Jointly Shaped Dual Polarization Systems

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Abstract: We present a probabilistic shaping algorithm whereby both polarization streams of a dual-polarized system are shaped together. The proposed method offers 0.2-0.92 dB gains over existing shaping schemes for the same block-length. © 2021 The Author(s)

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1. Introduction

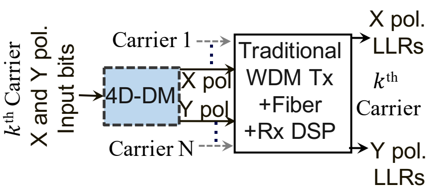
Probabilistic shaping (PS) is a well-known technique to offer a shaping gain up to 1.53 dB over uniformly distributed symbols transmission and enable rate adaptivity with a fixed forward error correction (FEC) code rate [1, 2]. Recently, PS has attracted a considerable attention to improve the spectral efficiency (SE) of the next generation optical fiber networks. One particular PS architecture, known as probabilistic amplitude shaping (PAS) [3], has grown popularity for efficiently realizing a FEC coded PS system. PAS requires a symbol-level distribution matching (SL-DM) algorithm implemented via arithmetic coding (AC), which operates on the in-phase and quadrature components of a square quadrature amplitude modulation (QAM) constellation to produce the shaped amplitudes. Despite the superior performance of SL-CCDM for large block-lengths, the traditional PAS design suffers from the following two major drawbacks: (a) SL-CCDM with large block-lengths entails significant complexity and latency due to the highly sequential AC operations, and (b) SL-CCDM incurs substantial rate loss as the block-length reduces, and thereby, its performance is limited for shorter block-lengths. To reduce the impact of rate loss, several alternative PS architectures have been proposed in the literature. For example, product distribution matching (PDM) [4,5] replaces the SL-CCDM operation with multiple binary DMs operating in parallel. For short block-lengths, PDM exhibits a lower rate loss by transmitting symbols that are not restricted to be a constant composition sequence [5]. Two-dimensional DM (2D-DM) [6] is another strategy whereby the complex QAM symbols are directly shaped to provide further performance improvements over PDM.

In this paper, we present a PS method implemented by four-dimensional DM (4D-DM) to jointly shape both polarization (pol.) streams of a dual polarized (DP) transmission. Notably, DP systems have become a de-facto standard for coherent optical fiber transmission due to its ability to double the data rate. By jointly optimizing the bit-probabilities of the component binary DMs and the bit-mapping over the two pols., 4D-DM introduces additional degrees of freedom into the DM design. Our numerical results show that the proposed 4D-DM outperforms the existing shaping methods by 0.2-0.92 dB when a DP Nyquist wavelength division multiplexing (WDM) system enabling 800 Gbps data rate per carrier is transmitted over a 300 km standard single mode fiber (SSMF).

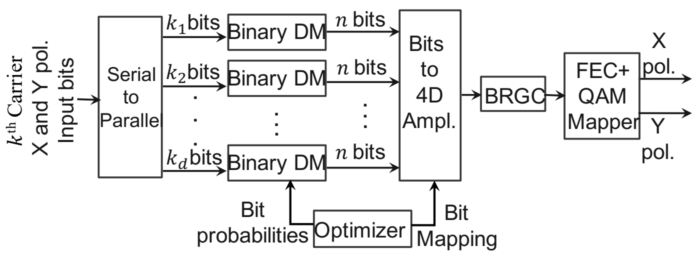
2. 4D-DM: Signal Shaping across Polarization

Schematics of the proposed DP 4D-DM WDM transmission system are illustrated in Fig. 1a. Uniformly distributed input bits from the X and Y pol. of each carrier are jointly processed by the 4D-DM to generate the shaped QAM symbols for the DP data streams. Thereafter, the transmission data-path involves traditional transmitter processing of a typical Nyquist WDM system, followed by fiber propagation and coherent detection of each carrier at the receiver to produce log-likelihood ratios (LLR) for both pol. branches.

A detailed block diagram of the 4D-DM algorithm is shown in 1b. After serial to parallel conversion, the uniformly distributed input bits from both pol. branches are fed as inputs to multiple binary DMs



(a) Generic system model for a 4D-DM DP Nyquist WDM transmission with N carriers. The shaded block performs joint processing of the input bits from both pol. streams of the k^{th} carrier, $k = 1,2,\ldots,N$.



(b) 4D-DM block diagram.

Fig. 1. System model.

operating in parallel. The length of the input bit sequences, denoted by $k_1, k_2, k_3, \ldots$, depends on the binary bit probabilities $\boldsymbol{p} = [p_1, p_2, p_3 \ldots]$ of the respective DMs. The outputs of the binary DMs are bit sequences of a fixed length n, which represents the shaping block-length. Thereafter, the n-length output bits from all binary DMs are mapped to 4D amplitudes, which are vectors in the first orthant of the 4D DP signal space, using a mapping μ. The "Optimizer" shown in Fig. 1b computes the optimal $\boldsymbol{p}$ and μ, using an algorithm as described next. Finally, individual amplitudes of the 4D vectors are converted back to bits using a binary reflected Gray code (BRGC) mapping, followed by FEC coding and QAM mapping, similar to a conventional PAS architecture [3].

We note that reducing the root-mean square (RMS) power of the transmitted constellation is a key to improve the performance of a PS scheme to achieve a desired target SE [4, 6]. The RMS power of the DP constellation in the proposed 4D-DM is determined by the binary probabilities $\boldsymbol{p}$ and the bits-to-amplitude mapping μ. However, traditional mapping, such as the natural binary code (NBC) employed in [4], is not the optimal choice when multidimensional shaping is considered [6]. Therefore, we aim to accomplish the RMS power reduction through jointly optimizing $\boldsymbol{p}$ and μ by solving the following optimization problem:

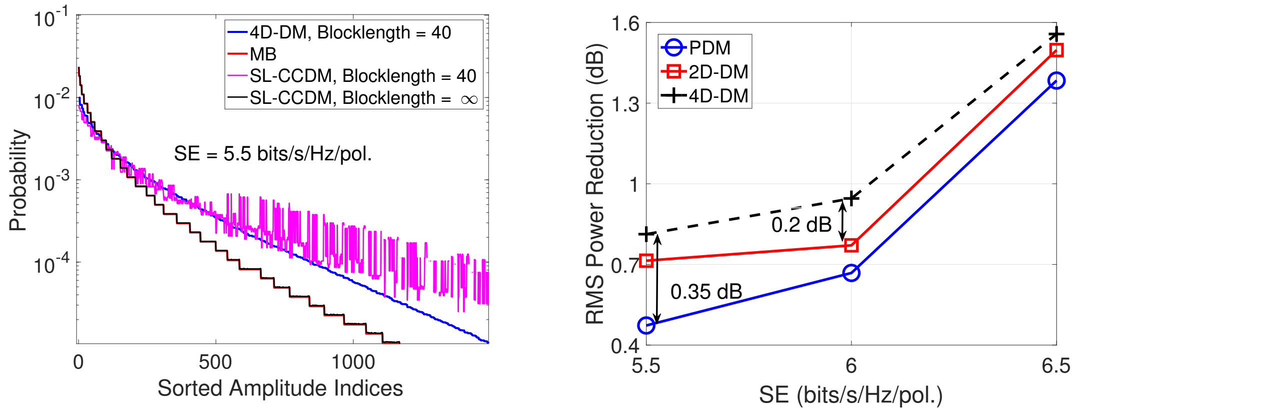
$$\begin{aligned} \boldsymbol{p} &= \arg \min_{p_1, p_2, p_3, \ldots} \mathbb{E}\left[\|\boldsymbol{X}\|^2 \right] \\ \text{subject to: (a)} & \sum_j \frac{k_j}{n} = \text{constant for a target SE}\,, \\ \text{(b)}\ & 0 \le p_i \le 1\,, \forall i\,, \end{aligned} \tag{1}$$

where $\boldsymbol{X}$ represents the 4D amplitudes of the DP signal, $k_j = \left\lfloor \log_2 \binom{n}{\mathrm{round}(np_j)} \right\rfloor$, the notations $\lfloor \cdot \rfloor$, $\mathrm{round}(\cdot)$, $\mathbb{E}(\cdot)$, and $\binom{\cdot}{\cdot}$ denote the flooring, rounding and expectation operators, and the binomial coefficient, respectively. The above optimization problem can be solved offline, without any requirement for additional computational complexity. For a target SE, $\boldsymbol{p}$ and μ can be pre-computed and stored as entries of a look-up table (LUT). Instead of using identical DM parameters for each pol. branch, 4D-DM provides additional flexibility to configure the binary DMs jointly for both pol., and thereby, offers reduced rate loss compared to individually shaped DP transmission, as numerically validated in the next section.

3. Numerical Results

To present our numerical results, we simulate a DP 4D-DM 256-QAM Nyquist WDM sytem with 3 carriers over 4 spans of 75 km SSMF. We choose a normalized generalized mutual information (NGMI) threshold of 0.8, which corresponds to a 800 Gbps data rate per carrier. We consider 80 Gbaud symbol rate per carrier with a root raised cosine (RRC) roll-off of 0.1, such that each carrier is packed within a 88 GHz bandwidth. We choose a fixed DM output block-length of 40 for our results to keep the complexity and latency of the DM implementation low [6]. The remaining fiber and transmission parameters are listed in Table 1.

We begin our analysis by investigating the probabilities of the 4D DP amplitudes, as shown in Fig. 2a, that are effectively being generated by different shaping methods, for the example of a target SE value of 5.5 bits/s/Hz/pol. Maxwell Boltzmann (MB) distribution, known to yield optimal performance under an additive white Gaussian noise channel, is also included in the figure as a theoretical reference. When the SL-CCDM is operating on a very large block-length (labeled "SL-CCDM, Blocklength = ∞"), the probabilities of the 4D amplitudes match with those of the optimal MB distribution, at the expense of a higher serialism requirement to implement the DM algorithm [4]. However, when the block-length is 40, due

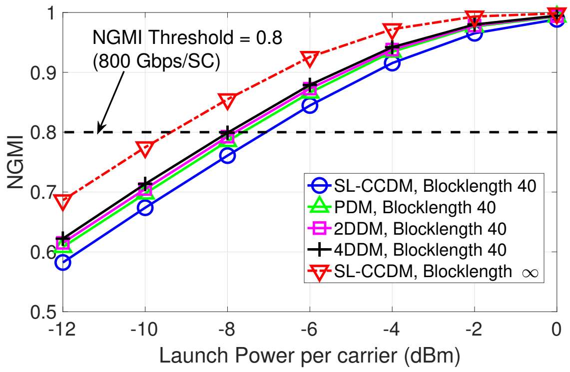


(a) 4D amplitude probabilities. (b) RMS power reduction compared to SL-CCDM.

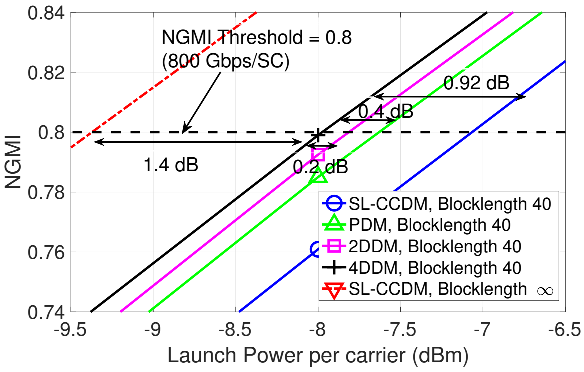
Fig. 2. Amplitude probabilities and RMS power reduction, illustrating the benefits of 4D-DM.

Parameters	Values
SSMF spans	4×75 km
CD	17 ps/nm/km
Nonlinearity parameter	1.4 $W^{-1}km^{-1}$
NGMI Threshold	0.8
Raw SE (bits/s/Hz/pol.)	6
Baud rate/carrier (Gbaud)	80
Channel Spacing (GHz)	88
Data rate/carrier (Gbps)	800

Table 1. Simulation parameters.



(a) NGMI vs. Lauch Power.



(b) Zoomed-in version of Fig. 3a.

Fig. 3. NGMI vs. launch power for a DP 3×256-QAM Nyquist WDM system.

to the quantization operations associated with a finite block-length, the DP amplitude probabilities with the SL-CCDM significantly deviate from the MB distribution, and exhibits non-monotonicity. Such non-decreasing probabilities increases the RMS power of the transmitted constellation, as we shall analyze next. On the other hand, the proposed 4D-DM with the same block-length (labeled "4D-DM, Blocklength = 40") removes the non-monotonic behavior and brings the probabilities relatively closer to an MB distribution. In Fig. 2b, we show the reduction of the RMS power of the QAM constellation for different shaping algorithms compared to the SL-CCDM for a block-length of 40. We observe that 4D-DM is superior to SL-CCDM, PDM, and 2D-DM for all SE values of 5.5, 6, and 6.5 bits/s/Hz/pol. For example, 4D-DM yields an RMS power reduction of approximately 1 dB and 0.2 dB compared to SL-CCDM and 2D-DM when SE = 6 bits/s/Hz/pol.

In Fig. 3a, we show the NGMI achieved by different shaping methods for an SE of 6 bits/s/Hz/pol., as a function of the launch power. We also include a plot for the SL-CCDM using a block-length of 16000 (labeled "SL-CCDM, Blocklength ∞"), as a reference. To highlight the difference between the shaping methods with more clarity, we zoomed into Fig. 3a around an NGMI value of 0.8, and show the magnified plots in Fig. 3b. We observe that the gains of 4D-DM predicted from Fig. 2b are reflected in the NGMI plots. For example, 4D-DM with a block-length of 40 outperforms SL-CCDM, PDM and 2D-DM by 0.92 dB, 0.4 dB and 0.2 dB, respectively, for the same block-length. However, SL-CCDM with a 16000 block-length is shown to yield a 1.4 dB gain over the proposed 4D-DM with a block-length of 40, at the price of significantly higher complexity and latency due to highly sequential DM operations required for a longer block-length.

4. Conclusion

We presented 4D-DM as a novel PS strategy to jointly shape both polarization streams of a DP system. By processing the input bits from the X and Y pol. together, 4D-DM is able to significantly reduce the rate loss associated with short block-lengths. Our numerical results showed that the proposed PS method outperformed SL-CCDM, PDM, and 2D-DM having the same block-length by 0.92 dB, 0.4 dB and 0.2 dB, respectively, to enable a DP Nyquist WDM transmission over a 300 km SSMF achieving 800 Gbps data rate per carrier.

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