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201 Broadway, Cambridge, Massachusetts 02139

Design of Constant Modulus Modulation Considering Envelopes

Keisuke Kojima, Toshiaki Koike-Akino, David S. Millar, and Kieran Parsons
Mitsubishi Electric Research Laboratories (MERL), 201 Broadway, Cambridge, MA 02139, USA
kojima@merl.com

Abstract:
We propose a method of designing modulation schemes for increasing Euclidean distance white minimizing power fluctuations during transitions. Simulations show that this has $0.8 \sim 1.0$ dB higher loss budget than DP-BPSK and 4D Simplex modulation over 6,000 km links.

OCIS codes: 060.4080 Modulation; 060.4510 Optical communications.

1. Introduction

Various modulation formats have been studied for coherent optical communications [1, 2].

Typically, constellation designs are conducted such that Euclidean distance first, and then bit labeling so that we minimize Union Bound (UB), which gives an upper limit for a bit error rate (BER). This is good as long as the additive white Gaussian noise is dominant. However, this does not hold when fiber nonlinearity plays a role, in which case additional phase noise may dominate. Constant modulus constellations are shown to be effective in reducing the nonlinear interferences [3, 4]. In this paper, we extend the concept and design a constellation by simultaneously minimizing the UB and peak-to-average power ratio (PAPR). The designed constellation is a 4-dimensional (4D) code with the same spectral efficiency as dual polarization binary phase-shift keying (DP-BPSK) and 4D Simplex, and has $0.8 \sim 1.0$ dB higher span loss budget than these according to 6,000 km transmission simulations.

2. Constellation Design

We consider a modulation scheme with the same spectral efficiency as DP-BPSK. We compare with the best-known Euclidean distance optimal 4D lattice code (a.k.a. Simplex) [5, 6]. Our constellation is based on 4D code with 4 constellation points, where modulation of the orthogonal dimensions is interdependent. In addition, for every even time slots, we multiply a unitary matrix $\mathbf{U} = \exp(\mathbf{A})$ with 6 degrees of freedom (DoF) [7], where $\mathbf{A}$ is a skew-symmetry matrix expressed as

$$\mathbf{A} = \begin{bmatrix} 0 & a & b & c \\ -a & 0 & d & e \\ -b & -d & 0 & f \\ -c & -e & -f & 0 \end{bmatrix}. \tag{1}$$

For arbitrary real-values of $a \sim f$, the multiplication of the unitary matrix $\mathbf{U}$ guarantees constant power at each symbol time. In order to further reduce the power variation during the transition, we optimized the constellation and the unitary matrix, by minimizing the following metric

$$\min \quad p_{\text{union}} + \lambda \varepsilon_{\text{env}}, \tag{2}$$

where λ is a weighting factor. p_{union} is an UB, which can be expressed as

$$p_{\text{union}} = \frac{1}{M} \sum_{i=1}^{M} \sum_{j=1}^{M} d_{\text{H}}(s_i, s_j) \frac{1}{2} \text{erfc} \sqrt{\frac{d_{\text{E}}^2(s_i, s_j)}{4\sigma^2}}, \tag{3}$$

where M is the total cardinality over adjacent blocks, d_{H} is the Hamming distance and d_{E} is the Euclidean distance, over the 4D constellation points for data s_i and s_j. ε_{env} is the envelop variance taken from the center 2 symbols of 6 symbols span with 16 oversampling, which is expressed as

$$\varepsilon_{\text{env}} = \frac{\mathbb{E}[\|\mathbf{w}_m - \mu \mathbf{1}\|^2]}{\mu^2} = \frac{NM \sum_m \|\mathbf{w}_m\|^2}{(\sum_m \mathbf{1}^T \mathbf{w}_m)^2} - 1, \tag{4}$$

where μ is the mean of the samples, $\mathbf{w}_m$ is the envelope of m-th codeword given transmitter impulse response, N is the number of samplers, and $\mathbf{1}$ is a ones vector.

We used a root-raised cosine (RRC) filter with a roll-off parameter of 0.1 for the transmitter, and the covariance matrix adaptation evolutionary strategy (CMA-ES) algorithm [8] to optimize multiple parameters efficiently. After evaluating multiple results with different values of λ, we chose the cases of $\lambda = 0$ and 0.01. The former corresponds to the case where only UB was optimized. The latter case takes both UB and envelope optimization into account, and their constellations are shown in Fig. 1. Note that even though constellation odd and even time slots are shown, this is purely a 4D modulation, since there is no constraint on the combination of constellation points across the time slots.

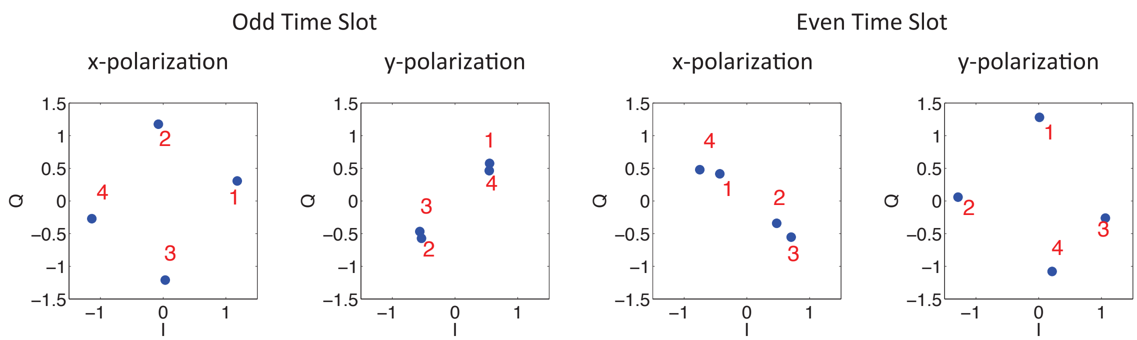

Fig. 1: Constellation of x- and y-polarizations for the odd and even time slots.

Figures 2 (a) and (b) show the envelope of the intensity of x- and y-polarizations and sum of both polarizations, before and after the RRC filter, respectively, and (c) shows the histogram of the intensity of the sum of both polarizations, all for the case of the 4D-Simplex case. Note that there is a long tail in the histogram, and the standard deviation (SD) normalized to the mean was 0.430. Figures 2 (d) through (f) are for the proposed UB and enveloped optimized modulation. The intensity distribution does not have a long tail, and the SD is 0.323.

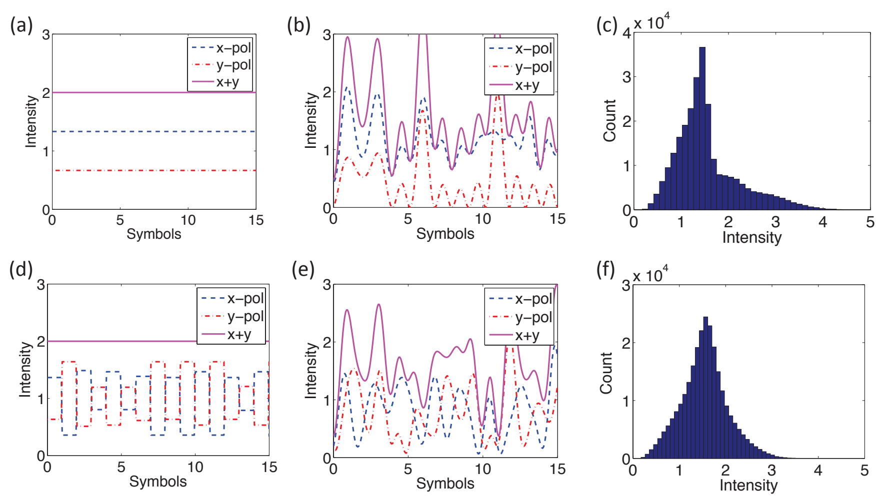

Fig. 2: (a) Intensity (power) of x-, y-, and x+y polarizations before the RRC filtering, (b) after the RRC filtering, (c) histogram of the intensity of the x+y polarizations, for the Simplex modulation. (d), (e), (f) are for the UB and envelope-optimized modulation. Roll-off parameter of 0.1 and oversampling of 16 were used.

3. Transmission Simulation

We simulated transmission performance over a 6,000 km standard single-mode fiber (SSMF) or 90 % compensated non-zero dispersion shifted fiber (NZDSF) link at a rate of 62.5 Gb/s (31.25 GBd) per wavelength. Modulated symbols are mapped to the two-dimensions (DP-BPSK) and four-dimensions (Simplex and envelop-optimized). At the transmitter, DP-I/Q modulators were driven by rectangular pulses, filtered by a RRC filter with a roll-off parameter of 0.1. Five wavelength channels with the same modulation format were simulated with 35 GHz spacing and no optical filtering. The link comprises of 75 spans of 80 km SSMF or NZDSF with loss compensated by Erbium doped fiber amplifiers with 5.0 dB noise figure. In order to quantify performance over a single link for multiple modulation formats, span loss budget was used as a performance metric [9]. SSMF parameters were as follows: γ = 1.2 /W/km; D = 17 ps/nm/km; α = 0.2 dB/km. NZDSF parameters were, γ = 1.6 /W/km; D = 3.9 ps/nm/km; α = 0.22 dB/km, where 90 % of the dispersion was compensated at the end of each span. No pre-dispersion was considered for both cases. Other fiber effects such as dispersion slope and polarization mode dispersion were not simulated. An ideal homodyne coherent receiver was used, with a transfer function described by a RRC filter, followed by sampling at twice the symbol rate. Following this, ideal chromatic dispersion equalization and data-aided least mean square equalization were employed. We assumed a BER threshold of 1×10^{-2} for a 20% FEC [10]. The plots for span loss budget vs. launch power for the three modulation formats are given in Fig. 3 for SSMF, and Fig. 4 for NZDSF.

For the case of the SSMF link, in the low launch power regime (-4 dBm), where linear propagation effects are dominant, our UB and envelope-optimized modulation (UB & Env-Opt) gives the same margin as Simplex, which is 0.6 dB higher than DP-BPSK. For higher launch powers where nonlinearity is dominant, performance improvements become more significant, and the peak margin is higher by 0.8 dB than both cases. We also plotted the UB optimized (UB-Opt) modulation where constant modulus is maintained at each time slot, but not the envelope. It is clearly seen that nonlinear behavior is much worse than the UB and envelope-optimized case, indicating the importance of envelope optimization.

For the case of dispersion managed NZDSF case, our UB and envelope-optimized modulation scheme gives 0.8 dB and 1.0 dB higher span loss budget than DP-BPSK and Simplex, respectively.

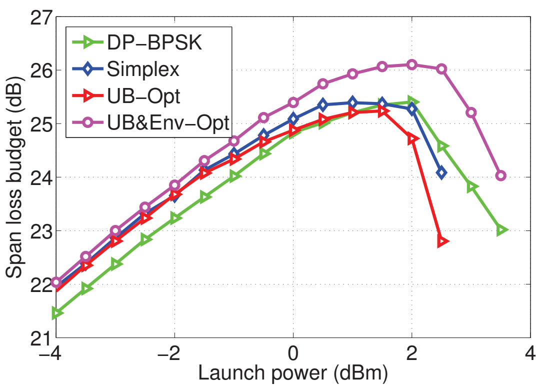

Fig. 3: Link budget margin for 75 spans of 80km SSMF.

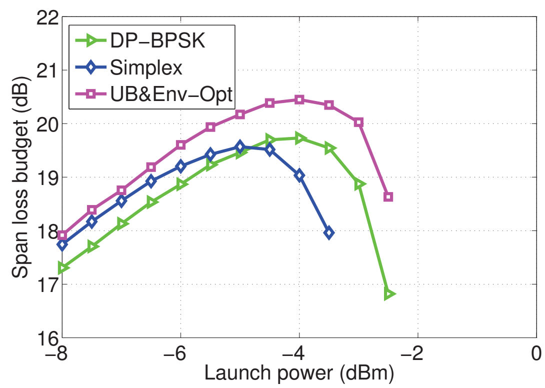

Fig. 4: Link budget margin for 75 spans of 80km NZDSF with 90 % compensation

4. Summary

We proposed a method of optimizing modulation schemes, where constant modulus is nearly maintained during the transitions between symbols, while minimizing UB at the same time. This was applied to 2-bit 4D case, and was shown to exhibit 0.8 $\sim$ 1.0 dB higher span loss budget than the conventional DP-BPSK and Simplex cases both for 6,000 km of SSMF and dispersion-managed NZDSF links.

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