Transmission of Hybrid Probabilistically and Geometrically Shaped 256QAM at 49-Gbaud in a 50-GHz Spacing WDM System

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Abstract *We experimentally demonstrated 10×614.4-Gbps 256QAM coherent WDM transmission over 400-km SSMF based on a new hybrid probabilistically and geometrically shaped signal with 50-GHz frequency spacing, obtaining 2-dB shaping gain compared with regular 256QAM.*

Introduction

High-order QAM formats which can provide high spectral efficiency have been widely used in WDM system to meet the demand of high-capacity transmission[1]–[2]. 256QAM with spectral efficiency (SE) of 12 bit/s/Hz has been demonstrated employing 23.6-GBaud polarization multiplexing (PM) 256QAM signal in 25-GHz grid WDM system over 200-km transmission[1]. SE of 10.67 bit/s/Hz/mode has been achieved using 24.5-Gbaud 256-QAM signal over 55-km three-mode fiber[2]. Recently, in order to increase the channel capacity and transmission distance in the WDM system, the application of probabilistic shaping (PS) and geometric shaping (GS) techniques is also being focused. 82-GBaud PM PS-256QAM in 100 GHz-spacing with 8 bit/s/Hz SE over 400-km has been achieved[3].96-GBaud PS-256QAM signal in 100-GHz grid over 100-km fiber has been demonstrated with SE of 10 bit/s/Hz[4]. Given the capacity-approaching superiority of PS and GS, it appears attractive to combine both shaping techniques and design a novel hybrid PS/GS constellation of high-order QAM to provide performance very close to the Shannon limit[5]–[7].

In this paper, we have experimentally demonstrated 49-Gbaud PM hybrid PS/GS 256QAM signal transmission based on a 10-channel coherent WDM system with 50-GHz frequency spacing. Thanks to the joint pre-equalization and offline digital signal processing (DSP), 6.144 Tb/s WDM transmission with SE of 12.288 bit/s/Hz over 400-km SSMF can be realized and satisfy the 0.8-NGMI SD-FEC threshold with 25% overhead. We maintain the same net bit rate and compare the performance among PS, hybrid PS/GS and regular 256-QAM in the experiment. The designed novel hybrid PS/GS-256QAM constellation reaches a more Gaussian-like distribution, which achieves 2-dB shaping gain compared with 256QAM and outperforms PS-256QAM in both single-channel and WDM cases. To the best of our knowledge, we realize 256QAM signal transmission with the highest SE.

Experimental setup

The experimental setup and offline DSP procedure of transmitter and receiver are depicted in Fig. 1 and Fig. 2. We add the symmetry constraint to reduce the complexity of GS constellation deign for high-order QAM, which also enables the constellation to be shaped probabilistically. We achieve the optimized constellation with geometric and probabilistic

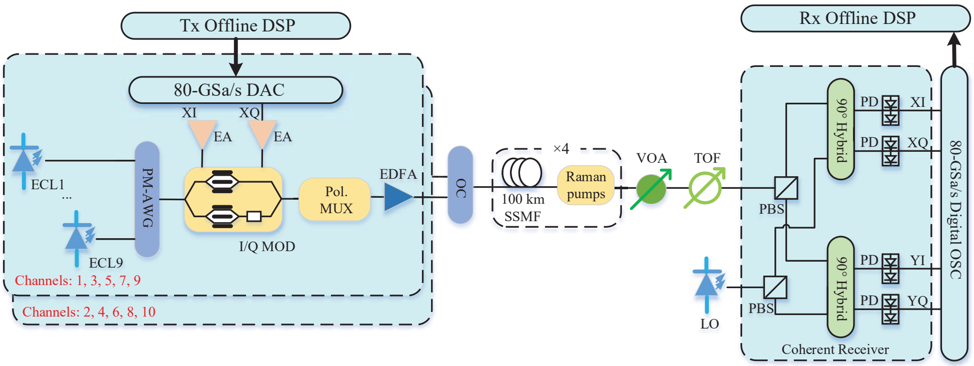

Fig. 1: Experimental setup for 10-channel WDM transmission.

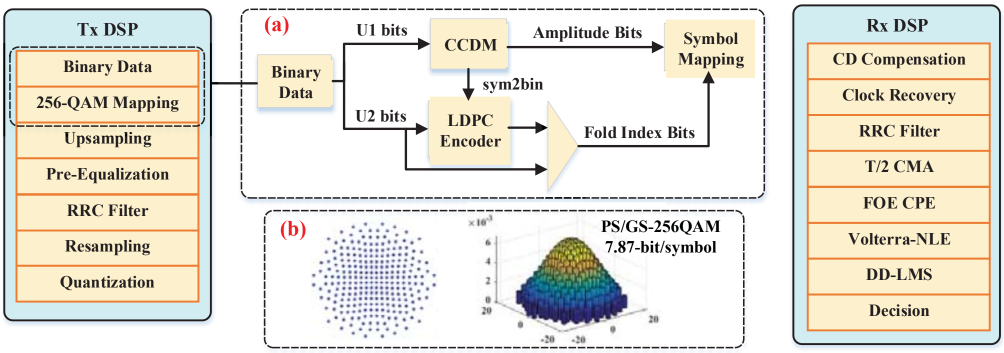

Fig. 2: Offline DSP procedure of transmitter and receiver: (a) Block diagram of PS signal generation; (b) Constellation and probability distribution of hybrid PS/GS-256QAM.

shaping by the generalized pairwise optimization (GPO) algorithm[7] to achieve near-Shannon performance. We adopt the probabilistic fold shaping (PFS) scheme[8], which is suitable for the 4-fold rotationally symmetrical 256-QAM. Fig. 2(a) shows the block diagram of PS signal generation. Amplitude bits are obtained by CCDM while fold index bits are obtained by LDPC encoder with 25% overhead (4/5 code rate). They are combined and transformed into a sequence of PS-256-QAM or hybrid PS/GS-256QAM symbols with an entropy of 7.87 bit/symbol/polarization. The constellation and corresponding probability distribution of hybrid PS/GS-256QAM are illustrated in Fig. 2(b). Considering the FEC code rate of 4/5, the transmission rate[8] of PS symbols is 7.87-8×(1-4/5) =6.27 bit/symbol while it is 6.4 bit/symbol for regular 256QAM symbols. Therefore, to keep the same net bit rate, the baud rate of PS-256-QAM and hybrid PS/GS-256QAM should be 49Gbaud when the baud rate of regular 256QAM is 48Gbaud. The net bit rate is 614.4 Gbit/s and the SE is 12.288 bit/s/Hz, which is the highest SE, to our knowledge.

The symbol sequence is ×2 oversampled and sent into a pre-equalization filter based on the 21-tap constant-modulus algorithm (CMA) FIR in the back-to-back (BtB) case to compensate for the channel response. Root-raised-cosine (RRC) pulse shaping with 0.01 roll-off factor is used to eliminate the impact of crosstalk from adjacent channels. Then the symbol sequence is resampled and quantized in 8-bits before being uploaded into an 80-GSa/s DAC with 3-dB bandwidth of 20-GHz.

At the transmitter, ten channels are used for the generation of WDM signals, including odd-channel group (Ch. 1, 3, 5, 7 and 9) and even-channel group (Ch. 2, 4, 6, 8 and 10), which are both combined by a polarization-maintaining arrayed waveguide grating (PM-AWG). The CW lightwaves of all channels are generated from ten ECLs with a linewidth less than 100 kHz, operating from 194.996 to 195.446 THz. The frequency spacing is 50 GHz which is close to the signal bandwidth. The electrical signals are first boosted by parallel drivers and then fed into a 30-GHz I/Q modulator. PM optical signals are generated with the aid of a polarization multiplexer (pol. MUX) and amplified by an EDFA. The odd-channel group and the even-channel group carrying PM signals are combined by an optical coupler (OC) before they are launched into 4 spans of 100-km SSMF with an attenuation coefficient of 0.188-dB/km and a chromatic dispersion coefficient of 17.5-ps/(nm*km) at 1550 nm. A backward-pumped Raman amplifier with ~18-dB ON-OFF gain is employed to compensate for the signal loss for each span. In addition, a variable optical attenuator (VOA) is used to adjust the received optical power.

At the receiver, the optical signal in the test channel is selected by a tunable optical filter (TOF) and then sent into the coherent receiver. The coherent receiver consists of two polarization beam splitters (PBSs) and two 90° optical hybrids, which are used for optical polarization diversity and phase diversity. The output signals of the hybrids are detected by four balanced photodetectors (PDs) to achieve optical-to-electrical conversion. Another ECL with a linewidth less than 100 kHz is utilized as an optical local oscillator (LO), which works at the same frequency as the test channel. Finally, the A/D conversion and sampling are realized by a real-time digital oscilloscope with 80-GSa/s sample rate and 36-GHz electrical bandwidth. The off-line DSP includes resampling, CD compensation, clock recovery, T/2-spaced CMA equalization, frequency offset estimation (FOE), carrier phase estimation (CPE), 401-nonlinear-tap Volterra nonlinear equalization (VNLE) and DD-LMS equalization.

Results and Discussion

Experimental results are shown in Fig.3 and Fig.4. The optical spectra of 10-channel WDM regular 256QAM signals before and after 400-km fiber

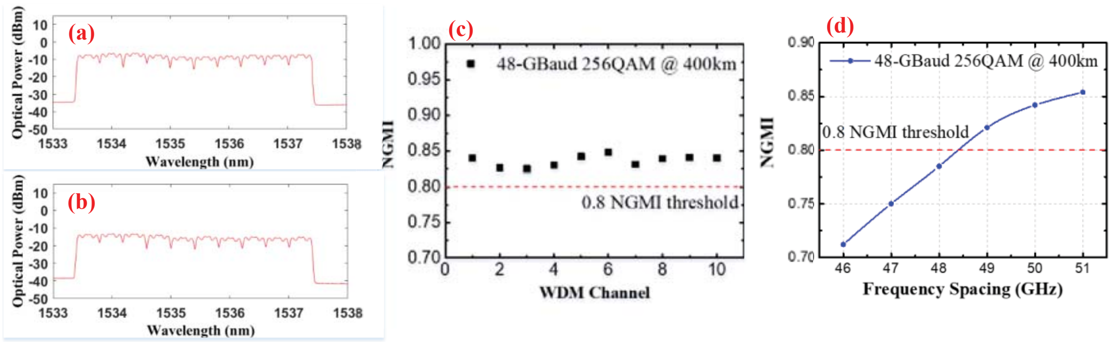

Fig. 3: Optical spectra of 10-channel WDM regular 256QAM signals (a) before and (b) after 400-km fiber transmission; (c) NGMI of all ten channels after fiber transmission; (d) NGMI versus frequency spacing.

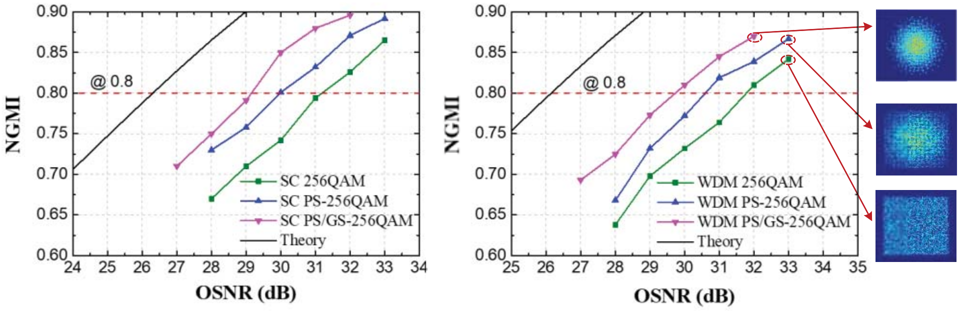

Fig. 4: NGMI versus OSNR in (a) single-channel and (b) WDM cases.

transmission are given in Fig. 3(a) and (b), respectively. By changing the LO frequency at the receiver, Fig. 3(c) shows the measured NGMI values of 10-channel WDM signals after fiber transmission, which are all above 0.8-NGMI SD FEC threshold with 25% overhead. Therefore, the total net bit rate of WDM 256QAM signals is 6.144 Tb/s. By changing the wavelengths of Ch.4 and Ch.6, the frequency spacing among Ch.4, Ch.5 and Ch.6 is adjusted from 46 GHz to 51 GHz. Fig. 3(d) gives the measured NGMI of 48-Gbaud regular 256QAM versus frequency spacing in the 5th WDM channel. When the frequency spacing is slightly wider than the signal bandwidth, transmission over 400-km SSMF can be realized based on WDM 256QAM, considering the 0.8-NGMI threshold.

In addition, as shown in Fig. 4(a) and (b), we compare the NGMI performance of three 256QAM formats with the same net bit rate in both single-channel and WDM cases. The theoretical result of 48-GBaud PM 256QAM is also given. For WDM transmission with 50-GHz frequency spacing, there is around 0.6-dB OSNR penalty compared with the single-channel case. In the 5th WDM channel, the required OSNR is about 30.6 dB for PS-256QAM signal at the NGMI threshold of 0.8, which obtains around 1.2-dB OSNR gain compared with regular 256QAM. Meanwhile, the proposed hybrid PS/GS-256QAM outperforms PS-256QAM by around 0.8-dB OSNR gain in both single-channel and WDM cases. While compared to uniformly-distributed 256QAM signal, hybrid PS/GS-256QAM at the same net bit rate can provide the shaping gain of 2-dB. The recovered symbols of three 256QAM formats are also shown in Fig. 4(b).

Conclusions

We have successfully demonstrated for the first time 10-channel WDM transmission with 50-GHz frequency spacing over 400-km SSMF employing 49-Gbaud PM hybrid PS/GS-256QAM signal, achieving the total net bit rate of 6.144 Tb/s and SE of 12.288 bit/s/Hz. The experimental results show the proposed hybrid PS/GS-256QAM outperforms PS-256QAM by 0.8-dB OSNR gain and obtains 2-dB shaping gain compared with regular 256QAM at the same net bit rate in both single-channel and WDM cases.

Acknowledgements

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References

[1] Y. Yu, *et al.*, “400 x 377.6 Gb/s C+L Band Seamless Transmission over 200 km with Raman Amplifier Using PDM-256QAM,” *ECOC 2018*, 1-3.

[2] G. Rademacher, *et al.*, “Highly spectral efficient transmission of 183 x 24.5 GBaud 256-QAM spatial super channels over 55 km three-mode fiber,” *ECOC*

2019, 1-4.

[3] M. Nakamura, *et al.*, “Spectrally Efficient 800 Gbps/Carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM,” *ECOC 2018*, 1-3.

[4] A. Matsushita, M. Nakamura, F. Hamaoka and Y. Kisaka, "41-Tbps C-band transmission with 10-bps/Hz spectral efficiency using 1-Tbps 96-GBd PS-256QAM for DCI,” *ECOC 2019*, 1-3.

[5] Z. Qu, *et al.*, “Universal hybrid probabilistic-geometric shaping based on two-dimensional distribution matchers”, *OFC 2018*, M4E.4.

[6] S. Zhang *et al.*, “Design and Comparison of Advanced Modulation Formats Based on Generalized Mutual Information”, *Journal of Lightwave Technology*, vol. 34, no. 7, pp 99, 2017.

[7] S. Zhang *et al.*, “Constellation design with geometric and probabilistic shaping”, *Optics Communications*, vol. 409, pp 7-12, 2018.

[8] J. Ding, J. Zhang, Y. Wei, F. Zhao, C. Li and J. Yu, “Comparison of Geometrically Shaped 32-QAM and Probabilistically Shaped 32-QAM in a Bandwidth-Limited IM-DD System”, *Journal of Lightwave Technology*, vol. 38, no. 16, pp 4352-4358 2020.