Nonlinearity-tolerant time domain hybrid modulation for 4-8 bits/symbol based on 2A8PSK

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Abstract

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Abstract: We propose time domain hybrid modulation to cover 4-8 bits/symbol range, based on 5, 6, and 7 bits/symbol 4D-2A8PSK. Simulation results indicate that they have up to 1.6 dB higher span loss budget than the hybrid modulation based on conventional modulation formats in nonlinear channels.

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1. Introduction

In order to cover wide range of channel conditions, multiple modulation formats with different spectral efficiency are studied systematically [1–5]. In particular, time-domain hybrid (TDH) modulation has been studied considerably, due to its flexibility in choosing the nearly arbitrary spectral efficiency [6–8]. One of the difficulty of TDH modulation comes from fiber nonlinearity. Within the range of 4 - 8 bits per 4D symbol, except for Dual polarization (DP)-quadrature phase shift keying (QPSK) (4 bits/symbol), most of the conventional formats, including 32 set partitioned (SP)-quadrature amplitude modulation (QAM) (5 bys/symbol), DP-Star-8QAM (6 bits/symbol), 128SP-QAM (7 bits/symbol), and DP-16QAM (8 bits/symbol) suffer from strong fiber nonlinearity.

Recently, we proposed a family of four-dimentional (4D) two-amplitude eight phase shift keying (2A8PSK) for 5, 6, 7 bits/symbol. They have excellent linear characteristics, as well as nonlinear characteristics due to their constant modulus property. [9, 10].

In this paper, we propose TDH modulation in the region of 4 - 8 bits/symbol using this new 2A8PSK family, and compare it to TDH modulation using more conventional formats (32SP-QAM, DP-S8QAM, 128SP-QAM) for their nonlinear transmission performance.

2. Modulation Format

For the selection and optimization of the formats, we use generalized mutual information (GMI) as a metric for bit-interleaved coded modulation (BICM) systems [11]. We chose the normalized GMI of 0.85 [12] as a typical operation condition for the state-of-the-art SD-FEC [13].

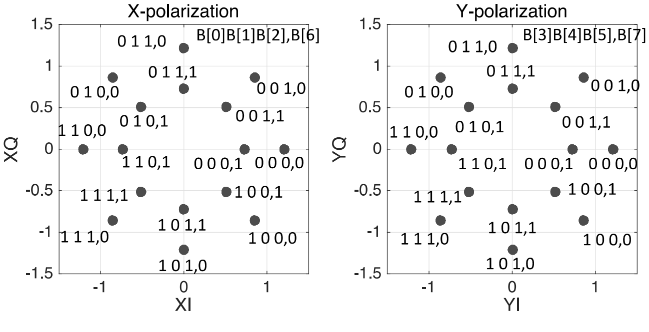

Fig. 1: Constellation and bit-to-symbol mapping of 2A8PSK [10].

We use 3 coded modulation formats based on 2A8PSK for 5, 6, and 7 bits/symbol. The generic constellation of the 2A8PSK family is shown in Fig. 1. It is essentially 8PSK, with two different radii, r_1 and r_2. We call r_1/r_2 as a ring ratio. 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., if r_1 is chosen for one polarization, then r_2 should be used for the other, we can achieve 4D constant modulus property, leading to excellent nonlinear transmission characteristics.

Fig. 1 also includes the mapping rule of 4D-2A8PSK. $B[0]-B[2]$ and $B[3]-B[5]$ represent the Gray-mapped 8PSK for X- and Y-polarizations, respectively. $B[6]$ and $B[7]$ determine whether the inner or the outer ring is chosen.

5b4D-2A8PSK is constructed as a linear code, where information bits are $B[0]$-$B[4]$, and the parity bits $B[5]$-$B[7]$ can be written as, $B[5]=B[0]\oplus B[1]\oplus B[2]$, $B[6]=B[2]\oplus B[3]\oplus B[4]$, and $B[7]=\overline{B[6]}$. This showns 0.25 dB improvement compared to that of [10], which was constructed as a nonlinear code.

For 6b4D-2A8PSK, the two parity bits are, $B[6]=B[0]\oplus B[1]\oplus B[2]\oplus B[3]\oplus B[4]\oplus B[5]$, and $B[7]=\overline{B[6]}$ [10]. For 7b4D-2A8PSK, $B[0]-B[6]$ are the information bits, and the parity bit can be expressed as $B[7]=\overline{B[6]}$ [10].

We use DP-QPSK (4 bits/symbol) and QP-16QAM (8 bits/symbol) in conjunction with 5b4D, 6b4D, and 7b4D-2A8PSK to widen the range of TDH. For a comparison, we also use TDH modulation using conventional modulation formats, i.e., DP-QPSK, 32SP-QAM, DP-S8QAM, 128SP-QAM, and DP-16QAM. We use bit-to-symbol mapping for 32SP-QAM and 128SP-QAM as described in [2] and that for DP-S8QAM as described in [12].

3. 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 the previous work [10]. At the transmitter, pulses were filtered by a root-raised-cosine (RRC) filter with a roll-off factor of 10%. Eleven WDM channels using the same modulation format were simulated with 37.5 GHz spacing and no optical filtering. The link comprised 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 [14]. 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. Dispersion precompensation was applied at the transmitter side using 50% of the residual dispersion of the full link. An ideal homodyne coherent receiver was used, with 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, where EDFA noise figure of 5 dB is assumed.

For 5b4D, 6b4D, and 7b4D-2A8PSK formats, we choose the ring ratio of 0.60, 0.65, and 0.59 for the best nonlinear performance. For all the THD modulation, we use 1:1 ratio with alternating formats, however, in actual systems, any arbitrary ratio can be used. The important parameter for TDH is the power ratio, i.e., how much power will be allocated for each time slot. We optimize the power ratio for the best nonlinear performance.

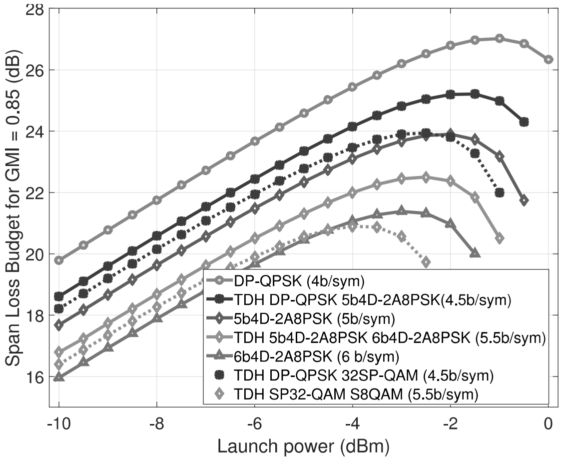

Fig. 2: Span loss budget for various modulation formats in the range of 4 - 6 bits/symbol.

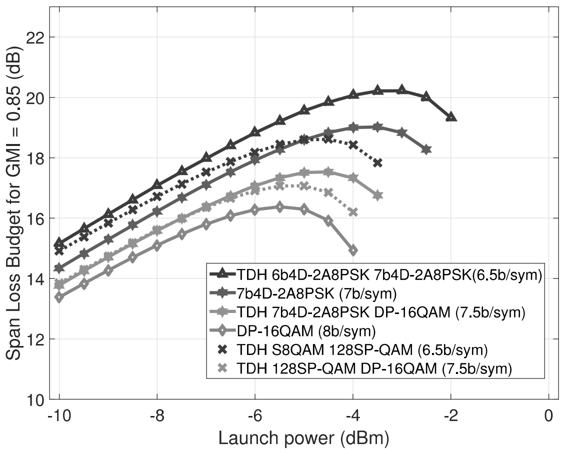

Fig. 3: Span loss budget for various modulation formats in the range of 6.5 - 8 bits/symbol.

Fig. 2 shows the calculated span loss budget for 4-6 bits/symbol modulation formats, including the 2A8PSK-based and the conventional TDH modulation. DP-QPSK and 6b4D-2A8PSK data are also included as a reference. Fig. 3 shows the span loss budget for 6.5-8 bits/symbol modulation formats. From these figures, we can see that the TDH modulation based on 2A8PSK has much better nonlinear performance than that based on the conventional modulation formats, due to their constant modulus property.

The peak span loss budget for various spectral efficiency is shown in Fig. 4. Here, 4.5, 5.5, 6.5, 7.5 bits/symbol TDH based on 2A8PSK used DP-QPSK, 5b4D-2A8PSK, 6b4D-2A8PSK, 7b4D-2A8PSK, and DP-16QAM. TDH based on

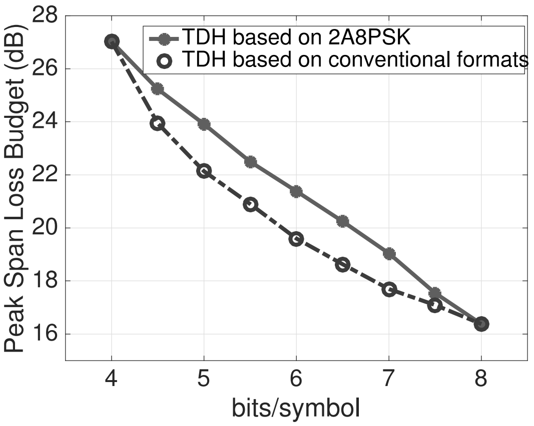

Fig. 4: Span loss budget for TDH modulation based on the 4D-2A8PSK formats, and that on the conventional modulation formats.

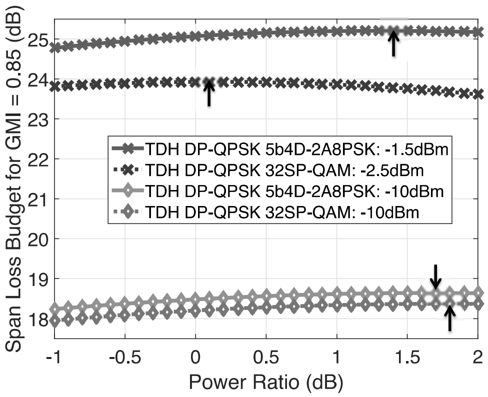

Fig. 5: Span loss budget for the 2A8PSK-based and the conventional TDH at 4.5 bits/symbol, as a function of power ratio, at the nonlinear and linear regions. The arrows indicate the optimum power ratio

the conventional formats used DP-QPSK, 32SP-QAM, S8QAM, 128SP-QAM, and DP-16QAM. We observed 1.3, 1.6, 1.6, and 0.6 dB increase in peak span loss budget, when TDH used 2A8PSK, at 4.5, 5.5, 6.5, and 7.5 bits/symbol, respectivelty. This shows the versatility of the 4D-2A8PSK family.

Fig. 5 shows the span loss budget as a function of the power ratio for the THD of the 2A8PSK family and of the conventional formats at 4.5 bits/symbol. In the linear region (-10 dBm launch power), both of them have similar optimum power ration of 1.7-1.8 dB, indicating we need to allocate more power for the low sensitivity formats. However, near the peak span loss budget region (-1.5 or -2.5 dBm), TDH of the conventional formats requires very different power ratio of 0.1 dB. This means, because 32SP-QAM causes more nonlinear penalty than DP-QPSK, more power cannot be allocated. This is in contrast to the case of TDH using DP-QPSK and 5b4D-2A8PSK, where both are constant modulus and do not suffer such serious penalty, and the optimum power ratio is 1.4 dB.

4. Conclusion

We investigated TDH modulation based on the recently proposed constant-modulus 5b4D, 6b4D, and 7b4D-2A8PSK. Based on the numerical simulations for the 2,000 km dispersion managed NZDSF link, we observed up to 1.6 dB advantage in the peak span loss budget, compared to the TDH based on the conventional modulation formats such as 32SP-QAM, DP-S8QAM, and 128SP-QAM.

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