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Unrepeatered 240-km 64-QAM Transmission Using Distributed Raman Amplification over SMF Fiber †

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Abstract: We present a theoretical and experimental investigation of unrepeatered transmission over standard single-mode fiber (SMF-28) using several schemes of distributed Raman amplification, including first, second, and dual order. In order to further extend the transmission distance, we utilize advanced bidirectional higher-order ultra-long Raman fiber laser-based amplification, where we use fiber Bragg gratings (FBGs) to reflect Stokes-shifted light from the secondary pumps. Our work demonstrates the possibility of transmission up to 240-km span length with a total span loss of 52.7 dB. Here, we use a 28-Gbaud signal using a 64-quadrature amplitude modulation (QAM) modulation format. Our results highlight the contribution of nonlinear compensation using digital back propagation in a digital signal processor (DSP) code at the receiver.

Keywords: distributed Raman amplification; digital backpropagation; unrepeatered 64-QAM transmission

1. Introduction

In fiber-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 maximize the transmission distance while using high-order modulation formats, it is essential to maintain an acceptable OSNR through the system, which is critical while using advanced modulation formats with a large number of constellation points that consequently increase the number of bits transmitted per sample. Distributed Raman amplification (DRA) reduces signal decay in the fiber span by distributing the power over whole length of a transmission span, which results in higher received OSNR, allowing longer reach in long-haul transmission or longer total distance in unrepeatered systems [1–5]. Ultra-long Raman fiber laser (URFL)-based second-order amplification can reduce the signal power variation by pushing an amplification even further into the fiber. A similar method was shown by Papernyi et al. [6], where the authors demonstrated cascaded sixth-order distributed Raman amplification using several FBGs, improving the receiver's sensitivity by 10 dB. These methods are proven advantageous in comparison with systems based only on erbium-doped fiber amplifier (EDFA) [7–9] in both long-haul and unrepeatered transmission systems.

In this paper, we experimentally investigate the performance of a single-channel 28-GBaud 64-QAM transmission with coherent detection over different Raman amplification schemes and confirm the results with numerical simulations. Our results illustrate the potential improvement attainable just through the use of digital back propagation (DBP) adequately combined with careful distributed amplifier design in an unrepeatered standard single-mode fiber (SMF-28) span without the need for a remote optically pumped amplifier (ROPA), large effective area, or ultra-low-loss fiber that surely could extend the transmission distance even further. Here, we can refer to Reference [10] where authors presented unrepeatered transmission up to 370 km using combinations of different low-loss/effective-area fibers, with forward and backward ROPA combined with amplification map optimization. By employing only low-loss fibers (0.169 dB/km) in our system, theoretically, we could extend our achievable distance from 200 km (41 dB) up to 242 km, which gives almost 25% total improvement, without forward and backward ROPA, using a simple design of distributed Raman amplifiers [9] instead. These are first-order counter-pumped, hybrid dual-order (both first and second order), and URFL Raman-based amplification with second-order counter-pumping.

2. Experimental Set-Up of the Raman Amplifier

Figure 1 represents the experimental set-up for a 28-Gbaud Nyquist-shaped optical 64-QAM signal. The transmitter consisted of two synchronized 50-GSa/s arbitrary waveform generators (AWGs), an optical IQ modulator, and an external cavity laser (ECL) with less than 100-kHz linewidth (LW). A pseudo-random bit sequence with a word length of $2^{15} - 1$ (PRBS15) was generated and then Gray-mapped to generate a 28-Gbaud 64-QAM signal followed by Nyquist pulse shaping with a 0.15 roll-off factor. The sequence was then resampled to match the sampling rate of the AWGs. At the output of the IQ modulator, the optical signal was amplified using an erbium-doped amplifier (EDFA). Then, the signal was fed into the 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) was used to convert the signal into the digital domain with offline demodulation where chromatic dispersion (CD) and nonlinear noise were compensated for digitally using digital back propagation with simulated Raman power profiles, specific to each configuration.

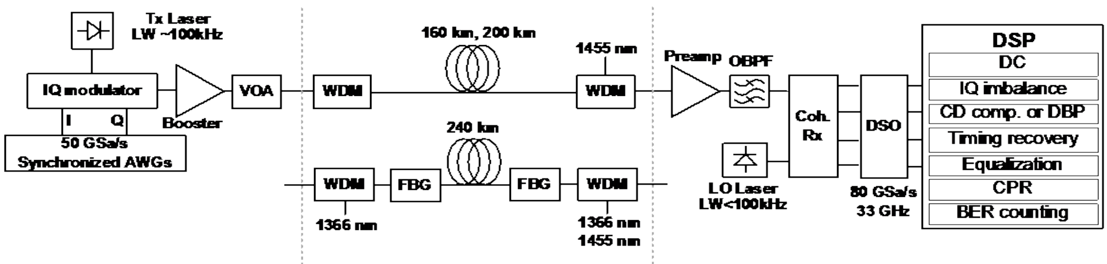

Figure 1. Experimental set-up of a 28-Gbaud Nyquist-shaped optical 64-quadrature amplitude modulation (QAM) signal (left), transmission line with Raman amplification schemes for each distance (middle), and receiver with DSP schematic (right).

The transmission fiber used in the experiment was a 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) links including splices was 33.6 dB, 41 dB, and 52.7 dB, respectively. The loss from the forward and backward wave division-multiplexer (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 amplification with the pump centered at 1455 nm was sufficient to achieve a bit error rate (BER) below the soft forward error correction (FEC). However, given the strong OSNR constraints of the system at longer distances links, in the 240-km experiment, we used a second-order hybrid dual/URFL bidirectional Raman pumping scheme with the highly depolarized forward and backward pumps centered at 1366 nm. Random distributed feedback (rDFB) lasing in the forward direction was generated, seeded by the reflected Stokes-shifted light by a high-reflectivity (95%) fiber Bragg grating (FBG) centered at 1455 nm with a 0.5-nm bandwidth and fed back by distributed Rayleigh backscattering in the long link [11,12]. Backward pumping (BW) was provided by two Raman pumps at 1366 nm and 1455 nm, respectively. All pump and signal launch powers used in experiments are listed in Figure 3 and Figure 4 in Section 3. To combine and demultiplex the Raman pumps and the signal, we used 1 × 3 WDM couplers at the beginning and at the end of the span. In all set-ups, there was an EDFA implemented before and after the transmission line.

Digital post-processing included full simulation of distributed Raman power profiles where each spectral component was calculated numerically using an extended model that accounts for the residual Raman gain shift from the lower-order pumps to the transmitted signal and pump depletion from all components. Individual signal power profiles were then fed into the DBP code, realized by a fixed step algorithm followed by resampling to one sample per symbol [13]. A multi-modulus algorithm (MMA) equalizer was applied to compensate for linear polarization effects and, finally, a filtered blind phase search (F-BPS) for carrier frequency and phase recovery followed by error counting [14].

3. Transmission Results and Discussions

Due to the constrains caused by available hardware limitations, the error-free back-to-back performance of the 64-QAM transmitter was not achievable. The optimal performance versus OSNR was measured experimentally and confirmed with theoretical and numerical simulations. Data presented in Figure 2 show great agreement with all approaches.

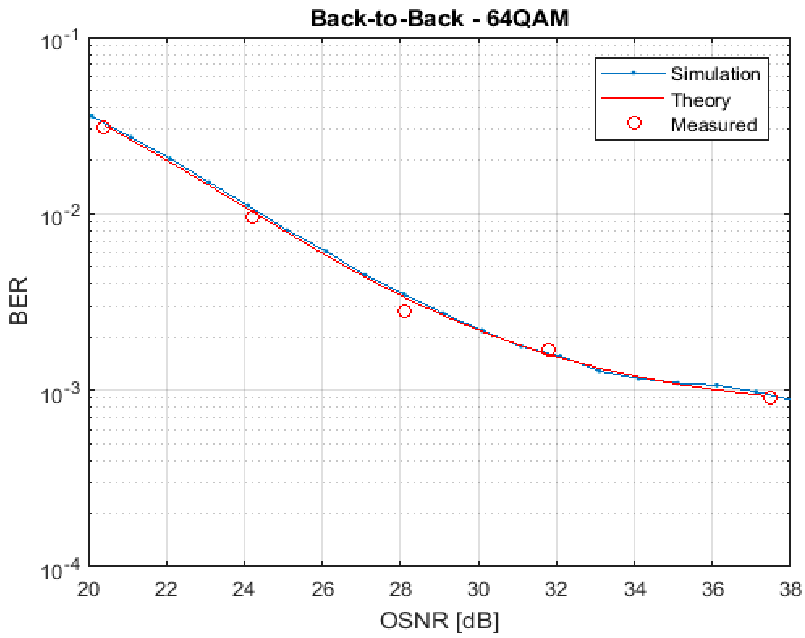

Figure 2. Experimental and theoretical back-to-back performance of a 64-QAM transmitter versus optical signal-to-noise ratio (OSNR).

The limits imposed by the launch signal in the transmitter reduce the overall potential achievable distance that could be reached with better back-to-back performance and give very little room for any extra noise; hence, proper optimization of the Raman amplification scheme in this case is very important. The bit error rate (BER) results using first-order backward Raman amplification with different input powers (I/P) over 160-km and 200-km fiber are shown in Figure 3. As expected, in both experiments, the best BER improvement using digital back propagation (DBP) was obtained for the highest launch powers due to higher nonlinearities experienced primarily 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 limited by amplified spontaneous emission (ASE) noise. The maximum span length in the unrepeatered transmission experiment with average BER (based on 10 consecutive measurements) below the soft FEC limit (1.9×10^{-2}) was 200 km, as shown in Figure 3.

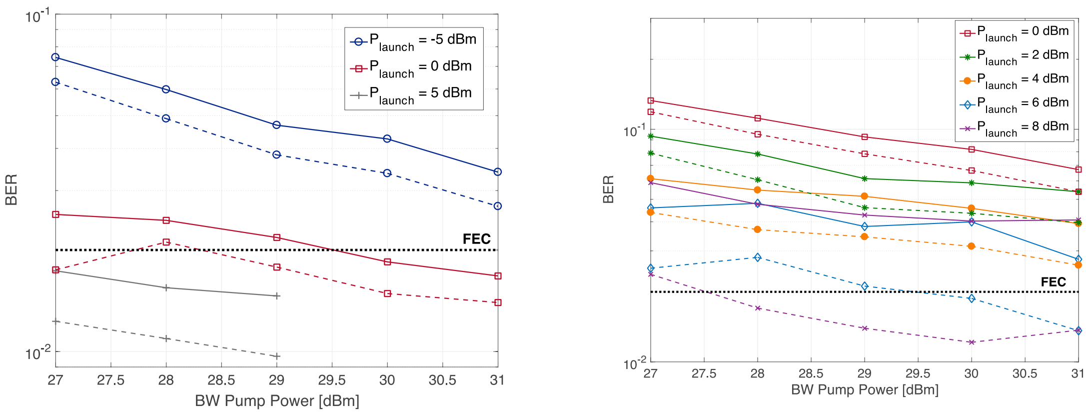

Figure 3. Bit error rate (BER) vs. back propagation (BP) powers for different launch powers in 160-km (left) and 20- km (right) experiments with (dashed) and without (solid) DBP.

Although higher-order amplification was proven [3–5] to be superior in long-haul and unrepeatered transmissions, we could not achieve BER performance that was below the FEC limit in a 240-km experiment using any of the proposed higher-order, bidirectional, and hybrid Raman pumping schemes. Based on previous experimental knowledge in unrepeatered experiments with lower-order modulation formats (QPSK and 16-QAM) using the proposed amplification scheme [5,15,16], we believe that, with improved back-to-back performance, a successful 240-km SMF–28 transmission with BER below FEC is achievable. The achievable distance would also be improved considerably by the implementation of low-loss fibers.

Here, out of the two amplification schemes (second-order Raman with the additional first-order backward pump at 1455 nm and second-order pump at 1366 nm and URFL), we only present the best results, which were achieved with the URFL configuration. Since it is difficult to predict optimal forward and backward pump powers, we took the measurements for all the possible combinations, varying pump powers by 100-mW steps for input signal powers ranging from 0 to 8 dBm (for clarity, we show the signal power P_{launch} with a 2-dB step), and then processed the data offline. The results for the 240-km transmission approach with and without DBP for different launch and total pump powers are shown in Figure 4. We can notice that, similarly to previous transmission experiments, the highest BER improvement employing DBP was achieved for the signal with the highest launch power. A further increase of pump powers introduces noise and effectively deteriorates achievable transmission results. To visually illustrate the transmission improvement using DBP in Figure 5, we show the best scenario constellation diagrams for all distances before (top) and after (bottom) applying a DBP algorithm. Even with such a low BER in the 240-km case, there is a visible improvement using DBP (Figure 6e,f).

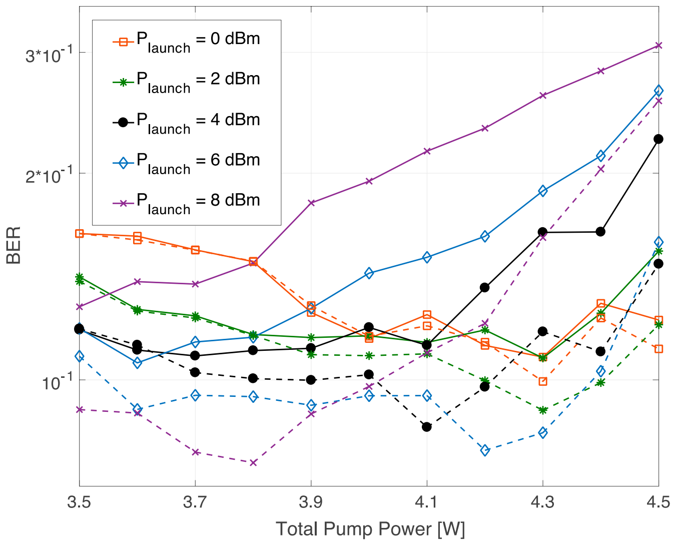

Figure 4. BER vs. total pump powers for different launch powers in a 240-km experiment with (dashed) and without (solid) DBP.

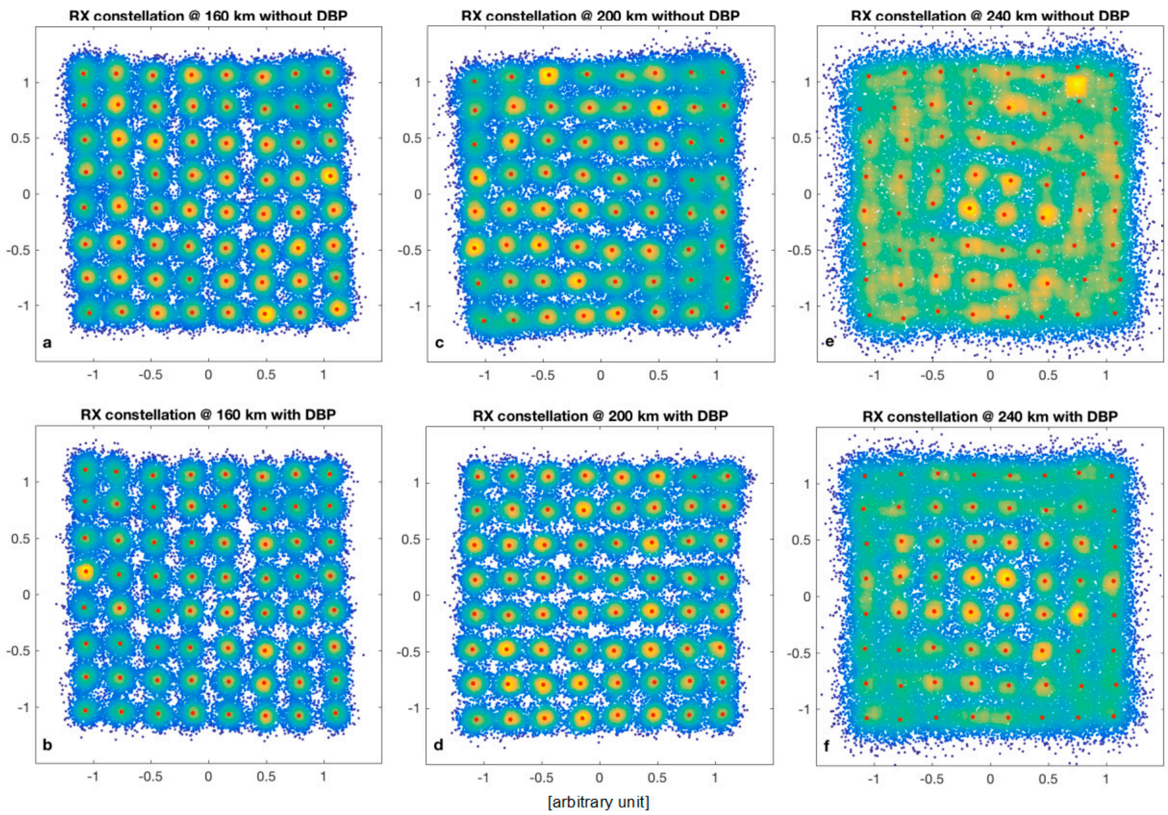

Figure 5. Constellation diagrams showing the best-case experimental result out of several configurations (see Figures 3 and 4) with (bottom) and without (top) applying DBP.

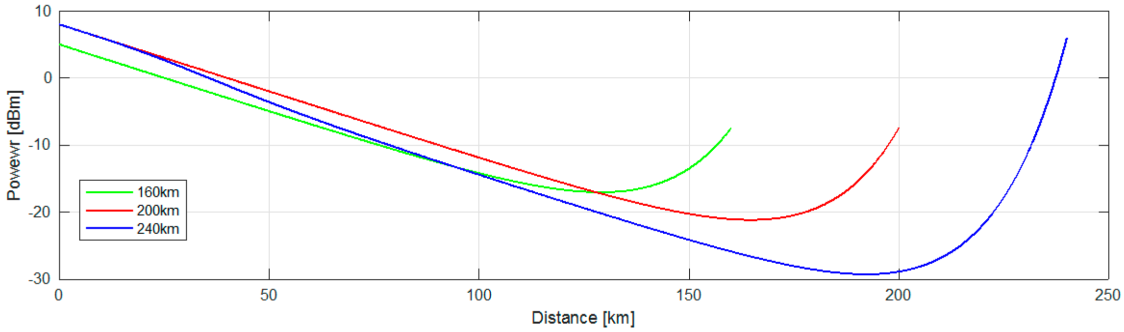

Figure 6. Signal power distribution in fiber with distributed Raman amplification.

4. Simulations

To investigate the possible performance improvement using the current system set-up (Figure 1) assuming an ideal error-free launch signal, we simulated the transmission of the 28-Gbaud Nyquist-shaped optical 64-QAM signal with pump powers as in the optimal experimental results obtained at each distance. In each Raman configuration, signal power excursion was simulated using the experimentally verified model with appropriate boundary conditions that were fully described in References [7,17,18]. In simulations, we used room temperature with the assumption that Raman pumps are fully depolarized. The noise was calculated in a bandwidth of 0.1 nm. The Raman gain and attenuation coefficients at the laser wavelength were obtained from measured gain and attenuation curves for standard SMF silica fiber [18]. The values of the Rayleigh backscattering coefficients for the pump wavelength at 1366 nm, the lasing at 1455 nm, and the frequency of the signal were assumed to be 1.0×10^{-4}, 6.5×10^{-5}, and 4.5×10^{-5} km^{-1}, respectively. In Figure 6, we show numerically calculated optimal signal power profiles for the best-performing results for each distance (see Figures 3 and 4).

To simulate transmission results, a random binary sequence of length 2^{15} was firstly mapped into the complex plane using 64-QAM, oversampled by a factor of four, and then passed through a Nyquist filter to generate a Nyquist-shaped signal. The filter length was 80 and the baud rate was 28 Gbaud. The propagation of the signal in the fiber was simulated using a split-step Fourier method, with a step size of 0.1 km considering the simulated Raman gain and noise profiles shown in Figure 6.

Figure 7 shows, for illustration, simulation results of the impact of nonlinear distortion only without ASE and chromatic dispersion for the three transmission distances considered.

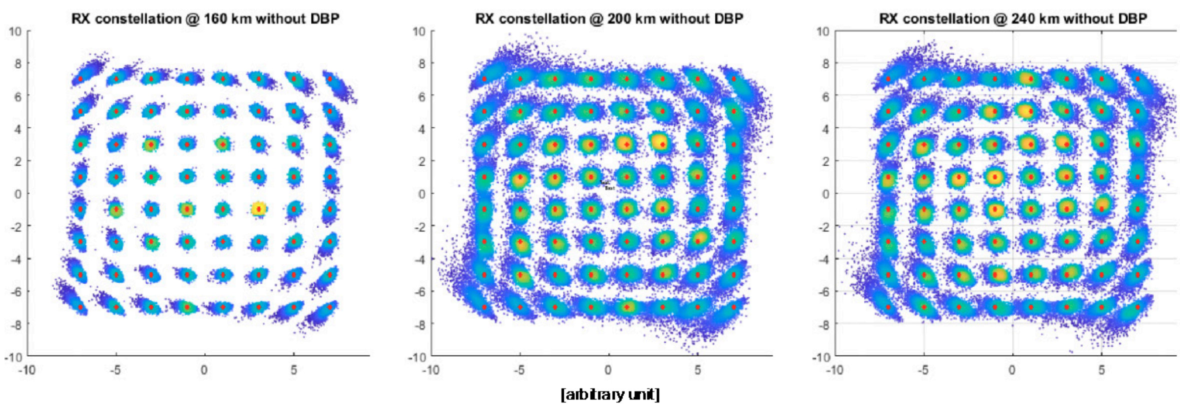

Figure 7. Constellation diagrams of simulated nonlinear distortion.

The results of the simulated error-free launch signal are shown in Figure 8, where we present simulated constellation diagrams for all distances with and without applying DBP. Finally, a comparison of the optimal experimental (Figures 3–5) and simulation (Figure 8) results is shown as a function of the received OSNR in Figure 9. The simulation confirms that, with an ideal error-free 64-QAM launch signal, a 240-km transmission is possible using the proposed Raman configuration.

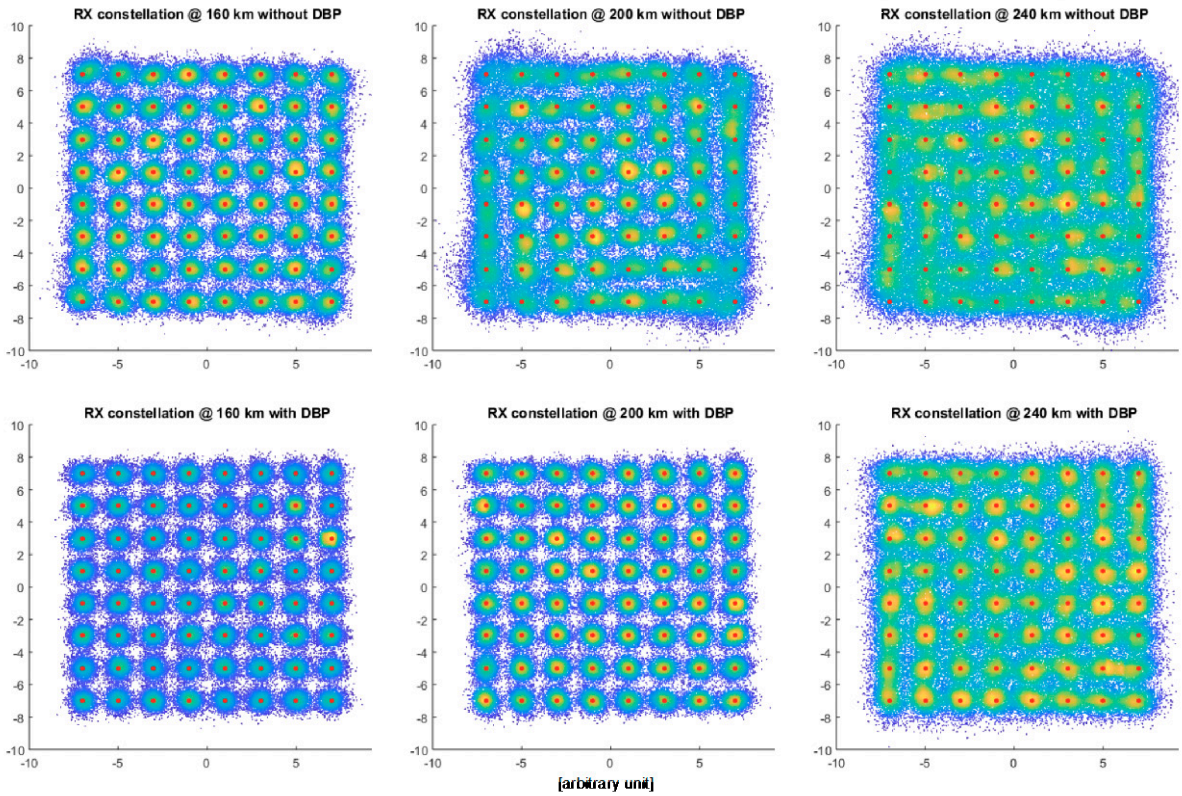

Figure 8. Constellation diagrams showing the simulation of best-case results assuming an ideal launch signal with (bottom) and without (top) applying DBP.

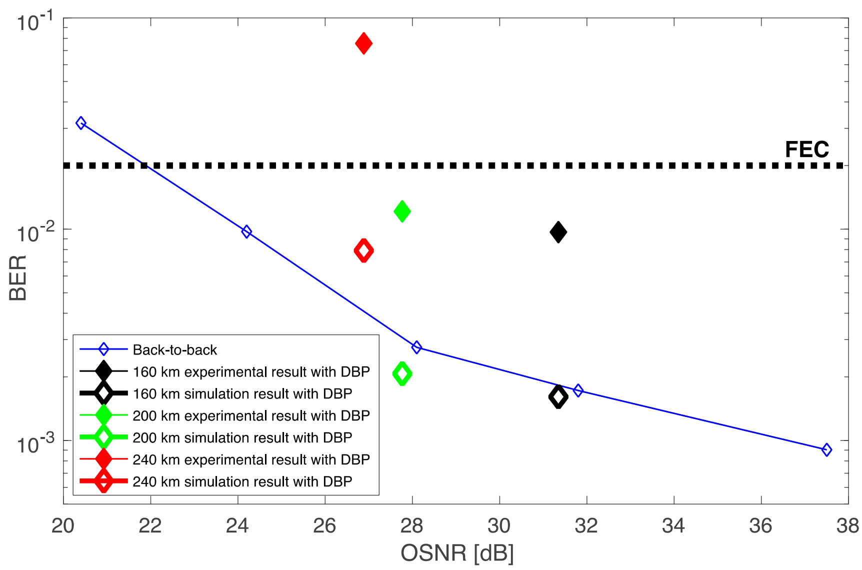

Figure 9. Comparison of optimal experimental and simulation results.

5. Conclusions

The possibility of unrepeatered transmission of a 28-Gbaud Nyquist-shaped optical 64-QAM signal up to 240 km was demonstrated by combining experimental and numerical results. Theoretical investigation through numerical simulations shows considerable improvement in the valid achievable distance below the FEC limit if the hardware constraints in the transmitter are suppressed. Taking into account the measured loss of standard SMF-28 fiber in our experimental set-up, theoretically, the distance could be extended with implementation of low-loss fiber, using simple random DFB fiber laser-based Raman amplification with a single pump wavelength. This amplification method is compatible with direct detection [4], advanced formats with coherent modulation [5,15,16], and ROPA [19] using both low-loss and standard SMF fiber. This means that our proposed set-up could be readily used to upgrade existing installed standard single-mode fib-r links.

Author Contributions: Conceptualization, P.R., G.R., and J.D.A.-C.; methodology, P.R., G.R., X.P., O.O., and A.U.; software, X.P. and M.J.; formal analysis, J.D.A.-C.; investigation, P.R., G.R., X.P., O.O., A.U., and M.T.; resources, J.D.A.-C, S.S., and M.T.; writing—original draft preparation, P.R.; writing—review and editing, J.D.A.-C.; visualization, G.R. and X.P.; supervision, J.D.A.-C.; project administration, J.D.A.-C. and S.S.; funding acquisition, J.D.A.-C., S.P., G.J., R.S., S.S., and M.M. All authors have read and agreed to the published version of the manuscript.

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