatered experiments using lower order modulation formats (QPSK[5] and 16QAM[11)] using proposed amplification scheme, we believe that with improved back-to-back performance a successful 240 km SMF-28 transmission with BER below FEC is achievable. The distance could be improved considerably using low loss fibers.
Here, out of two amplification schemes that was dual order Raman with the first order backward pump at 1455 nm and second order at 1366 nm and URFL, we only present best results that were achieved with URFL configuration. The results of a 240 km transmission with and without DBP for different launch and total pump powers are shown in Fig. 4. We can notice that similarly to previous transmission experiments, the highest BER improvement employing DBP is for the signal with the highest launch power (yellow and green curves in Fig. 3 and Fig. 4).

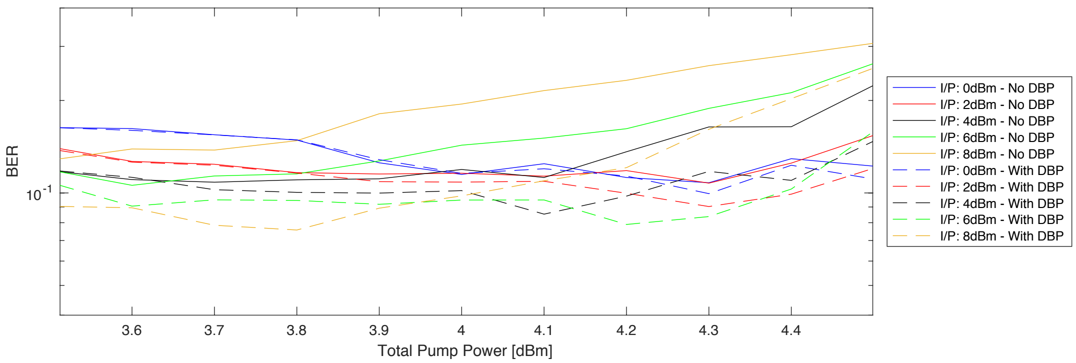

Fig. 4. BER vs total pump powers for different input powers (I/P) in a 240 km experiment with (dashed) and without (solid) DBP.

3. Conclusion

Unrepeatered transmission of a 28 Gbaud Nyquist-shaped optical 64-QAM signal up to 200 km has been experimentally demonstrated. Taking into account the loss of SMF-28 fiber, theoretically the distance could be extended with low loss fiber with using simple random DFB fibre laser based Raman amplification with a single pump wavelength that is compatible with both direct detection[4], and advanced coherent modulation[5], which means that our proposed setup could be readily used to upgrade existing installed standard single mode fibre links.

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