Multilevel pulse-position modulation for optical power-efficient communication

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Abstract: A family of modulation formats is derived by combining pulse-position modulation (PPM) with multilevel dual-polarization signal constellations. With 16-PPM, gains of up to 5.4 dB are obtained over dual-polarization QPSK, at the cost of reduced spectral efficiency.

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

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1. Introduction

Fiber-optic coherent transmission technologies are becoming increasingly popular for a number of reasons, the most important being (i) increased spectral efficiency, which comes from a practical use of multilevel and multidimensional modulation [1, 2] and (ii) increased receiver sensitivities, stemming from the coherent optical receiver, which can detect both amplitude and phase [1, 3]. With these technological breakthroughs, the system performance falls back on issues that may seem well known and textbook-like, such as the choice of modulation format. However, since the signal space can have four, or as we will see below even more dimensions, the choice of modulation scheme deserves an elaborate discussion.

If the constellation space is limited to four dimensions (4d), we recently showed [4, 5] that the most power-efficient format is obtained by transmitting quadrature phase-shift keying (QPSK) data in one of two orthogonal polarization states at each time, which yields the so-called polarization-switched QPSK (PSQPSK). The corresponding signal constellation is the 4d cross-polytope. For asymptotically low bit-error rate (BER), it has an asymptotic power efficiency (PE) of 1.76 dB. The PE equals the sensitivity gain over the conventional QPSK at very low BERs, and at a BER of 10^{-3}, the gain reduces to 0.97 dB [5], as was recently verified experimentally [6]. For quantum-limited coherent receivers, the sensitivity in photons per bit can then be directly obtained from the PE and the known sensitivity for QPSK. The PSQPSK format was recently demonstrated to enable, e.g., (i) increased attenuation per amplifier span [7], (ii) increased total transmission distance in long-haul systems [8], or (iii) reduced nonlinear distortion in wavelength-division multiplexed systems [9].

There are a number of ways of increasing the sensitivity and/or the spectral efficiency further (without resorting to improved hardware), and they all involve increasing the dimensionality of the constellations. Additional dimensions can be obtained by transmitting dependent signals (i.e., coding) over several time slots or frequency bands. Then each time slot or frequency band will provide a new degree of freedom in which we can, in principle, modulate 4d signals. If we use K such subsequent time slots, we will thus have a $4K$-dimensional signal space. Furthermore, if only one of the K slots is selected for modulation, and the rest are kept powerless, we have an example of multilevel pulse-position modulation (PPM). PPM was discussed for optical lines already in [10] and more recently in [11, 12], and it is known to have good (essentially unbounded) sensitivity as K increases, however at the expense of spectral efficiency. For finite K, there are interesting trade-offs between spectral efficiency and sensitivity that can be explored by overlaying PPM with a conventional modulation format, as recently suggested by Liu et al. [12]. In that work, it was demonstrated that 16-PPM combined with polarization-multiplexed QPSK (PMQPSK), and which we will refer to as 16-PPM-PMQPSK, can obtain 3 dB of increased sensitivity over regular QPSK and PMQPSK. In a recent report [13], a single-hop link over 370 km based on 4-PPM-PMQPSK was demonstrated, and exact analytical expressions for the bit-error rate (BER) of some PPM-based formats were derived as well.

The purpose of this paper is to, for the first time, systematically evaluate and compare the PE and SE of known power-efficient 2-dimensional (2d) and 4d formats together with PPM. We will then give specific examples on the SE–PE trade-off for those formats. Some surprises are revealed, e.g., that QPSK and PMQPSK have *no longer* equal performance under PPM, and that binary phase-shift keying (BPSK), QPSK and PSQPSK all have *equal performance* albeit with different orders of PPM. The PSQPSK format will again show better sensitivity than other 2d and 4d formats with PPM.

2. PPM-based modulation formats

The comparison of modulation schemes involves in general two main parameters; the spectral efficiency *SE*, which quantifies the bitrate gain over BPSK, and the power efficiency *PE*, which equals the (low-BER) sensitivity gain over QPSK, transmitting the same data rate. In the

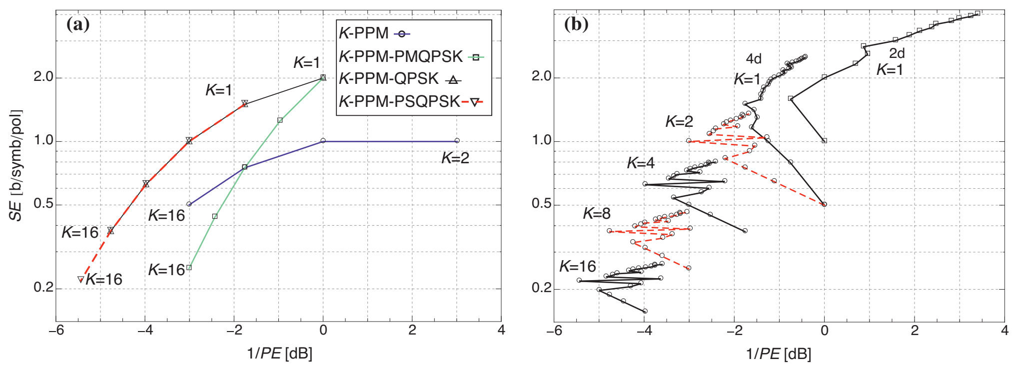

Fig. 1. **(a)** Chart over the asymptotic sensitivity penalty $1/PE$ vs. spectral efficiency SE for K-PPM, K-PPM-QPSK, K-PPM-PMQPSK and K-PPM-PSQPSK, where $K = 1$, 2, 4, 8, and 16. **(b)** Performance of K-PPM-$\mathscr{C}_{4,m}$ for $m = 2, 3, \ldots, 21$, where $\mathscr{C}_{4,m}$ is the most power-efficient 4d constellations known from [5]. Included for reference are the best known m-ary constellations in 2d ($m = 2, \ldots, 16$) and 4d ($m = 2, \ldots, 32$) without PPM, i.e., for $K = 1$.

absence of error-correcting coding, these quantities are, for an N-dimensional, M-level modulation scheme given by [5]

$$SE = \frac{\log_2(M)}{N/2}, \qquad PE = \frac{d_{min}^2}{4\bar{E}_s}\log_2(M) \tag{1}$$

where $\bar{E}_s$ is the average energy per symbol and d_{min} is the smallest Euclidean distance between any pair of symbols in the constellation. This definition gives SE in units of "bits per symbol per dimension pair," where we can often replace "dimension pair" with "polarization." The physical interpretation of PE is the power gain over QPSK when transmitting the same bit rate at low BERs.

2.1. Basic PPM

Conventional K-ary PPM (K-PPM) is usually assumed to use a pulse with energy E_s in one of K consecutive time slots, while the rest are zero. The dimensionality is then K, as is the number of modulation levels, making the spectral efficiency $SE = 2\log_2(K)/K$. After reaching a maximum at $K = 3$, SE decreases monotonically with K, which is characteristic for PPM. The minimum distance is $d_{min} = \sqrt{2E_s}$, since the constellation consists of K points located at a distance $\sqrt{E_s}$ from the origin, each on one of the K orthogonal coordinate axes. PE is therefore $\log_2(K)/2$, which is clearly unbounded with K. This means that PPM can have arbitrarily low sensitivities, and the price paid is spectral efficiency. This is illustrated in Fig. 1 (a), showing spectral efficiencies vs. sensitivity penalties for K-PPM (circles) with $K = 2$, 4, 8, and 16.

2.2. Multilevel four-dimensional PPM

An attractive way of improving K-PPM is, as suggested in [12], by combining it with a more efficient modulation format $\mathscr{C}$. For example, a symbol from an n-dimensional m-ary constellation can be transmitted in one of the K time slots and the zero vector in the other $K-1$ time slots. Then the total dimensionality will be $N = nK$, the number of modulation levels $M = mK$, and the spectral efficiency $SE = 2\log(mK)/(nK)$. The evaluation of PE requires a bit more care, as the minimum distance in the format is given by

$$d_{min} = \min\left\{d_{min}^{\mathscr{C}}, \sqrt{2E_{s,min}^{\mathscr{C}}}\right\}, \tag{2}$$

where $d_{min}^{\mathscr{C}}$ is the smallest Euclidean distance between pairs of points in $\mathscr{C}$ and $E_{s,min}^{\mathscr{C}}$ is the smallest Euclidean norm (i.e., distance to the origin) of a point in $\mathscr{C}$. This indicates that mul-

Table 1. Parameters of PPM and multilevel PPM.

Format	Dimensionality N	No. of levels M	SE [b/symb/pol]	PE
K-PPM[a]	K	K	$2\log_2(K)/K$	$\log_2(K)/2$
K-PPM-BPSK[a]	K	$2K$	$2\log_2(2K)/K$	$\log_2(2K)/2$
K-PPM-QPSK	$2K$	$4K$	$\log_2(4K)/K$	$\log_2(4K)/2$
K-PPM-PSQPSK	$4K$	$8K$	$\log_2(8K)/(2K)$	$\log_2(8K)/2$
K-PPM-PMQPSK	$4K$	$16K$	$\log_2(16K)/(2K)$	$\log_2(16K)/4$

[a]Limited to $K \geq 2$.

tilevel PPM is not useful for constellations with a constellation point at (or near) the origin, since for that symbol it is hard to detect the transmitted PPM slot. For PPM-QPSK and PPM-PSQPSK, $d_{min}^{\mathscr{C}} = \sqrt{2E_{s,min}^{\mathscr{C}}}$, implying that PPM is a reasonable extension of these formats. For PPM-PMQPSK, however, $d_{min}^{\mathscr{C}} = \sqrt{E_{s,min}^{\mathscr{C}}}$, which means that the PMQPSK constellation bits are more error prone than the PPM bits.

We have evaluated the SE and the PE for some of the most straightforward generalizations of PPM, namely with QPSK, PSQPSK, and PMQPSK (which was demonstrated in [12]). The properties of these formats are tabulated in Table 1, and they are plotted in Fig. 1 (a) for $K = 2$, 4, 8 and 16-PPM. It can be observed that K-PPM-PSQPSK, $2K$-PPM-QPSK, and $4K$-PPM-BPSK (not shown) are equivalent, which is not surprising given that PSQPSK, which is transmission of QPSK in one of two polarizations, is essentially the same as 2-PPM-QPSK, and analogously, QPSK is the same as 2-PPM-BPSK.

In Fig. 1 (b), K-PPM is combined with the previously explored 4d power-efficient formats [5]. Just as in the conventional case without PPM, the PSQSPK format turns out to have the best sensitivity. Some constellations, such as those for $m = 7$ and 9, are remarkably weak with PPM. This deficiency is even more prominent for the most power-efficient 4d constellations with $m \geq 22$ and 2d constellations with $m \geq 5$ (not included in the figure). The reason is that these constellations have a small "PPM distance" $\sqrt{2E_{s,min}^{\mathscr{C}}}$ due to a constellation point near the origin [14]. Obviously K-PPM-PSQPSK is most sensitive, and its relative gain over K-PPM-PMQPSK is $2\log_2(8K)/\log_2(16K)$, which approaches 3 dB for large K.

2.3. Multilevel one- and two-dimensional PPM

The above findings confirm analytically the observation recently made in [12], that PPM in combination with a multilevel modulation format such as PMQPSK can achieve better sensitivities than what is possible with any uncoded (i.e., 2d or 4d) modulation format. The results in Fig. 1 and Table 1 also suggest that further improvements, in SE and/or PE, are possible by replacing PMQPSK with a more power-efficient format. To maintain a fair comparison, however, one should maintain the dimensionality. This means that K-PPM-PMQPSK should be compared with K-PPM-PSQPSK, or 2 independent streams of K-PPM-QPSK, or 4 independent streams of K-PPM-BPSK. In Figure 2 this is illustrated schematically for $K = 4$. The PPM symbol is shown with thick and the time slots with thin vertical bars. All shown formats occupy a sixteen-dimensional signal space (4 PPM-time slots and 4 quadratures). In Fig. 2(a) 4-PPM-PMQPSK is shown, occupying both polarizations in every time slot, and transmitting 2 PPM bits and 4 PMQPSK bits, i.e., 6 bits per PPM symbol. In Fig. 2(b) 4-PPM-QPSK is shown in two independent polarizations. This format transmits 2 PPM bits and 2 PMQPSK bits, i.e., 4

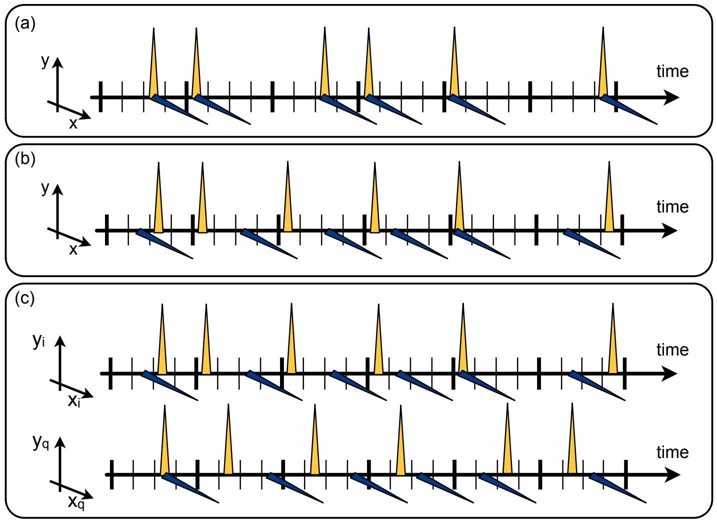

Fig. 2. A 4-PPM example of the use of different 4-d multilevel PPM formats: (a) PMQPSK or PSQPSK, (b) QPSK and PPM independently in two polarizations, (c) BPSK and PPM independently in 4 quadratures. Only intensities are indicated, and the polarization directions are indicated by "x" and "y", and the in-phase (quadrature) phases are denoted $x_i(x_q)$ and $y_i(y_q)$ respectively.

bits per polarization, and 8 bits per PPM symbol. The most spectrally efficient format, however, is found in Fig. 2(c), showing 4 independent streams of 4-PPM-BPSK. The transmitted rate in this case is 2 PPM bits and 1 BPSK bit per stream, i.e., $4(2+1) = 12$ bits per PPM symbol.

Generalizing this example to K-PPM. we can expect K-PPM-BPSK to be most spectrally efficient, in general being $4\log_2(2K)/\log_2(16K)$ times more spectrally efficient than K-PPM-PMQPSK, which approaches 4 for large K.

3. Examples

We will now compare the above formats in two illustrative cases; 16-PPM with the same bandwidth (5 GHz), or with the same data rate (2.5 Gbit/s).

3.1. 16-PPM at 312.5 Mbaud

It is interesting to note that K-PPM-QPSK and K-PPM-PMQPSK, which are equivalent for $K =$ 1 (no PPM), are no longer equivalent when PPM is used. This is evident in the specific example of 16-PPM at a PPM rate of 312.5 Mbaud, which was experimentally demonstrated in [12]. The used bandwidth in this case is $16 \times 0.3125 = 5$ GHz. We may then wonder which format has the best spectral efficiency and sensitivity in such a situation. The results are summarized in Table 2. Note that the power per unit bandwidth, i.e, per PPM pulse, is the most relevant power measure in bandwidth-limited systems rather than power per bit, and therefore we define the *symbol power efficiency*, as $SPE = d_{min}^2 K/(4\bar{E}_s)$, which gives the power gain over BPSK (or QPSK or PMQPSK) at the same bandwidth and (low) uncoded BER. The highest SE (and hence data rate) is, as discussed above, obtained by using 4 parallel 16-PPM-BPSK channels, which gives $4(1+4) = 20$ bits per PPM symbol, i.e., 6.25 Gbits/s. The least spectral efficiency is obtained for 16-PPM-PSQPSK. The 16-PPM-PMQPSK requires 3 dB more power than the others to reach a low bit error rate, due to its lower minimum distance within the PMQPSK constellation.

Table 2. Format comparison at 312.5 Mbaud, and 4×16 dimensional signal space.

Format	Bandwidth [GHz]	Bitrate [Gbit/s]	*SPE* [dB]
16-PPM-BPSK	5.0 GHz	6.25 Gbit/s	9.0 dB
16-PPM-QPSK	5.0 GHz	3.75 Gbit/s	9.0 dB
16-PPM-PSQPSK	5.0 GHz	2.19 Gbit/s	9.0 dB
16-PPM-PMQPSK	5.0 GHz	2.5 Gbit/s	6.0 dB

Table 3. Format comparison at 2.5 Gbit/s, 4×16 dimensional signal space.

Format	Bandwidth [GHz]	Bitrate [Gbit/s]	*PE* [dB]
16-PPM-BPSK	2.0 GHz	2.5 Gbit/s	4.0 dB
16-PPM-QPSK	3.33 GHz	2.5 Gbit/s	4.8 dB
16-PPM-PSQPSK	5.71 GHz	2.5 Gbit/s	5.4 dB
16-PPM-PMQPSK	5.0 GHz	2.5 Gbit/s	3.0 dB

3.2. 16-PPM at 2.5 Gb/s

Another example is to compare different 16-PPM formats at the same bitrate, say 2.5 Gb/s, and using uncoded BPSK as the reference sensitivity. In this case we can directly use the values from Fig. 1(a), which compares formats at the same data rate. The results are summarized in Table 3. As shown in [12], 16-PPM-PMQPSK would require a bandwidth of 5 GHz, and gain 3 dB in sensitivity. For 16-PPM-QPSK in two parallel polarizations, 12 bits per symbol are transmitted, and the bandwidth requirement is $2.5*16/12 = 3.33$ GHz, with a sensitivity gain of 4.8 dB over conventional QPSK. Finally, the most sensitive format would be 16-PPM-PSQPSK, with the best *PE* of 5.4 dB but also with the highest bandwidth requirement of $2.5*16/7 = 5.71$ GHz. These trade-offs are clearly illustrated in Fig 1 (a).

It should be noted that these sensitivity values are asymptotic, which means that the improvement is smaller at finite BERs, such as the commonly used 10^{-3}, especially for basic PPM which have many neighbors in signal space. Exact expressions for the BER of PPM-PMQPSK and PPM-PSQPSK have been calculated by Liu *et al.* [12, 13].

4. Conclusions

We have demonstrated and discussed the spectral efficiency vs. sensitivity trade-offs given by using PPM together with some standard 4d modulation formats without error-correcting coding. It is well known that PPM improves the sensitivity, but at the prize of reduced spectral efficiency. The most sensitive 4d format with PPM is PSQPSK, giving 2.4 dB improvement over PMQPSK when used with 16-PPM. The most spectrally efficient format is four parallel channels of PPM-BPSK, and for 16-PPM it has 2.5 times better SE than PMQPSK. However, the complexity in the coherent receiver for such a PPM-BPSK format is significant, requiring novel schemes for phase and polarization recovery as well as for PPM symbol synchronization.

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