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Abstract

For long-haul and metro 100 Gb/s coherent optical transport, dual-polarized quadrature phase-shift keying (DPQPSK), with a spectral efficiency of 4 bits/symbol, is a standard solution. Also, polarization-switched quadrature phase-shift keying (PS-QPSK) [1] is commonly used for 3 bits/symbol. To optimize the spectral efficiency and the reach under various transmission conditions, it is important to have finer granularity in spectral efficiency. However, there is no de facto standard for 3.5 bits/symbol spectral efficiency. In long-haul transmission, fiber nonlinearity is the critical factor limiting the reach. One effective way is to use Grassmann code [2, 3] to be robust against state of polarization (SOP) rotation including cross polarization modulation (XPolM). Another way is to manage the SOP, such that its fluctuation is minimal [4]. In this paper, we propose two modulation formats targeting 3.5 bits/symbol spectral efficiency in different ways. One is to extend the 8D Grassmann code concept for this spectral efficiency. Another is to combine the block-coded high-dimensional modulation and the SOP management. Their excellent nonlinear transmission performances are demonstrated in simulations.

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Nonlinearity-tolerant modulation formats at 3.5 bits/symbol

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Abstract: We propose two nonlinearity-tolerant high dimensional modulation format for 3.5 bits/symbol, which can also be an alternative for PS-QPSK (3 bits/symbol) or DP-QPSK (4 bits/symbol).

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

1. Introduction

For long-haul and metro 100 Gb/s coherent optical transport, dual-polarized quadrature phase-shift keying (DP-QPSK), with a spectral efficiency of 4 bits/symbol, is a standard solution. Also, polarization-switched quadrature phase-shift keying (PS-QPSK) [1] is commonly used for 3 bits/symbol. To optimize the spectral efficiency and the reach under various transmission conditions, it is important to have finer granularity in spectral efficiency. However, there is no de facto standard for 3.5 bits/symbol spectral efficiency. In long-haul transmission, fiber nonlinearity is the critical factor limiting the reach. One effective way is to use Grassmann code [2, 3] to be robust against state of polarization (SOP) rotation including cross polarization modulation (XPolM). Another way is to manage the SOP, such that its fluctuation is minimal [4].

In this paper, we propose two modulation formats targeting 3.5 bits/symbol spectral efficiency in different ways. One is to extend the 8D Grassmann code concept for this spectral efficiency. Another is to combine the block-coded high-dimensional modulation and the SOP management. Their excellent nonlinear transmission performances are demonstrated in simulations.

2. Modulation Formats

The first proposed format is a Grassmann code-based 7-bit 8D code, whose schematic is shown in Fig. 1. 2-ary amplitude QPSK (2AQPSK) and 2-ary amplitude 8PSK (2A8PSK) are used for the first and the second time slots, respectively. x_1, x_2, y_1, y_2 are x- and y-polarization component of the first and second time slot, respectively. Let b_0-b_6 the information bits. In a similar manner as described in [5], for the 2AQPSK part, b_0 and b_1 are used for the angle of x_1, and b_2, b_2 are used for the angle of y_1, respectively. For x_2, b_4–b_6 are used for the angle representation of 2A8PSK. All use Gray coding for the angle. The radius of x_1 is expressed as $XOR(b_4, b_5, b_6)$, where "0" means the larger radius, and "1" means the smaller radius. The ratio of the radii is called the ring ratio. The radius of y_1 is expressed as $\overline{XOR(b_4, b_5, b_6)}$. Both 2AQPSK and 2A8PSK share the same ring ratio of 0.70, which was optimized for the nonlinear performance. The radius of x_2 is expressed as $XOR(b_0, b_1, \ldots, b_6)$. y_2 is calculated from the Grassmannian condition $x_1\, y_1^* + x_2\, y_2^* = 0$. This guarantees the 4D constant modulus condition for both time slots.

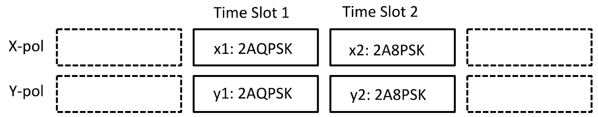

Fig. 1: Structure of the 7b8D-Grassmann code

The second modulation format uses seven information bits and one parity bit, and the total of eight bits are mapped to two time slots of QPSK signals. Because of the parity bit, the minimum Euclidean distance increases by a factor of $\sqrt{2}$ compared to the standard DP-QPSK. In the baseline (SOP-unmanaged) 7b8D format, the parity bit is expressed as $XOR(b_0, b_1, \ldots, b_6)$. On the other hand, in our proposed SOP-managed format, we use $\overline{XOR(b_0, b_1, \ldots, b_6)}$. Just like in [4] for the 6b8D code, the SOP is randomized over S_2 and S_3 spaces in two time slots. In other words, if the first time slot has circular polarization, the second time slot has 45 deg linear polarization, and vice versa.

Current optical communication systems usually rely on soft-decision (SD) forward error correction (FEC) coding based on bit-interleaved coded modulation (BICM). For that, generalized mutual information (GMI) is a better metric for comparing multiple modulation formats [6] than bit error ratio (BER). We use target normalized $GMI = 0.86$ ($Q = 5.0$ dB) as the criteria for the error-free transmission of the state-of-the-art SD-FEC. We also used $GMI = 0.92$ ($Q = 6.2$ dB) corresponding to additional Q margin.

3. Optical Transmission Performance

Simulation procedures and parameters are similar to [5, 7]. At the transmitter, rectangular pulses were filtered by a root-raised-cosine (RRC) filter with a roll-off factor of 0.1. Nine-wavelength channels with the same code were simulated at a rate of 35, 40, or 46.67 GBd per wavelength with channel spacing which is 1.15 times of the Baud rate. We used the Manakov equation to model the nonlinear fiber transmission. The link comprised 75 spans of 80 km non-zero dispersion shifted fiber (NZDSF) with loss compensated by Erbium-doped fiber amplifiers (EDFAs). Inline compensation of 90% and precompensation of 50% of the residual dispersion of the full link are used. In a homodyne coherent receiver, we used an RRC filter with a roll-off factor of 10%, followed by sampling at twice the symbol rate. Following this, ideal chromatic dispersion equalization and data-aided least-mean-square equalization were employed. All the optical noise due to the EDFA is loaded just before the receiver. We varied the optical signal-to-noise ratio (OSNR) such that the target GMI is reached. The obtained required OSNR is used to calculate the span loss budget. An EDFA noise figure of 5 dB is assumed for the span loss budget calculations.

Simulated results are shown in Figs. 2 and 3, with the target normalized GMI of 0.86 and 0.92, respectively. Among the 3.5 bits/symbol formats, the 7b8D-Grassman code has the highest nonlinear threshold because of the zero-SOP property, and its benefit is especially high for $GMI = 0.92$. On the other hand, 7b8D-SOP-managed format has very good linear performance due to its large minimum Euclidean distance, while its benefit of SOP management is 0.1 dB for $GMI = 0.86$ and 0.2 dB for $GMI = 0.92$, respectively, both at the launch power of -2.5 dB. Considering that the two proposed formats have better nonlinear performance than DP-QPSK of the same data rate, they can be possible alternative formats, achieving longer distance. Furthermore, since their performance penalty is modest compared to PS-QPSK, they can be alternative options with higher spectral efficiency than PS-QPSK.

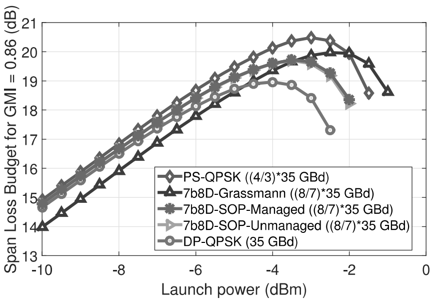

Fig. 2: Span loss budget as a function of launch power for the target normalized GMI = 0.86.

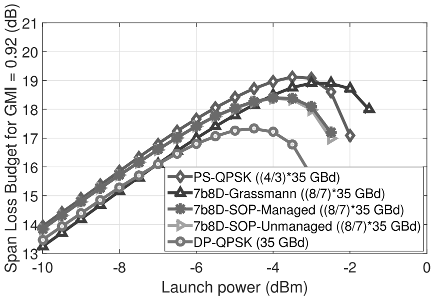

Fig. 3: Span loss budget as a function of launch power for the target normalized GMI = 0.92.

4. Conclusions

We proposed two modulation formats targeting 3.5 bits/symbol which have high nonlinearity tolerance. These could be alternative modulation formats for PS-QPSK and DP-QPSK.

References

1. E. Agrell and M. Karlsson, *JLT* **27** 22, 5115–5126 (2009).
2. A. D. Shiner, M. Reimer, A. Borowiec, S. O. Gharan, J. Gaudette, P. Mehta, D. Charlton, K. Roberts, M. O'Sullivan, *Opt. Exp.* **22** 17, 20366–20374 (2014).
3. T. Koike-Akino, K. Kojima, and K. Parsons, *SPPCOM* SpS3D.6 (2015).
4. T. Yoshida, K. Kojima, T. Koike-Akino, D. S. Millar, K. Matsuda, K. Parsons, K. Kubo, K. Uto, and T. Sugihara, *OECC* (2016).
5. K. Kojima, T. Yoshida, T. Koike-Akino, D. S. Millar, K. Parsons, and V. Arlunno, *ECOC* W.2.D.1 (2016).
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).