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Abstract

8-ary quadrature-amplitude modulation (8QAM) plays an important role in filling the gap between quaternary phaseshift keying (QPSK) and 16QAM in terms of bit rates and reach. To achieve the same spectral efficiency with improved sensitivity, quaternary code and sphere-cut lattice codes, 4D honeycomb lattice codes, Circular-8QAM, and 4D 2-ary amplitude 8-ary phase-shift keying (4D-2A8PSK) have been proposed. 4D-2A8PSK is especially attractive among these 3-/s/Hz/pol formats, since it has the properties of Gray coding and constant modulus. Current optical communication systems usually rely on soft-decision (SD) forward error correction (FEC) coding based on bit-interleaved coded modulation (BICM). Therefore, using the BICM mutual information, also called generalized mutual information (GMI), is a better metric for comparing multiple modulation formats. Several 8QAM constellations were compared using GMI in the linear region and the nonlinear region. More recently, two new modulation formats, (4D) 64 set-partitioned (SP-) 12QAM and DP-Circular-8QAM with optimized inner/outer circle radius ratio, which are shown to have better performances than some previous modulation formats. However, the direct comparison among all the latest modulation formats have not been done yet. In this work, we compare the nonlinear transmission characteristics of four 2D/4D modulation formats, i.e., 4D- 2A8PSK, 4D-64SP-12QAM, optimized DP-Circular-8QAM, and the conventional DP-Star-8QAM using GMI.

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BICM capacity analysis of 8QAM-alternative 2D/4D modulation formats in nonlinear fiber transmission

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Abstract: Nonlinear performance of 8QAM-alternative modulation formats are compared to evaluate the BICM capacity. Simulation results show that the recently proposed 4D-2A8PSK, optimized DP-Circular-8QAM, and 64SP-12QAM all have at least 0.7 dB margins than DP-Star-8QAM.

OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

8-ary quadrature-amplitude modulation (8QAM) plays an important role in filling the gap between quaternary phase-shift keying (QPSK) and 16QAM in terms of bit rates and reach. To achieve the same spectral efficiency with improved sensitivity, quaternary code and sphere-cut lattice codes [1], 4D honeycomb lattice codes [2], Circular-8QAM [3, 4], and 4D 2-ary amplitude 8-ary phase-shift keying (4D-2A8PSK) [5] have been proposed. 4D-2A8PSK is especially attractive among these 3-b/s/Hz/pol formats, since it has the properties of Gray coding and constant modulus.

Current optical communication systems usually rely on soft-decision (SD) forward error correction (FEC) coding based on bit-interleaved coded modulation (BICM). Therefore, using the BICM mutual information, also called generalized mutual information (GMI), is a better metric for comparing multiple modulation formats [6]. Several 8QAM constellations were compared using GMI in the linear region [4] and the nonlinear region [7]. More recently, two new modulation formats, (4D) 64 set-partitioned (SP-) 12QAM [8] and DP-Circular-8QAM with optimized inner/outer circle radius ratio [9], which are shown to have better performances than some previous modulation formats. However, the direct comparison among all the latest modulation formats have not been done yet.

In this work, we compare the nonlinear transmission characteristics of four 2D/4D modulation formats, i.e., 4D-2A8PSK, 4D-64SP-12QAM, optimized DP-Circular-8QAM, and the conventional DP-Star-8QAM using GMI.

2. Modulation Formats

In this paper, we evaluate four different modulation formats. The baseline format is DP-Star-8QAM. Constellation for the 4D-2A8PSK formats shown in Fig. 1 [5]. This has the properties of constant modulus, i.e., the total power summed over the two polarizations is constant. It also uses Gray coding. The ratio of outer/inner circle radius of 1.54 is chosen, after optimizing for the best nonlinear performance. DP-Circular-8QAM with optimized radius shows $\sim$ 0.3 dB improvement compared to the standard DP-Circular-8QAM. The ratio of outer/inner circle radius of 1.4 is chosen as described in [9]. 64SP-12QAM [8] is a 4D modulation format and a subset of DP-16QAM, and the selection was made to maximize the Euclidean distances between words. It has an advantage of using a regular 16QAM grid. Table 1 summarizes the properties of the four formats. Euclidean distances were calculated when the symbol energy per polarization was normalized.

3. Optical Transmission Performance

Simulation procedures and parameters are similar to [7], except for the number of channels. The modulated symbols are mapped to the four dimensions (4D-2A8PSK, 64SP-12QAM), or two dimensions (DP-Circular-8QAM, DP-Star-8QAM). At the transmitter, rectangular pulses were filtered by a root-raised-cosine (RRC) filter with a roll-off factor of 0.1. 11-wavelength channels with the same code were simulated at a rate of 34 GBd per wavelength with 37.5 GHz spacing and no optical filtering. We used the Manakov equation to model the nonlinear fiber transmission. The link

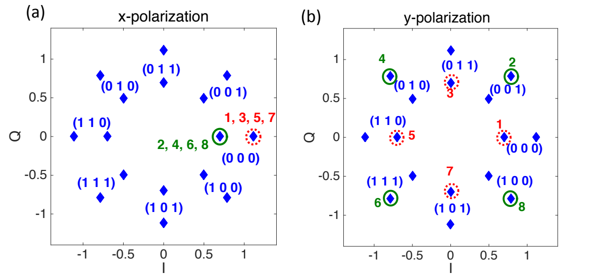

Fig. 1: Constellation and labeling of 4D-2A8PSK for (a) x-polarization, and (b) y-polarization [5].

Format	Eucl. Dist.	Gray Coding	Const. Mod.
4D-2A8PSK	0.938	Yes	Yes
Opt. DP-Circular-8QAM	0.859	Almost	No
64SP-12QAM	1.000	No	No
DP-Star-8QAM	0.919	No	No

Table 1: Summary of the four modulation formats

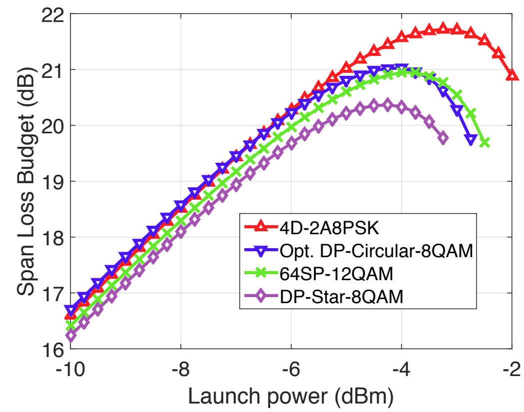

Fig. 2: Span loss budget of the four modulation formats for the dispersion managed link with a target GMI of 2.55 b/s/Hz/pol.

loss was compensated by Erbium-doped fiber amplifiers (EDFAs). All the EDFA noise (4.0 dB noise figure) is loaded just before the receiver. To quantify performance over a single link for multiple modulation formats, span loss budget was used [10]. An ideal homodyne coherent receiver was used, with a transfer function described by the RRC filter of a roll-off factor of 0.1, followed by sampling at twice the symbol rate. Following this, ideal chromatic dispersion equalization and data-aided least-mean-square equalization were employed. We used non-zero dispersion shifted fiber (NZDSF) link. NZDSF parameters were, $\gamma = 1.6$ /W/km; $D = 3.9$ ps/nm/km; $\alpha = 0.2$ dB/km. Other fiber effects such as dispersion slope and polarization mode dispersion were not simulated. At the end of each span, 90% of the chromatic dispersion was compensated as a lumped linear dispersion compensator. We used pre-compensation of the 50% of the total chromatic dispersion at the beginning of the link. We evaluated the span loss budget with the target GMI per bit of 0.85 [4] (GMI = 2.55 b/s/Hz/pol) for the state-of-the-art SD-FEC of a code rate of 0.8 [11]. The optical noise is added onto the transmitted signal including nonlinear distortion, and the GMI is calculated. The required optical SNR (ROSNR) is to meet the target GMI is used for calculating the span loss budget.

The calculated span loss budget for the five modulation formats are shown in Fig. 2. In the low launch power regime (-10 dBm) where linear propagation effects are dominant, optimized Circular-8QAM has a higher margin than other formats. For higher launch powers where nonlinearity is dominant, the margin for 4D-2A8PSK becomes higher. Overall, the peak span loss budgets for 4D-2A8PSK, optimized DP-Circular-8QAM, 64SP-12QAM are higher than DP-Star-8QAM by 1.4 dB, 0.8 dB, and 0.7 dB, respectively. Highest nonlinear threshold of 4D-2A8PSK mostly comes from its constant modulus property.

4. Conclusions

We compared DP-Star-8QAM with three new 2D/4D modulation formats at the same spectral efficiency for nonlinear transmission. The margins of 4D-2A8PSK, optimized DP-Circular-8QAM, and 64SP-12QAM are higher than DP-Star-8QAM by 1.4 dB, 0.8 dB, and 0.7 dB, respectively.

References

1. D. S. Millar, T. Koike-Akino, S. Ö. Arik, K. Kojima, and K. Parsons, *OFC* M3A.4 (2014).
2. H. Buelow, X. Lu, L. Schmalen, Z. Klekamp, and F. Buchali, *OFC* M2A.6 (2014).
3. R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, *JLT* **28** 4, 662–701 (2010).
4. R. Rios-Mueller, J. Renaudier, L. Schmalen, and G. Gharlet, *OFC* W3K.4 (2015).
5. K. Kojima, D. S. Millar, T. Koike-Akino, and K. Parsons, *ECOC* P.3.25 (2014).
6. A. Alvarado and E. Agrell, *JLT* **33** 10, 1993–2003 (2015).
7. K. Kojima, T. Koike-Akino, D. S. Millar, and K. Parsons, *Tyrrhenian Int'l Workshop on Digital Comm.* 57–59 (2015).
8. T. Nakamura, E. L. D. d. Gabory, H. Noguchi, W. Maeda, J. Abe, and K. Fukuchi, *ECOC* Th.2.2.2 (2015).
9. S. Zhang, K. Nakamura, F. Yaman, E. Mateo, T. Inoue, and Y. Inada, *ECOC* Mo.3.6.5 (2015).
10. P. Poggiolini, G. Bosco, A. Carena, V. Curri, and F. Forghieri, *Opt. Exp.* **18** 11, 11360–11371 (2010).
11. K. Sugihara, Y. Miyata, T. Sugihara, K. Kubo, H. Yoshida, W. Matsumoto, and T. Mizuochi, *OFC* OM2B.4 (2013).