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Abstract *We propose 5 and 7 bit/symbol 4D modulation formats based on 2A8PSK, which outperform previously known modulation formats for each spectral efficiency. Combined with the recently reported 6 bit/symbol 2A8PSK, the 2A8PSK family covers 5–7 bits without significant hardware modifications.*

Introduction

In order to cover wide range of channel conditions, multiple modulation formats with different spectral efficiency are studied systematically[1–6]. Dual polarization (DP)-quadrature phase shift keying (QPSK), star-8 quadrature amplitude modulation (QAM), and 16 QAM are widely used for 4, 6, and 8 bit/symbol transmission. It has been recognized that DP-Star-8QAM is not the ideal format for 6 bit/symbol, and many formats have been investigated[7]. In particular, 4D-2A8PSK has been shown to outperform many other formats in linear and nonlinear performance, due to its large Euclidean distance, 4D constant modulus (constant power) characteristics, and Gray labeling[8,9].

For implementation in a digital signal processor (DSP), it is highly desirable that multiple modulation formats share the function blocks, such as an adaptive equalizer and a carrier phase estimator (CPE). Therefore, it is important that modulation formats have common features, including constellations.

In this paper, we propose new 5 bit/symbol and 7 bit/symbol modulation formats based on 2A8PSK and demonstrate their superior characteristics through nonlinear transmission simulations.

Modulation formats

During the selection and optimization of the formats, we used generalized mutual information (GMI) as a metric for bit-interleaved coded modulation (BICM) systems[10]. Here, we chose the normalized GMI of 0.85 as a target[7] for the state-of-the-art SD-FEC with a code rate around 0.8[11]. The constellation of the 2A8PSK family is shown in Fig. 1. It is essentially 8PSK, with two different radii, r_1 and r_2. For the combined x- and y-polarizations (i.e., 4D), there are 256 possible combinations. By superimposing a condition that two polarizations have complimentary radius, i.e.,

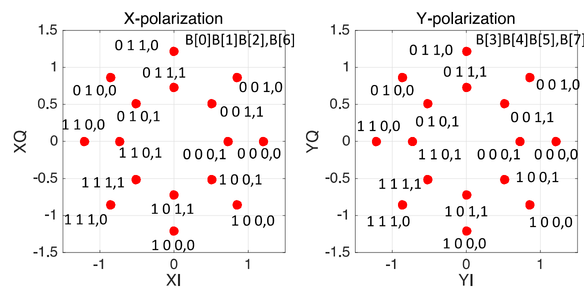

Fig. 1: Constellation and bit-to-symbol mapping of 2A8PSK.

if r_1 is chosen for one polarization, then r_2 should be used for the other polarization, we can achieve 4D constant modulus property, leading to excellent nonlinear transmission characteristics. Fig. 1 also includes the mapping rule of 4D-2A8PSK. Set-partitioning can be applicable. $B[0]-B[2]$ and $B[3]-B[5]$ represent the Gray-mapped 8PSK for X- and Y-polarizations, respectively.

In the case of 6b4D-2A8PSK (SP64-2A8PSK), bit $B[6]$ is a parity of single-parity-check code which is an exclusive OR (XOR) of all the modulation bits $B[0]$-$B[5]$, expressed as

$$B[6] = B[0] \oplus B[1] \oplus B[2] \oplus B[3] \oplus B[4] \oplus B[5],$$

and the other parity bit $B[7]$ is expressed as

$$B[7] = \overline{B[6]}.$$

The amplitudes of X and Y polarizations are modulated by $B[6]$ and $B[7]$, respectively. The power of each 4D symbol is constant due to the complementary ASK in the two polarizations.

In the case of 7b4D-2A8PSK (SP128-2A8PSK), $B[0]-B[6]$ are the modulation bits, and the parity bit $B[7]$ is

$$B[7] = \overline{B[6]}.$$

5b4D-2A8PSK (SP32-2A8PSK) is constructed as a nonlinear code, where original bits are $b[0]$, $b[1]$,

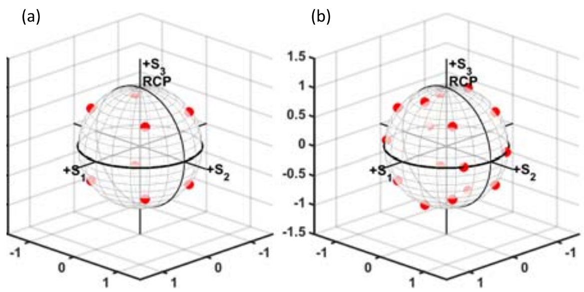

Fig. 2: Stokes space representation of a) 5b4D-2A8PSK and (b) 7b4D-2A8PSK

$b[2]$, $b[3]$, $b[4]$. The final bits $B[0]$-$B[7]$ can be written as,

$$
\begin{aligned}
B[0] &= b[0],\\
B[1] &= b[1],\\
B[2] &= b[2],\\
B[3] &= \overline{b[1] \oplus b[4]} \oplus ((b[0] \oplus b[1]) \ \& \ \overline{b[3] \oplus b[4]}),\\
B[4] &= (b[0] \oplus b[3]) \oplus ((b[0] \oplus b[1]) \ \& \ \overline{b[3] \oplus b[4]}),\\
B[5] &= b[2] \oplus b[3] \oplus b[4],\\
B[6] &= b[3] \oplus b[4],\\
B[7] &= \overline{b[3] \oplus b[4]}.
\end{aligned}
$$

The stokes representations for 5b4D-2A8PSK and 7b4D-2A8PSK are plotted in Fig 2 (a) and (b), respectively.

In all the formats (5b4D, 6b4D, and 7b4D-2A8PSK), Gray labeling is possible, which is another advantage of the 2A8PSK family.

Nonlinear transmission characteristics

We simulated transmission performance over a 2,000 km non-zero dispersion shifted fiber (NZDSF) link at a rate of 34 GBaud per channel to investigate the effect of high fiber nonlinearity. Simulation procedures are similar to that reported in previous works[9]. At the transmitter, pulses were filtered by a root-raised-cosine (RRC) filter with a roll-off factor of 0.1. Five WDM channels with the same modulation were simulated with 37.5 GHz spacing and no optical filtering. The link comprises 25 spans of 80 km NZDSF with loss compensated by Erbium-doped fiber amplifiers (EDFAs). In order to quantify performance over a single link for multiple modulation formats, the span loss budget achieving the target GMI was used as a performance metric[12]. NZDSF parameters were, $\gamma = 1.6$ /W/km; $D = 3.9$ ps/n-m/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 com-

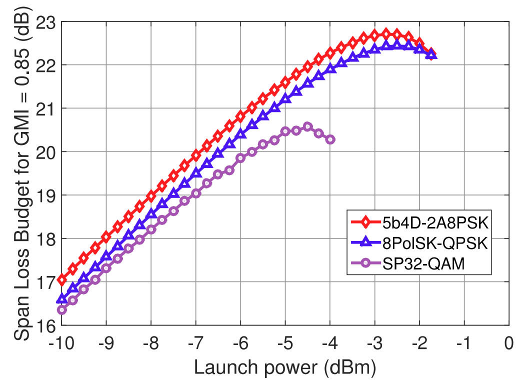

Fig. 3: Span loss budget of three 5 bit/symbol modulation formats as a function of launch power.

pensated as a lumped linear dispersion compensator. 50% of the residual dispersion was pre-compensation at the transmitter side. An ideal homodyne coherent receiver was used, with an RRC filter with 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. All the optical noise due to the EDFA (5.0 dB noise figure) 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 was used to calculate the span loss budget.

Three 5 bit/symbol formats were compared as shown in Fig. 3. In this case, $r_2/r_1 = 0.6$ is optimized for 5b4D-2A8PSK for maximizing the span loss budget. The span loss budget for SP32-QAM saturates quickly due to large power variations, since it is based on 8QAM (set partition of 16QAM). On the other hand, 8PolSK-QPSK[13] has 0.4 dB worse OSNR for the linear case, the saturation characteristics is very similar to 5b4D-2A8PSK, due to its 4D constant modulus property. Overall, 5b4D-2A8PSK has the increased maximum span loss budget by 0.3 dB over 8PolSK-QPSK, and by 2 dB over SP32-QAM.

Three 7 bit/symbol formats and DP-16QAM of the same data rate ((7/8)*34 GBd) were compared as shown in Fig. 4. Here, $r_2/r_1 = 0.59$ is chosen for 7b4D-2A8PSK to maximize the span loss budget. DP-16QAM suffer from fiber nonlinearity, since it has strong power variations. SP128-QAM suffers also from fiber nonlinearity, since it is based on 16QAM. Time-domain hybrid format here uses 50%:50% mixture of 6b4D-2A8PSK and DP-16QAM. In other to minimize the nonlinear effect, the power for 6b4D-2A8PSK was optimized to be higher than that for DP-16QAM by

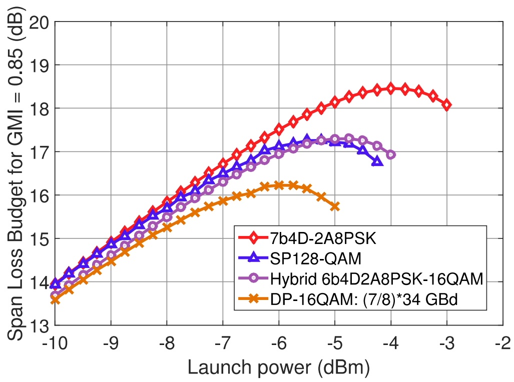

Fig. 4: Span loss budget of three 7 bit/symbol modulation formats and DP-16QAM with the same data rate as a function of launch power.

0.9 dB, which is not an ideal power allocation in the linear region. Overall, 7b4D-2A8PSK outperforms other formats by at least 1.1 dB.

Rate-adaptive modulation

Time-domain hybrid modulation QAM has been proposed to achieve rate-adaptive modulation[3]. There are two issues associated with it. One is that two dissimilar formats have different instantaneous powers and can lead to enhanced nonlinearity issues. Another is that digital signal processing, in particular the adaptive equalizer and CPE have to be able to accommodate multiple formats in time domain. On the other hand, our proposed modulation formats, covering 5, 6, 7 bits/symbols, share the same basic constellation of 2A8PSK. Therefore, if they are used for the components of time-domain hybrid for spectral efficiencies such as 3.25 or 5.5 bit/symbol, the same signal processing building blocks can be used over a wide spectral efficiency range.

Conclusions

We have proposed 5 and 7 bit/symbol modulation formats based on 4D-2A8PSK constellation. They fill the gap between DP-QPSK and DP-8QAM, and DP-8QAM and DP-16QAM, respectively. Their nonlinear transmission performances exceed all known formats at each spectral efficiency. Especially the proposed scheme outperforms DP-16QAM of the same data rate. They are also very suitable for 5-7 bits/symbol rate-adaptive modulation formats.

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