High spectral efficiency 8D polarization-ring-switching modulation formats

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High Spectral Efficiency 8D Polarization-ring-switching Modulation Formats

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Abstract—We propose two 8-dimensional (8D) modulation formats (8D-2048PRS-T1 and 8D-2048PRS-T2) with spectral efficiency of 5.5 bit/4D-sym, where the 8 dimensions are obtained from two time slots and two polarizations. Both formats provide high nonlinearity tolerance by selecting symbols with nonidentical states of polarization (SOPs) in two time slots. The performance of these novel 8D modulation formats is assessed in terms of the effective signal-to-noise ratio (SNR) and normalized generalized mutual information. 8D-2048PRS-T1 is more suitable for high SNRs, while 8D-2048PRS-T2 is shown to be more tolerant to nonlinearities. Up to 1.6 dB sensitivity improvement by maximizing NGMI is demonstrated. For a long-haul nonlinear optical fiber system, 2000 km (28.6%) reach increase with respect to polarization-multiplexed 8-ary quadrature-amplitude modulation (PM-8QAM) is observed.

Index Terms—Achievable information rates, fiber nonlinearity, generalized mutual information, multidimensional modulation, mutual information.

I. INTRODUCTION

OPTICAL fiber nonlinearities are considered to be one of the limiting factors for achieving higher information rates in coherent optical fiber transmission systems [1], [2]. Over the last decade, a variety of digital signal processing (DSP) algorithms with varying degrees of computational complexity have been investigated to reduce the impact of intra-channel and inter-channel nonlinearities and to improve the system performance [3]. Advanced modulation formats with probabilistic and geometric shaping have been extensively explored with the aim of increasing achievable information rates (AIRs). Signal shaping has also been used to mitigate the effects of fiber nonlinearities.

Polarization multiplexing (PM) naturally allows modulation on a four-dimensional (4D) space. PM has the potential to increase achievable information rates when the modulation is truly designed in 4D. Conventional PM-formats such as PM-M/16QAM, however, are only optimized per two dimensions independently, and thus, they do not exploit all the available degrees of freedom. Several power-efficient modulation formats have been proposed using sphere-packing and lattice constructions in 4D and 8D space [4]–[7]. These designs, however, aim at optimizing the minimum Euclidean distance of the constellation, and thus, they are optimum only for asymptotically high SNR, in the linear additive white Gaussian noise (AWGN) channel, and for uncoded metrics such as symbol- and bit-error probability only [8, Sec. IV-A]. Some of these multidimensional (MD) modulation formats were also shown to give high mutual information (MI), but are not well-suited for coded systems based on a bit-wise decoder such as bit-interleaved coded modulation (BICM), i.e., their generalized mutual information (GMI) is quite low [9]. Furthermore, a performance penalty of these modulation formats was observed in the presence of nonlinearities [7]. Designing spectrally-efficient 8D GMI-maximizing modulation formats is still an open research problem.

MD constant-modulus modulation formats have been proposed [10]–[12] to mitigate the nonlinear interference. One example of this is the 4D 64-ary polarization-ring-switching (4D-64PRS) format we recently proposed in [13]. 4D-64PRS was obtained by jointly optimizing the coordinates and labeling and shown to outperform other modulation formats at SE of 6 bit/4D-sym. 8D modulation formats have twice as many degrees of freedom, and thus, can improve the AIRs and nonlinearity tolerance. The 8 dimensions can be obtained by for example using two frequencies [14] or two consecutive time slots [6], [15]. In this paper, we take the latter approach and design 8D formats using two time slots.

Our work builds upon the polarization-balancing concept, proposed for a SE of 2 bit/4D-sym in [15]. This concept was further investigated in terms of the SE and nonlinearity tolerance trade-off in [16], [17]. All the previous works using this concept only consider PM-QPSK with added constraints, and thus, only 8D formats at SE below 4 bit/4D-sym were considered. Generalizing those formats to higher SEs is non-trivial, specially when both the constellation and its binary labeling are taken into account.

In this paper, we propose an approach to construct two nonlinearity-tolerant modulation formats with SE of 5.5 bit/4D-sym. The formats are based on set-partitioning 4D-64PRS in two consecutive time slots. The first format is suitable for a high code rate coded modulation system. The second is well-suited for lower code rates and also exhibits...
higher nonlinearity tolerance. Numerical simulations demonstrate increased nonlinearity tolerance and transmission reach increase compared to other modulation formats.

II. 8D POLARIZATION-RING-SWITCHING FORMATS

In optical transmission systems, the performance of a given modulation format is determined by its tolerance to both nonlinear interference arising from the Kerr effect, and accumulated amplified spontaneous emission (ASE) noise. Therefore, designing modulation formats which increase the AIRs in the presence of linear and nonlinear impairments is crucial. In [13], we designed the 4D-64PRS format with SE 6 bit/4D-sym, which has a constant modulus and an optimized binary labeling. 4D-64PRS provides excellent linear gain and nonlinear gain with respect to other modulation formats at the same SE. The structure and binary labeling of 4D-64PRS is shown in Fig. 1. The bits \( b_1, b_2, b_4, b_5 \) determine the two 2D quadrants while \( b_3, b_6 \) determine the actual transmitted symbol.

Let \( S = [S_1, S_2, S_3] \) denote the Stokes vectors with \( S_1 = |X|^2 - |Y|^2, S_2 = 2R(X^Y), \) and \( S_3 = 2\{XY^*\} \), and where \( X \) and \( Y \) are complex number representing the constellation symbols in x- and y-polarization, resp. The symbols 4D-64PRS result in 16 distinct states of polarization (SOPs) and a has constant modulus (\( \|S\| = 1 \)). This is shown in Fig. 2 (ignoring the colors). If the 4D-64PRS format was to be used in two consecutive time slots \( (T_1 \) and \( T_2) \), there are \( 2^{12} = 4096 \) 8D symbols as a set \( \mathcal{X} \in \mathbb{R}^8 \), which can be represented by 12 bits \( b_1, b_2, \ldots, b_{12} \). In this paper we are interested in designing formats a SE of 11 bit/8D-sym, and thus, we will use \( b_{12} \) as parity bit to effectively remove 2048 out of the 4096 symbols.

In order to achieve better performance for optical fiber communication system, we designed 8D modulation formats with a better sensitivity and a high nonlinearity tolerance by selecting symbols with larger minimum Euclidean distance and smaller degree of polarization (DOP) in consecutive time slots. The DOP for \( i \)th transmitted 8D symbol is defined as \( p_i = \frac{\|S_{i1} + S_{i2}\|}{\|S_{i1}\| + \|S_{i2}\| + \|S_{i3}\|} \), where \( 0 \leq p_i \leq 1 \), \( t_1 \) and \( t_2 \) indicate time slot 1 and time slot 2. It is known that the worst symbols for nonlinearity tolerance are polarization identical (PI) symbols with zero DOP \( (p = 0) \), which has identical SOPs. Therefore, we first avoid all the strongest XPolM-inducing PI symbols contained in 4D-64PRS and then jointly consider SOP and minimum Euclidean distance to select 2048 polarization nonidentical symbols \( (p < 1) \) in 4D-64PRS constellation set. We obtained two Types 8D modulation formats with 11 bit/8D-sym. The one overhead bit to choose points from the set \( \mathcal{X} \) and can be obtained by the following methods:

- **Type 1**: \( b_{12} \) is a parity bit of single-parity-check code to protecting all information bits, which is an exclusive or (XOR) of all the bits \( b_3, b_5, \ldots, b_{11} \). In this case, the nearest neighboring symbol are removed to maximize minimum ED, which perform better at higher SNR. The parity bit \( b_{12} \) can be obtained as

\[
\bar{b}_{12} = b_1 \oplus b_2 \oplus b_4 \oplus b_5 \oplus b_6 \oplus b_7 \oplus b_8 \oplus b_9 \oplus b_10 \oplus b_{11},
\]

where \( \oplus \) and \( \ominus \) denote the modulo-2 addition and negation, respectively.

- **Type 2**: \( b_{12} \) is used to protect only the least significant bits, which are \( b_3, b_6 \) and \( b_{11} \). In this case, the modulation will be good for medium SNR. In addition, it has more polarization balanced points in two time slots. The parity bit \( b_{12} \) can be obtained as

\[
\bar{b}_{12} = b_3 \oplus b_6 \ominus b_9.
\]

Fig. 2 (a) and Fig. 2 (b) show relationship of SOPs for transmitted symbols in two consecutive time slots for two designed 8D modulation formats. The color coding scheme used Fig. 2 shows the SOP constraint we imposed on the formats. When a blue point is transmitted in the first time slot, only red points is used in the second time slot. No PI symbols with \( p = 0 \) are allowed in both of these two 8D modulation formats.

In order to get intuition of linear and nonlinear performance, we list the properties of five modulation formats in Table I.
TABLE I

<table>
<thead>
<tr>
<th>SE</th>
<th>$d_E^2$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-8QAM</td>
<td>6</td>
<td>0.84</td>
<td>1</td>
<td>0.70</td>
</tr>
<tr>
<td>4D-2A8PSK [12]</td>
<td>6</td>
<td>0.88</td>
<td>1</td>
<td>0.65</td>
</tr>
<tr>
<td>4D-64PRS [13]</td>
<td>6</td>
<td>0.66</td>
<td>1</td>
<td>0.65</td>
</tr>
<tr>
<td>8D-2048PRS-T1</td>
<td>5.5</td>
<td>1.15</td>
<td>0.96</td>
<td>0.64</td>
</tr>
<tr>
<td>8D-2048PRS-T2</td>
<td>5.5</td>
<td>0.76</td>
<td>0.87</td>
<td>0.55</td>
</tr>
</tbody>
</table>

for comparison. The squared minimum Euclidean distance is denoted as $d_E^2$. In addition to constant modulus, we propose two performance metrics for evaluating modulation-dependent nonlinear interference: the maximum DOP and the average DOP, which are calculated for all the possible $M$ transmitted symbols in two consecutive time for a given modulation format. The maximum DOP is defined as $\alpha = \max_{i \in \{1, 2, \ldots, M\}} p_i$ and the average DOP is denoted as $\beta = \frac{1}{M} \sum_{i=1}^{M} p_i$, where $i \in \{1, 2, \ldots, M\}$. A larger $d_E^2$ should result in better sensitivity, while smaller $\alpha$ and $\beta$ should in principle result in higher nonlinear noise tolerance. Based on these properties of these formats, two $8D$ modulation formats should be better than other modulation formats for both linear and nonlinear regime, which will be shown in Sec. III-A and Sec. III-B.

III. PERFORMANCE EVALUATION

Here we compare the performance of three different modulation formats: PM-8QAM, 5.5b4D-2A8PSK, and the two proposed 8D-2048PRS formats. The constellation 5.5b4D-2A8PSK is generated by using 5b4D-2A8PSK and 6b4D-2A8PSK from [18] in a time-domain hybrid way with a 1:1 ratio. We use effective SNR, $Q^2$-factor, and normalized GMI (NGMI) as performance metrics. NGMI represents the largest code rate of an ideal soft-decision FEC in a BICM system.

A. Linear Channel Performance

Fig. 3 shows the NGMIs for the linear AWGN channel. 8D-2048PRS-T1 and 8D-2048PRS-T2 are shown to clearly outperform both PM-8QAM and 5.5b4D-2A8PSK for all NGMIs above 0.6 bit. At a NGMI of 0.85 (the state-of-the-art SD-FEC with 25% overhead) 8D-2048PRS-T1 offers gains of 1.15 dB and 0.25 dB with respect to PM-8QAM and 5.5b4D-2A8PSK, resp. These gains increase up to 1.6 dB and 0.7 dB at high SNRs (at NGMI of 0.965 bit).

B. Nonlinear Channel Performance

We consider a dual-polarization multi-span WDM system with 11 co-propagating channels generated at a symbol rate of 45 Gbaud with a root-raised cosine pulse shape and a roll-off factor of 0.1. Each WDM channel carries 2$^{16}$ 8D symbols in two polarizations at the same launch power per channel $P_{ch}$. Each span consists of an 80 km standard single mode fiber (SSMF), and is followed by an erbitium-doped fiber amplifier with a noise figure of 5 dB. Polarization mode dispersion (PMD) of the fiber is not considered.

First we compare the effective SNR (after fiber propagation and receiver DSP) as a function of the transmission distance using $P_{ch} = 0$ dBm (optimum $P_{ch}$ for 100 spans). The results are shown in Fig. 4. The two proposed 8D formats 8D-2048PRS-T1 and 8D-2048PRS-T2 provide a higher effective SNR than PM-8QAM and 5.5b4D-2A8PSK. Especially, 8D-2048PRS-T2 has a higher SNR gains due to its smaller nonlinearity-tolerant property of $\alpha$ and $\beta$ in Table I.

From the results above, we can observe that the proposed 8D-2048PRS formats outperform other modulation formats in both linear and nonlinear channel. The total nonlinear shaping gain is linear SNR gain (in Fig. 3) plus effective SNR gain (in Fig. 4). Below we will show how this translates into an error rate improvement in terms of $Q^2$-factor in Fig. 5 and a reach increase in Fig. 6.

Fig. 5 shows the $Q^2$-factor versus $P_{ch}$ at 8000 km for nonlinear performance. The linear performance is also shown as baselines, which are assumed with ASE noise only. In the linear case, both 8D-2048PRS-T1 and 8D-2048PRS-T2 improve the sensitivity by approximately 1.1 dB. For nonlinear optical transmission over an 8000 km link, 8D-2048PRS-T1 and 8D-2048PRS-T2 outperform both PM-8QAM and 5.5b4D-2A8PSK.
5.5b4D-2A8PSK in terms of $Q^2$-factor due to its excellent linear and also nonlinearity-tolerant property. Moreover, the nonlinearity-tolerance advantage of the 8D-2048PRS-T1 over PM-8QAM yields even larger gains: up to 1.3 dB at the optimum launch power.

To conclude, we study NGMI as function of the transmission distance using the optimal launch power at each distance. Fig. 6 shows this, where we also show the recovered 8D-2048PRS-T2 constellation after 20 spans (in Stokes space). Both proposed constellations yield a 36 spans (28.6%) reach increase and 8.6% data rate loss relative to PM-8QAM at NGMI of 0.85, but it offers much higher distance-capacity product. Meanwhile, 7 spans (6.7%) reach increase is achieved with the same data rate relative to 5.5b4D-2A8PSK.

IV. CONCLUSIONS

We have designed two new nonlinearity-tolerant 8D modulation formats at spectral efficiencies of 5.5 bits/4D-sym. The 8D-2028PRS formats outperforms standard PM-8QAM by increasing the transmission reach of 28.6% but 8.3% lower spectral efficiency, while offering higher distance-capacity product. Compare with the same spectral efficiency 5.5b4D-2A8PSK family for 5-7 bits/symbol spectral efficiency, “Journal Lightwave Technology, vol. 33, no. 10, pp. 1993–2003, May 2015.

Fig. 5. $Q^2$-factor as a function of $P_{ch}$.

Fig. 6. NGMI versus transmission distance. Inset: Stoke space projection of the received symbols for 8D-2048PRS-T2 after 20 spans.

REFERENCES


