Power Efficient Modulation Techniques for High Speed Optical Communication Networks

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Abstract: We study several modulation techniques that maintain both power and spectral efficiencies above traditional QAM schemes. The maximum achievable power efficiency under a constraint on spectral efficiency is determined and compared to that of QAM.

Keywords: Power efficiency, quadrature-amplitude modulation, spectral efficiency.

1. Introduction

In modern optical communications systems both spectral and power efficiencies are to be optimized simultaneously. This would ensure increasing the data transmission rate at a given bandwidth, while keeping the asymptotic bit-error rate reduced.

Spectral efficiencies can be increased by adopting multilevel signaling, e.g. quadrature-amplitude modulation (QAM), and/or polarization-division multiplexing (PDM) techniques. Recently, hybrid modulation formats have been proposed to increase the power efficiency of multilevel signals in optical links, e.g., polarization-switched QPSK (PS-QPSK) and PDM-QPSK superimposed on pulse-position-modulation (PPM) signals have been shown to provide higher power efficiency than PDM-QPSK at the expense of reduced spectral efficiency [1, 2]. By combining multi-pulse pulse-position modulation (MPPM) with BPSK, QPSK, PS-QPSK, and polarization-multiplexed QPSK (PM-QPSK), one can increase both the spectral and power efficiencies over pure traditional QPSK [3–6].

In [7], we have characterized the best power efficiency that can be achieved under a constraint on the spectral efficiency of a hybrid MPPM-*L*QAM technique. The simplicity of the obtained power efficiency expressions gives more insight about the sensitivity gains of the systems studied. Recently, new hybrid techniques have been proposed in literature, namely, two-level multipulse pulse-position modulation-*L*-ary differential phase shift keying (2*l*.MPPM-*ML*DPSK) [8] and polarization-assisted *L*-ary differential phase shift keying-multipulse pulse-position modulation (PA.*L*DPSK-MPPM) [9]. Our aim in this paper is to determine the best power efficiency that can be achieved from extended versions of these new schemes under a constraint on the spectral efficiency.

2. Preliminaries and Problem Statement

In this section, we cite the definitions of both power and spectral efficiencies, and introduce the problem statement.

2.1. Spectral and Power Efficiencies

The spectral efficiency η and the asymptotic power efficiency γ are defined as:

$$\eta \stackrel{\text{def}}{=} \frac{\log_2 M}{N/2} \text{ bit/sym/pol} \qquad \text{and} \qquad \gamma \stackrel{\text{def}}{=} \frac{d_{min}^2 \log_2 M}{4\mathscr{E}_s}, \tag{1}$$

respectively, where M is the number of constellation vectors (or symbols), N is the dimension of a constellation vector, $\mathscr{E}_s$ is the average symbol energy, and d_{min} is the minimum Euclidean distance between two symbols in the constellation space.

2.2. Problem Statement and Characterization

In this paper we aim at finding the maximum power efficiencies γ of both 2*l*.MPPM-*L*QAM and PA.MPPM-*L*QAM techniques under a constraint $\eta \le S_e$ on their spectral efficiencies. Our characterizations of corresponding constrained power efficiencies are given in Section 2.3 below.

2.3. *Main Result*

In $2l$.MPPM-LQAM and PA.MPPM-LQAM techniques, if the spectral efficiency threshold is S_e, then the constrained power efficiencies can be characterized as:

$$\theta_{2l.\text{MPPM-}L\text{QAM}}(S_e) = \max_{\substack{p\in(0,1],\ell\in\mathbb{N}:\\ \ell+h(p)\geq S_e}} \frac{3\left[\ell+h(p)\right]}{2(\kappa_\ell 2^\ell-1)(3p+1)} \quad \text{and} \quad \theta_{\text{PA.MPPM-}L\text{QAM}}(S_e) = \frac{3(\ell_1+1)}{2(\kappa_{\ell_1}2^{\ell_1}-1)}, \tag{2}$$

where $h(p)$ is the binary entropy function, $\ell_1 = \max\left\{\lceil 2S_e - 1\rceil, 2\right\}$, and κ_ℓ equals 1 if ℓ is even and equals 5/4 if ℓ is odd.

3. Numerical Results

Figure 1 shows a comparison for the constrained power efficiencies of MPPM-LQAM technique and its variants versus spectral efficiency constraint.

It is clear from the figure that PA.MPPM-LQAM technique is only power efficient for spectral efficiencies not exceeding 1.5 bit/sym/pol. The reason is that when the spectral efficiency threshold S_e increases, the corresponding QAM level is achieved at high values of L and the power efficiency would drop significantly.

On the contrary, the constraint power efficiency of $2l$.MPPM-LQAM technique is better than that of traditional QAM at all S_e levels. Improvement of about 3 dB is achievalbe at specific levels.

We can conclude that the most power/spectral efficient technique is MPPM-LQAM. It should be noticed than $2l$.MPPM-LQAM technique is slightly better that MPPM-LQAM over a small range of S_e.

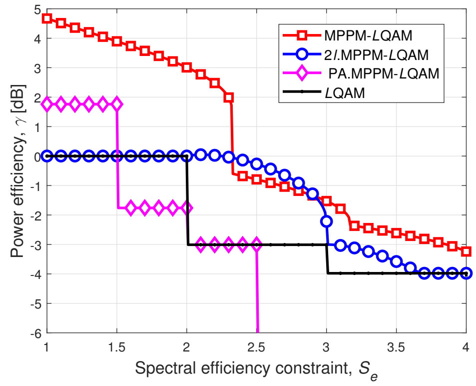

Fig. 1: Comparison between maximum power efficiencies of MPPM-LQAM, its variants, and traditional LQAM techniques versus spectral efficiency constraints.

References

[1] Erik Agrell and Magnus Karlsson. Power-efficient modulation formats in coherent transmission systems. *IEEE/OSA J. Lightwave Technol.*, 27(22):5115–5126, Nov. 15, 2009.

[2] Xiang Liu, Thomas H. Wood, Robert W. Tkach, and S. Chandrasekhar. Demonstration of record sensitivities in optically pream- plified receivers by combining PDM-QPSK and M-ary pulse-position modulation. *IEEE/OSA J. Lightwave Technol.*, 30(4):406–413, Feb. 15, 2012.

[3] H. Selmy, H. M. H. Shalaby, and Z.-I Kawasaki. Proposal and performance evaluation of a hybrid BPSK-modified MPPM technique for optical fiber communications systems. *IEEE/OSA J. Lightwave Technol.*, 31(22):3535–3545, Nov. 15, 2013.

[4] Hossam Selmy, Hossam M. H. Shalaby, and Zen Kawasaki. Enhancing optical multi-pulse pulse position modulation using hybrid QPSK-modified MPPM. In *Proc. IEEE Photonics Conference (IPC 2014)*, pages 617–618, San Diego, CA, Oct. 12–16, 2014.

[5] Jeroen H. B. Nijhof. Generalized L-out-of-K pulse position modulation for improved power efficiency and spectral efficiency. In *Proc. Optic. Fiber Commu. Conf. (OFC 2012)*, pages OW3H.7(1–3), Los Angeles, CA, Mar. 4-8, 2012.

[6] Tobias A. Eriksson, Pontus Johannisson, Benjamin J. Puttnam, Erik Agrell, Peter A. Andrekson, and Magnus Karlsson. K-over-L multidimensional position-modulation. *IEEE/OSA J. Lightwave Technol.*, 32(12):2254–2262, June 15, 2014.

[7] Hossam M. H. Shalaby. Maximum achievable constrained power efficiencies of MPPM-LQAM techniques. *IEEE Photonics Technol Lett.*, 27(12):1265–1268, June 15, 2015.

[8] Abdulaziz E. Elfiqi, Haitham S. Khallaf, Salem F. Hegazy, Amr Elsonbaty, Hossam M. H. Shalaby, and Salah S. A. Obayya. Chaotic polarization-assisted LDPSK-MPPM modulation for free-space optical communications. *IEEE Trans. Wireless Commun.*, 18(9):4225–4237, Sept. 2019.

[9] Haitham S. Khallaf, Ahmed E. Morra, Abdulaziz E. Elfiqi, Hossam M. H. Shalaby, and Steve Hranilovic. Hybrid two-level MPPM-MDPSK modulation for high speed optical communication networks. *OSA Appl. Opt.*, 58(36):9757–9767, Dec. 20, 2019.