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Abstract: We investigate the use of 4D constant modulus modulation format and probabilistic-shaped 16QAM combined with subcarrier modulation. 4D constant modulus format has larger advantage with lower baud rate down compared to the conventional format and PS-16QAM.

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1. Introduction

Fiber nonlinearity is usually the limiting factor in determining the transmission distance of long distance optical communications. One of the ways to mitigate fiber nonlinearity is to use multi-subcarrier (MSC) modulation. It has been theoretically and experimentally demonstrated that MSC modulation comprising of 2-4 GBd subcarriers is the best in terms of nonlinearity tolerance [1–3]. This is due to the fact that coherence among subcarriers decreases with narrower subcarriers. MSC has also been considered for flexible-rate transmission [3, 4]. So far, however, the study has been limited to classical quadrature amplitude modulation (QAM) as the constituent modulation formats.

At the same time, four-dimensional (4D) constant modulus modulation formats have also been shown to have nonlinenearity tolerance compared to conventional modulation formats in the conventional 31-34 GBd wavelength domain multiplexed (WDM) channels [5, 6]. Their benefit is higher in dispersion managed case, but it is also visible in dispersion uncompensated cases. They are also available in 5, 6, and 7 bits / 4D symbol spectral efficiencies. So the next question is how the 4D constant modulus modulation formats perform in the context of subcarrier modulation. Recently, probabilistic-shaping (PS) has been studied extensively [3, 7, 8]. However, it has not been studied in the context of subcarrier modulation down to 1 GBd.

In this paper, through nonlinear transmission simulations using a dispersion unmanaged link, we show that 4D constant modulus modulation formats retain the nonlinearity-tolerance, and indeed increase with narrower subcarriers.

2. Modulation format and simulation procedure

For the evaluation of the modulation formats, we use generalized mutual information (GMI) as a metric for bit-interleaved coded modulation (BICM) systems [9]. We chose the normalized GMI of 0.86 and 0.92.

The MCS configuration is shown in Fig. 1. Each subcarrier is modulated with 64, 32, 16, ..., 1 GBd with root raised cosine (RRC) filter with a roll-off parameter of 0.01. Subcarrier channel spacing is 1.01 times the baud rate. The total number of subcarriers are chosen such that the total bandwidth is identical. We used all the subcarriers in the shaded area in Fig. 1 to calculate the GMI of the signal.

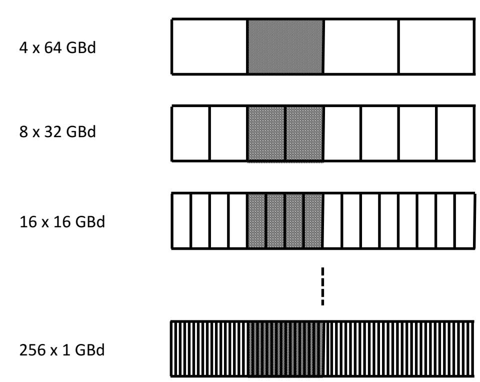

Fig. 1: Schematic of the multi-subcarrier modulation configuration. GMI is averaged over the shaded area.

We use a coded modulation formats based on 2A8PSK for 6 and 7 bits / 4D symbol, called 6b4D-2A8PSK and 7b4D-2A8PSK, respectively [6]. We used a ring ratio of 0.65 for 6b4D- and 0.59 for 7b-4D-2A8PSK, which are optimum for general nonlinear transmission conditions. The 4D signal is mapped to X- and Y-polarization in one time slot as a default, however, later in this paper, we evaluate the case of 4D signal mapped onto two time slots. We also used DP-Star-8QAM [10] as a comparison for 6b4D-2A8PSK, which has 3 bits / 2D symbol (i.e., 6 bits / 4D symbol). At a normalized GMI of 0.86 (total GMI = 3.44 b/s/Hz/4D), 6b4D-2A8PSK has 0.23 dB smaller required signal to noise ratio (SNR) than DP-Star-8QAM. 7b4D-2A8PSK and DP-PS-16QAM (Boltzman distribution) are compared at the same total GMI = 4 b/s/Hz per 4D symbol. This corresponds to the normailized GMI = 0.5714 and 0.5 for 7b4D-2A8PSK and DP-PS-16QAM, respectively. This rate was chosen such that PS-16QAM had large shaping gain. In this condition, PS-16QAM has the entropy of 3.4 per polarization and has 0.43 dB better senstivity than 7b4D-2A8PSK.

Simulation procedures are similar to that reported in the previous work [6]. For the transmitter, all the subcarriers were combined, and no optical filter was used. The link comprised 50 spans of 80 km standard single mode fiber (SSMF) without inline dispersion compensation. SSMF parameters are, $\gamma = 1.2$ /W/km; $D = 17$ ps/nm/km; $\alpha = 0.2$ dB/km. No dispersion pre-compensation was used. In order to quantify performance over the link for multiple modulation formats, the span loss budget achieving the target GMI was used as a performance metric [11]. Other fiber effects such as dispersion slope and polarization mode dispersion were not simulated. An ideal homodyne coherent receiver was used, with an RRC filter with a roll-off factor of 0.01, followed by sampling at twice the symbol rate. Following this, ideal chromatic dispersion equalization and data-aided least-mean-square equalization were employed. No laser linewidth was considered. 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. Nonlinearity compensation has not been applied.

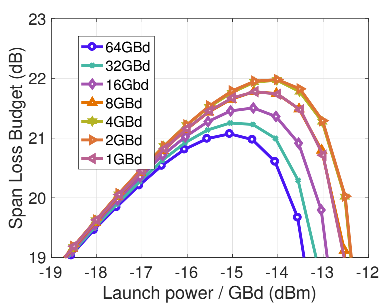

Fig. 2: Span loss budget for 6b4D-2A8PSK format as a function of launch power per GBd with a target normalized GMI = 0.86.

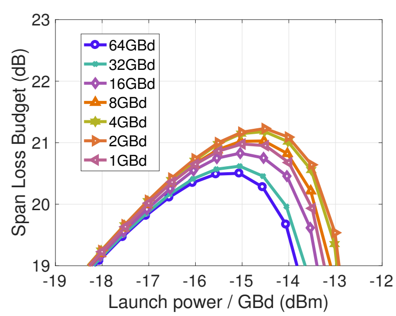

Fig. 3: Span loss budget for DP-Star-8QAM format as a function of launch power per GBd with a target normalized GMI = 0.86.

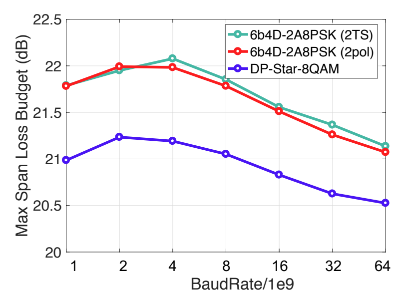

Fig. 4: Maximum span loss budget of the three modulation format as a function of baud rate, with a target normalized GMI = 0.86.

Fig. 2 shows the calculated span loss budget for 6b4D-2A8PSK as a function of the launch power per GBd (i.e., normalized by the bandwidth) with a target GMI of 0.86. The lowest peak span loss budget is when the subcarrier is modulated at 64 GBd. and it gradually increases as the baud rate decreases and the peak is when the baud rate is 2-4 GBd.

Fig. 3 shows the span loss budget for DP-Star-8QAM also with a target GMI of 0.86. By comparing Fig. 2 and Fig. 3 , we can conclude that the 4D constant modulus format is even more beneficial when the subcarrier baud rate if 2-4 GBd.

We also plotted the peak span loss budget of each modulation format as a function of the subcarrier baud rate as shown in 4 for the target normalized GMI of. If we compare the conventional 6b4D-2A8PSK (2 pol) over two polarizations and DP-Star-8QAM, the difference is 0.55 dB at 64 GBd, and it increases to 0.8 dB at 4 GBd. In another example, 4D symbol is mapped to two time slots, and there is no correlation between X- and Y-polariozations and is labeled as 6b4D-2A8PSK (2 TS). This format is on average 0.08 dB better than the 6b4D-2A8PSK (2 pol) between 4 and 64 GBd, while the difference is negligible at 1 and 2 GBd. When we evaluate at the target GMI of 0.92, the benefit of the 6b4D-2A8PSK (2 pol) over DP-Star-8PSK is even higher.

Next, we compared 7b4D-2A8PSK and DP-PS-16QAM. Fig.5 and 6 show the span loss budget for a target GMI = 4 b/s/Hz (4D). Even though PS-16QAM has 0.4 dB higher span loss budget in the linear region due to the shaping gain, it does not translate into higher peak span loss budget. The peak span loss budget for the two modulation formats

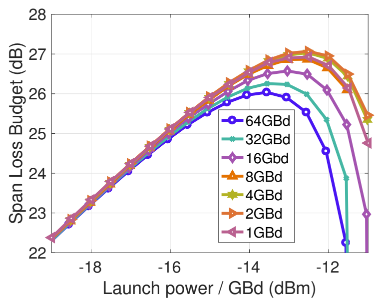

Fig. 5: Span loss budget for 7b4D-2A8PSK format as a function of launch power per GBd with a target GMI = 4 b/s/Hz (4D).

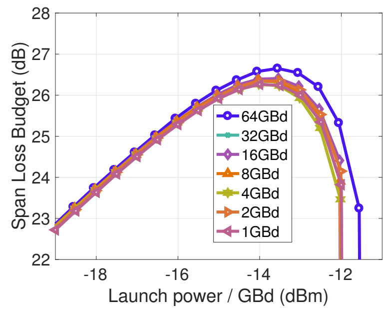

Fig. 6: Span loss budget for PS-16QAM format as a function of launch power per GBd with a target GMI = 4 b/s/Hz (4D).

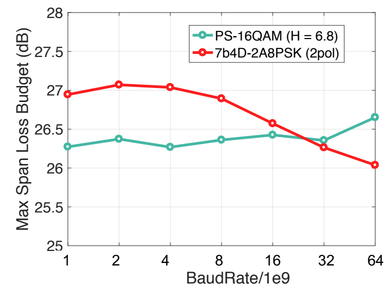

Fig. 7: Maximum span loss budget of the two formats as a function of baud rate, with a target GMI = 4 b/s/Hz (4D).

is shown in Fig.7. The 7b4D-2A8PSK shows improved maximum span loss budget with lower-rate subcarriers, while the PS-16QAM does not.

3. Conclusion

We investigated the use of 4D constant modulus formats as the constituent of the multi-subcarrier modulation through simulation over a dispersion uncompensated link. The benefit of the 4D constant modulus format is evident in the case of MSC, and it becomes even higher when the baud rate of the subcarrier becomes is 2-4 GBd. We also showed two types of 4D mapping, and 4D constant modulus over two time slots showed generally better results. Its benefit is clear in the context of subcarrier modulation, compared to probabiistic shaping.

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