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Trellis-Coded High-Dimensional Modulation for Polarization Crosstalk Self Cancellation in Coherent Optical Communications

Toshiaki Koike-Akino, Keisuke Kojima, Kieran Parsons
Mitsubishi Electric Research Labs. (MERL), 201 Broadway, Cambridge, MA 02139, USA. koike@merl.com

Abstract: We propose new trellis-coded high-dimensional modulation (TC-HDM) robust to polarization crosstalk in coherent optical communications. Since the modulation can automatically recover polarization crosstalk, it offers 2 dBQ improvement through the use of blind equalization.

OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

Coherent optical communications have been able to significantly increase spectrum efficiency by polarization division multiplexing (PDM). To exploit 4-dimensional signal space (real and imaginary parts for both x- and y-polarizations), high-dimensional modulations (HDM) [1], such as polarization-switched quaternary phase shift keying (PS-QPSK) [2], have received much attention. It was shown that 4-dimensional modulations achieve more than 1.5 dB gain in additive white Gaussian noise (AWGN) channels [1]. However, fiber-optic communications suffer not only from AWGN (mainly caused by amplifier spontaneous emission noise) but also from other fiber impairments; e.g., linear dispersion and nonlinear distortion. Those impairments cause a change of state of polarization (SOP) along time and frequency due to polarization mode dispersion (PMD) and cross polarization modulation (XPolM).

This paper studies HDM suited for alleviating the effect of SOP rotations. The proposed scheme is an extended version of differential modulations for higher-dimensional constellations. Differential PSK (DPSK) modulations are often used in conventional coherent optical systems so that it becomes robust against undesired phase rotations and cycle slips after a phase recovery. However, such conventional differential modulations do not perform well for any arbitrary SOP because the SOP rotation results in polarization crosstalk. Therefore, the receiver digital signal processing (DSP) usually requires polarization recovery techniques such as constant-modulus adaptation (CMA) blind filter.

The key idea behind the differential HDM lies in the fact that the x-polarization signals and the y-polarization signals are jointly designed to be mutually orthogonal. Because of the orthogonality, any polarization crosstalk, attenuation, and rotations in SOP can be automatically resolved in a blind manner. More importantly, such an SOP self-recovery nature can completely eliminate the need of the other phase and polarization recovery techniques.

The HDM are based on a family of unitary space-time modulations [3, 4], which have been studied intensively for wireless communications. Since space-time modulations were originally proposed to mitigate the effect of channel fading which typically does not exist in fiber channels, there are only a few literature which could demonstrate its substantial usefulness in fiber-optic communications [5–7]. We show that the differential HDM can achieve $1 \sim 2$ dBQ improvement even without phase and polarization recovery when compared to conventional DPSK. In addition, we introduce trellis coding [8] and an improved equalization scheme [4].

2. Trellis-Coded High-Dimensional Modulations (TC-HDM)

Fig. 1 shows a PDM coherent fiber-optic communications system. A digital bit data m is sent by differential HDM $\{\mathbf{U}_m\}$, which generates x/y-polarization constellations $s_{\mathrm{x}}(n)$ and $s_{\mathrm{y}}(n)$. After passing through an electrical filter and a digital-analog converter, the electrical signals are converted to optical signals via Mach-Zehnder modulators. The resulting optical signals propagate through a fiber link consisting of N_{sp} spans. The fiber platform is configured of a single-mode fiber (SMF) of length L and a dispersion-compensation fiber (DCF) of length L' as well as an erbium doped fiber amplifier (EDFA) per span. The length of DCF is chosen according to residual dispersion per span (RDPS).

At the receiver, the optically filtered signal is down-converted to electrical signals with a coherent optical receiver, analog-digital converters and electrical filters. The received signals are denoted by $r_{\mathrm{x}}(n)$ and $r_{\mathrm{y}}(n)$ for x and y polarizations at the n-th symbol. To detect the transmitted data, the receiver performs a generalized likelihood ratio test

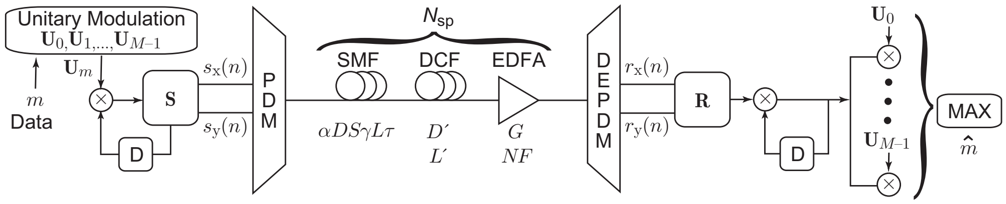


Fig. 1: Coherent optic communications systems with differential HDM.

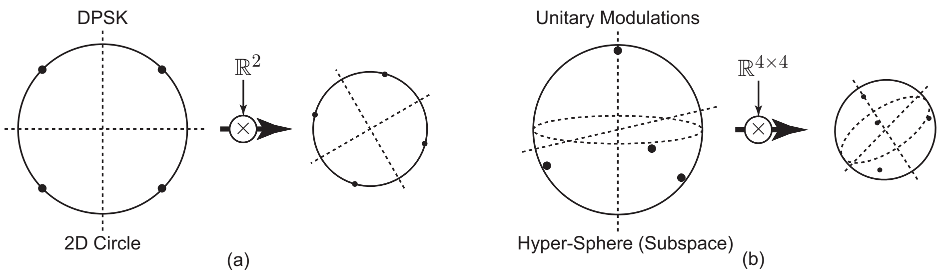


Fig. 2: Conceptual analogy between DPSK and differential HDM.

(GLRT) algorithm [4] which takes correlation between unitary modulations and differentially rotated receiving signals. Note that GLRT achieves the maximum-likelihood performance even without knowledge of SOP because of the orthogonality over x/y polarizations. When the linear dispersion such as PMD is dominant, the received signal is expressed by a linear transformation of the transmitted signal in frequency domain as

$$\begin{bmatrix} r_{\mathrm{x}}(\omega) \\ r_{\mathrm{y}}(\omega) \end{bmatrix} = \begin{bmatrix} h_{\mathrm{xx}}(\omega) & h_{\mathrm{xy}}(\omega) \\ h_{\mathrm{yx}}(\omega) & h_{\mathrm{yy}}(\omega) \end{bmatrix} \begin{bmatrix} s_{\mathrm{x}}(\omega) \\ s_{\mathrm{y}}(\omega) \end{bmatrix} + \begin{bmatrix} z_{\mathrm{x}}(\omega) \\ z_{\mathrm{y}}(\omega) \end{bmatrix} \quad \Longrightarrow \quad \mathbf{r}(\omega) = \mathbf{H}(\omega)\mathbf{s}(\omega) + \mathbf{z}(\omega), \tag{1}$$

where $\mathbf{H}$ denotes the channel coefficient which rotates the SOP depending on the frequency ω, and $\mathbf{z}$ is the additive noise. Similarly, when the nonlinearity dominates, it was shown [9, 10] that the received signals are well represented by a polarization crosstalk XPolM model in time domain as follows:

$$\begin{bmatrix} r_{\mathrm{x}}(n) \\ r_{\mathrm{y}}(n) \end{bmatrix} = \mathrm{e}^{\mathrm{j}\phi} \begin{bmatrix} \mathrm{e}^{\mathrm{j}\theta}\sqrt{1-|w(n)|^2} & -w^*(n) \\ w(n) & \mathrm{e}^{-\mathrm{j}\theta}\sqrt{1-|w(n)|^2} \end{bmatrix} \begin{bmatrix} s_{\mathrm{x}}(n) \\ s_{\mathrm{y}}(n) \end{bmatrix} + \begin{bmatrix} z_{\mathrm{x}}(n) \\ z_{\mathrm{y}}(n) \end{bmatrix} \quad \Longrightarrow \quad \mathbf{r}(n) = \mathbf{H}(n)\mathbf{s}(n) + \mathbf{z}(n), \tag{2}$$

where $[\cdot]^*$ denotes the complex conjugate, ϕ denotes a common phase noise, θ denotes a phase difference, $w(t)$ is a polarization crosstalk factor. An important implication from (1) and (2) is the fact that the received signal suffers from the change of SOP which causes polarization crosstalk.

To solve SOP rotations without using complicated recovery algorithms, we use unitary space-time constellations [3], which allow the use of differential encoding for $\mathbb{R}^{4\times4}$-dimensional modulations $\mathbb{U} \triangleq \{\mathbf{U}_1, \mathbf{U}_2, \ldots, \mathbf{U}_M\}$ with a cardinality of $M = 4^4$ for a spectral efficiency of 2 bps/Hz/pol. One of such constellations is proposed [3] as follows:

$$\mathbf{U}_m = \begin{bmatrix} \mathrm{e}^{\mathrm{j}\frac{2\pi m}{M}} & 0 \\ 0 & \mathrm{e}^{\mathrm{j}\frac{2\pi m k_1}{M}} \end{bmatrix} \begin{bmatrix} \cos\left(\frac{2\pi m k_2}{M}\right) & \sin\left(\frac{2\pi m k_2}{M}\right) \\ -\sin\left(\frac{2\pi m k_2}{M}\right) & \cos\left(\frac{2\pi m k_2}{M}\right) \end{bmatrix} \begin{bmatrix} \mathrm{e}^{\mathrm{j}\frac{2\pi m k_3}{M}} & 0 \\ 0 & \mathrm{e}^{\mathrm{j}\frac{-2\pi m k_3}{M}} \end{bmatrix}, \tag{3}$$

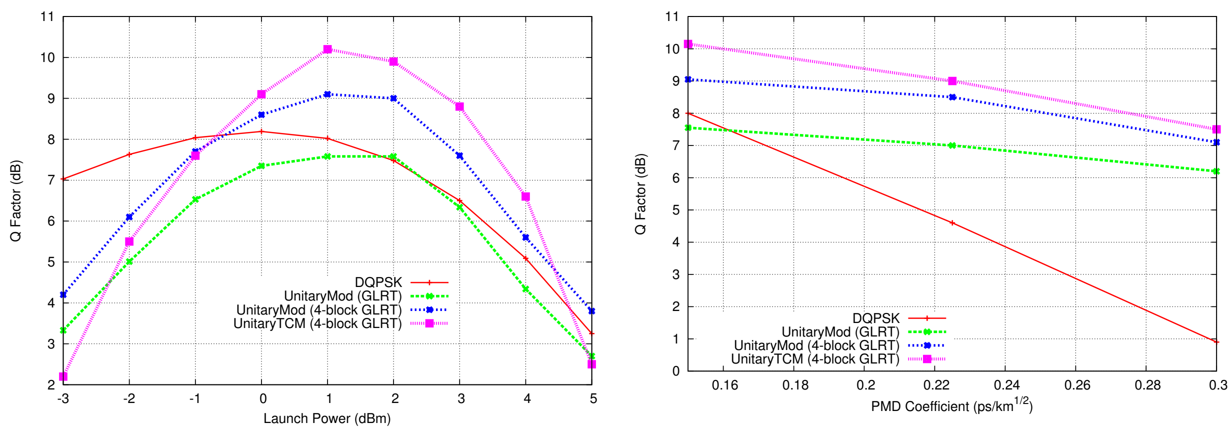
where integers $\{k_1, k_2, k_3\}$ are optimized to maximize the codeword distance [3], wherein optimal parameters are listed. Fig. 2 illustrates a conceptual extension of DPSK to higher-dimensional modulations. As shown in Fig. 2 (a), since the PSK constellations are mapped onto a circle, it can automatically recover any arbitrary complex-valued rotation by differential encoding. Analogously shown in Fig. 2 (b), the unitary constellations are mapped onto a hyper-sphere surface over a manifold subspace, which does not change against any matrix-valued multiplications.

As an improved blind equalization, we adopt a high-order super-block GLRT proposed in [4] to deal with time and frequency selectivity. To further improve performance, we introduce the use of trellis coding. We optimized the set $\{k_1, k_2, k_3\}$ such that the free distance can be maximized.

3. Performance Results

We consider system parameters of SMF attenuation 0.25 dB/km, SMF dispersion 17 ps/nm/km, SMF dispersion slope 0.09 ps/nm^2/km, SMF nonlinear factor 1.3 /W/km, SMF PMD coefficient 0.15 ps/km$^{1/2}$, SMF fiber length 80 km, DCF dispersion -85 ps/nm/km, DCF attenuation 0.60 dB/km, RDPS 5%, EDFA gain 29.12 dB, and its noise figure 6 dB. The transmission data rate is set up to be 112Gbps with a carrier frequency of 193.25 THz. We use 4-th order super-Gaussian optical filter whose bandwidth is 2.5-times wide of the baud rate, and 4-th order Bessel electrical filter whose bandwidth is 75% of the baud rate.

Fig. 3 shows the simulation results of Q-factor evaluations to compare dual-polarized DQPSK and unitary HDM as a function of a launch power and an PMD coefficient τ after 15 spans. One can observe that HDM itself has slightly worse performance than DQPSK whereas it becomes 1 dBQ better when using improved 4-block GLRT algorithm. Another 1 dBQ improvement can be seen with TC-HDM. The robustness against the SOP rotations is more visible when we have even higher PMD coefficient.



(a) Q vs. Launch Power

(b) Q vs. PMD Coefficient

Fig. 3: Q-factor evaluations.

4. Conclusions

We proposed differential HDM to recover the polarization rotations caused by linear/nonlinear fiber impairments in coherent optical communications. The orthogonality of dual-polarized signals resolves time-varying or frequency-dependent SOP fluctuations. With an improved detection scheme and trellis coding, we have shown that the proposed scheme can significantly improve performance by more than 1 dBQ.

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