Spectrally Efficient DP-1024QAM 640 Gb/s Long Haul Transmission using a Frequency Comb

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Abstract: We experimentally investigate the long haul transmission of an 8 GBd DP-1024QAM over fully Raman amplified fiber spans using an optical frequency comb. We reach a potential spectral efficiency of 8.7 bit/s/Hz at 3000 km transmission and a potential data rate of 640 Gb/s.

1 Introduction

Spectrally efficient systems promise higher throughput of existing fiber infrastructure, attracting interest to the development of highly spectrally efficient transceivers. A key challenge associated with spectrally efficient systems is the relative frequency stability of the carriers in wavelength division multiplexed (WDM) systems and the phase noise of the optical sources, as we seek to increase spectral efficiency we wish to decrease guard bands. Frequency unstable optical sources will limit the possible spectral efficiency of systems by forcing larger spectral guard bands. A solution to the problem of relative frequency stability is to use an optical frequency comb generated from a single laser source. This ensures the relative frequency stability, since when the laser drifts all the lines will drift accordingly and therefore remain stable relative to each other. A laser with low phase noise and high frequency stability can be employed to increase the fidelity of all transmitted lines in the comb. Another key feature of highly spectrally efficient systems is the use of higher order modulation formats which allow for better exploitation of the available optical signal to noise ratio (OSNR). Much research has gone into higher order modulation formats [1-5, 7], as a way to ensure high spectral efficiency, with efforts directed towards both long haul and short reach transmission. For long haul transmission the available OSNR is limited primarily by the amplifier noise. As the channel SNR decreases the performance of higher order modulation formats approaches that of lower order modulation formats. When choosing the modulation format, both the forward error correction (FEC) scheme and the achievable rate should also be considered. In this work we analyze the performance of an 8 and a 10 line frequency comb for short and long reach transmission. We analyze the crosstalk penalty from the spacing of the comb lines and we reach 8.7 bit/s/Hz of spectral efficiency at 3000 km transmission using DP-1024-QAM and pilot-aided digital signal processing (DSP). To the best of our knowledge, this result constitutes a state-of-the-art spectral efficiency for 3000 km transmission, and the only such result for pilot-aided DSP [7, 8].

2 Experimental Setup

The experimental setup is shown in Fig. 1. The frequency comb is electro-optically generated from a low-linewidth NKT Koheras BasiK seed fiber laser. A 3dB-coupler is used to split the output of the seed laser; one arm of the coupler is modulated by an intensity modulator driven at 8.5 GHz, creating two sidebands and suppressing the carrier. Once generated the sidebands are sent through a circulator into an injection locked laser (ILL). The ILL resonance is then thermally tuned to the frequency of the higher frequency sideband. The output of the ILL is retrieved using a circulator. To generate two frequency-locked combs with an 8.5-GHz relative frequency offset and five lines each with 17 GHz free spectral range (FSR) (see Fig. 1 insets (1) and (2)), the outputs directly from the fiber laser and the ILL are passed through individual phase modulators, each driven with a 17 GHz tone. This was changed to 10 GHz spacing (by increasing the generated combs to 20 GHz spacing) for longer transmission as the crosstalk penalties degraded the signal below the decoding threshold, specifically for the 3000 km 1024-QAM case. The maximum power variation between comb lines is 5 dB which is equalized using two Finisar wavelength selective switches (WSS) which also suppress unwanted comb lines. The combs are amplified separately to achieve equal power in all WDM channels. The spectrum of the resulting comb can be seen in Fig 1. The combs are data encoded separately on the five comb lines in each modulator which causes a penalty on the overall performance due to limitation on total optical power available. Such a penalty would not be present in a system carrying real data where each line would be modulated independently. The two combs are then interleaved to generate an odd-even decorrelated comb with all 10 lines frequency-locked to the seed laser. When using only 8 lines the WSSs were configured to generate 4 lines per comb. The resulting OSNR per 0.1 nm was 43 dB for the whole comb. The data are modulated onto the lines at 8 GBd. The transmission link is a fully Raman amplified loop, consisting of two 100-km ultra-low loss OFS SCUBA (0.155 dB/km) spans, for a total of a 200 km transmission for each turn. The loss of the acousto-optic modulator (AOM), used to loop the signal through the transmission span, is compensated by an erbium doped fiber amplifier (EDFA). Experiments were carried out for 64-, 256- and 1024-QAM and for varying amounts of loop turns. The data bits were a low-density parity-check (LDPC)-encoded pseudo random bit sequences. The LDPC codes used throughout this work are DVB.S-2 standardized FECs. For 64-QAM we use an LDPC code with rate 5/6 (20% overhead) which gives us a mutual information (MI) decoding threshold around ≈ 9.6 bits/symbol.

For the 0 – 2000 km points for the 1024-QAM we use an LDPC code with 4/5 (25% overhead) therefore landing at an MI threshold of around 15 bits/symbol. For the 3000 km 1024-QAM point we used 8 channels (the WSSs were used to remove the unwanted lines) at 8 GBd and an LDPC code with a rate of 2/3 (50% overhead). The required MI for decoding is then ≈ 10 bits/symbol. For the 256-QAM points we also used a LDPC code with a rate of 4/5 (25% overhead) requiring an MI of 12 bits/symbol to be decoded. With the system in the back-to-back configuration we changed the FSR of the comb and measured the performance of the middle line (6^{th}). We sought to investigate the crosstalk at the transmitter and to that end did a series of measurements varying the FSR of the generated combs between 17 and 18 GHz, where the results can be seen in Fig 3. We tested several launch powers and determined that the optimal launch power was −7.5 dBm per carrier.

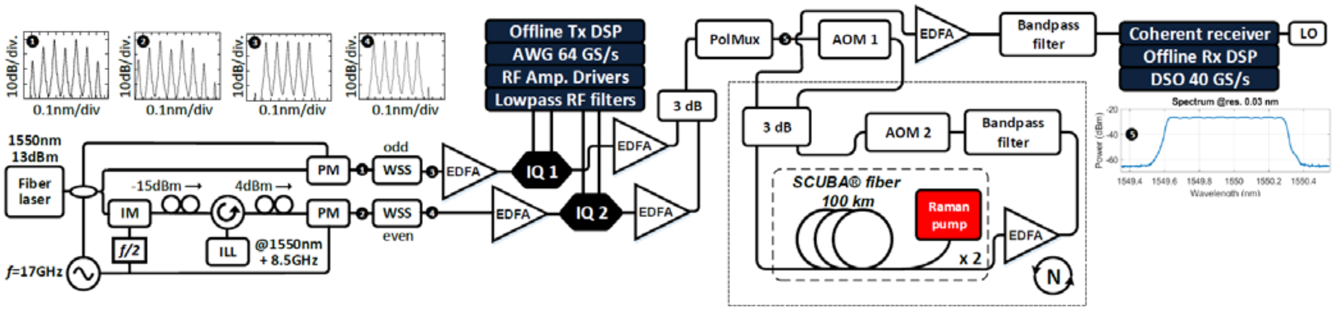
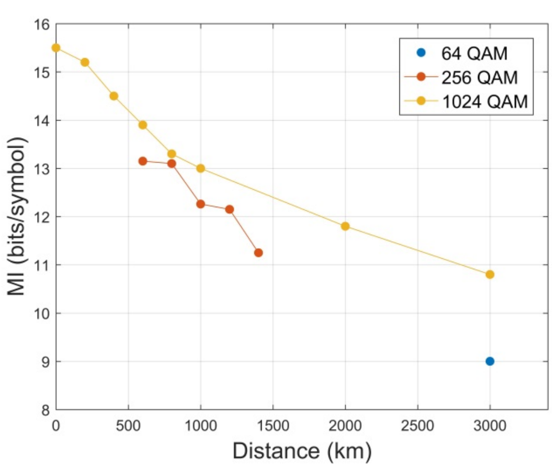


Fig.1 The Experimental Setup. Insets 1-5 show the spectra at the corresponding points on the schematic diagram.

3 Results

In Fig. 2 the MI results for 5% pilot-aided DSP is shown for three different modulation formats. We transmitted the signal over 3000 km using 64-QAM, resulting in 14.6 dB of measured SNR. This corresponds to an estimated MI of ≈ 9 bits/symbol, which is below the decoding threshold for the code rate used. This results in an achievable spectral efficiency of ≈ 8 bit/s/Hz. We calculated the spectral efficiency by multiplying log2(M), where M is the cardinality of the modulation format chosen (multiplied by 2 due to the symbols being dual polarization), with the code rate used. Then multiplying that number with the baud rate per WDM channel (8 GBd) and then with the number of carriers (8 or 10), we then divided with the total spectral width the used WDM channels (76.5 or 70 GHz). Finally, we subtracted the 5% pilots used for each modulation format. This calculation is only valid when the information transmitted is decodable, which is the case for the 3000 km 1024-QAM point, but not for the 64-QAM point, due to the larger overhead used for 1024-QAM transmission.



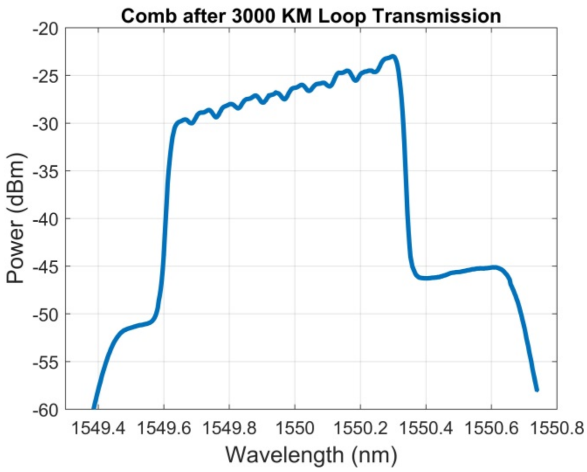


Fig. 2 (left) MI versus distance for various modulation formats. For the 3000 km point the carrier spacing was increased. Fig. 3 (right) The spectrum of the comb after 3000 km transmission, with data modulation on each line.

The 256 QAM performance degrades faster with distance than the 1024 QAM which is the expected outcome when performance is measured using MI. In terms of utilization of the maximum available MI for each modulation format the 256-QAM performs better for each distance. For the 1024-QAM transmission we see superior performance for all points, even at 3000 km, but we would expect the performance to converge for low enough SNRs. The substantial difference between the 64- and 1024-QAM is explained by the sufficient amount of SNR to utilize 1024-QAM. However the code rate for the 1024-QAM point at 3000 km is higher and the number of channels reduced. Therefore the data rate is lower than at the other 1024-QAM points.

3000 km transmission with 1024-QAM was decodable as the required MI for decoding is 10 bits/symbol and we reached an MI per line of ≈ 10.8 bits/symbol. The potential spectral efficiency at 3000 km transmission using 1024-QAM was measured as ≈ 8.7 bit/s/Hz which to our knowledge is in line with state-of-the-art performance at those distances, for pilot-aided DSP. To determine if the crosstalk at the transmitter could be improved, we tested the performance of the comb in the B2B configuration and using the 8.5 GHz spacing of the individual lines (17 GHz of the generated combs). In Table 1 the performance of the middle channel (channel 6) of the comb is shown versus FSR in terms of effective received SNR.

Table 1: Performance of the 6th Comb Line

FSR (GHz)	17	17.2	17.4	17.6	17.8	18
SNR (dB)	24.9	25.1	25.3	25.9	25.5	25.0

We varied the FSR of the comb to analyze the crosstalk and we observe no obvious correlation between the performance of the center channel as a function of the FSR. We conclude that for a 12.5% guard band the performance of the comb in B2B is equal to that of the single channel. The SNR in Table 1 is an average taken over 5 traces to reduce the impact of possible instabilities in the setup. This leads us to conclude that the crosstalk penalties preventing us from operating at 8.5 GHz spacing for the 1024-QAM transmission at 3000 km was not from the transmitter but rather from the loop and therefore transmission penalties. In Fig. 3 the comb spectrum after 3000 km transmission is shown. The gain tilt of the transmission setup is immediately noticeable, with a resulting MI variation of ≈ 1 bit/symbol for 1024-QAM. The outer channels perform slightly better and the odd comb lines, have slightly better performance due to being amplified less before transmission. The total OSNR, when integrating over the comb lines, is ≈ 40 dB. This demonstrates a very slight decrease in OSNR due to transmission even at 3000 km, which demonstrates the high performance of the transmission system comprising the Raman amplified SCUBA fiber and the comb. To further improve performance shaping could be implemented, as described in [6]. We maintain a data rate above 1 Tb/s until the 1000 km mark for 1024-QAM and 600 km for 256-QAM. For the 64-QAM we reach a potential data rate of 680 Gb/s slightly superior to that of the 640 Gb/s 3000 km 1024-QAM transmission, due to the reduced number of lines for the 1024-QAM case. However 64-QAM MI was below the decoding threshold while the 1024-QAM was above the decoding threshold for the code used.

4 Conclusion

We show that the transmission of frequency combs provides a strong option for spectrally efficient systems for long haul systems dominated by transmission penalties. Low baud rate long reach transmission systems are a viable spectrally efficient solution for higher order modulation formats. Finally, a potential spectral efficiency of approximately 8.7 bit/s/Hz and a data rate of 640 Gb/s at 3000 km transmission using 1024-QAM and 5% pilot-aided DSP is reached, outperforming a 64 QAM transmission using fewer lines and less bandwidth. This performance is in line with the state-of-the-art performance for those distances of systems not using frequency combs, to the best of our knowledge [7,8]. We would like to thank NKT for providing the Koheras BasiK fiber lasers, OFS for the TeraWave SCUBA fiber and the DNRF Center of Excellence, SPOC, ref. DNRF123 for the financial support.

5 References

[1] S. L.I. Olsson, J. Cho, S. Chandrasekhar, X. Chen, P. J. Winzer, and S. Makovejs, "Probabilistically shaped PDM 4096-QAM transmission over up to 200 km of fiber using standard intradyne detection," Opt. Express **26**, 4522-4530 (2018).

[2] S. Okamoto, M. Terayama, M. Yoshida, K. Kasai, T. Hirooka, and M. Nakazawa, "Experimental and numerical comparison of probabilistically shaped 4096 QAM and a uniformly shaped 1024 QAM in all-Raman amplified 160 km transmission," Opt. Express **26**, 3535-3543 (2018).

[3] S. Beppu, K. Kasai, M. Yoshida, and M. Nakazawa, "2048 QAM (66 Gbit/s) single-carrier coherent optical transmission over 150 km with a potential SE of 15.3 bit/s/Hz," Opt. Express **23**, 4960-4969 (2015).

[4] Y. Koizumi, K. Toyoda, M. Yoshida, and M. Nakazawa, "1024 QAM (60 Gbit/s) single-carrier coherent optical transmission over 150 km," Opt. Express **20**, 12508-12514 (2012).

[5] S. L. I. Olsson, J. Cho, S. Chandrasekhar, X. Chen, E. C. Burrows, and P. J. Winzer, "Record-High 17.3-bit/s/Hz Spectral Efficiency Transmission over 50 km Using Probabilistically Shaped PDM 4096-QAM," in Optical Fiber Communication Conference Postdeadline Papers, OSA Technical Digest (online) (Optical Society of America, 2018), paper Th4C.5.

[6] E. P. da Silva, F. Klejs, M. Lillieholm, S. Iqbal, M. P. Yankov, J. C. M. Diniz, T. Morioka, L. K. Oxenløwe, and M.Galili, "Experimental characterization of 10×8 GBd DP-1024QAM transmission with 8-bit DACs and intradynedetection," in Proc. of the European Conf. on Opt. Communications (ECOC), 2018, Th1D.3.

[7] S. Chandrasekhar, B. Li, J. Cho, X. Chen, E. C. Burrows, G. Raybon, and P. J. Winzer, "High-spectral-efficiency transmission of PDM 256-QAM with parallel probabilistic shaping at record rate-reach tradeoffs," Post deadline of the European Conf. on Opt. Communications (ECOC), 2016, Th.3.C.1.

[8] J. Yu, K. Wang, C. Hungchang, B. Zhu, X. Li, and J. Zhang, "8x528Gb/s PS-64QAM Transmission over 3000km in a Terrestrial System with an Amplifier Span of 100km'. in Proc. of the European Conf. on Opt. Communications (ECOC), 2018, We2.39.