Generalized 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.

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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, 10]. 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 symbol 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 [3, 4] 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 (APE) of $\gamma = 1.76$ dB. The APE equals the sensitivity gain over the conventional QPSK at very low BERs, and at a BER of $10^{-3}$, the gain reduces to 1 dB, as was recently verified experimentally [5].

There are a number of ways of increasing the sensitivity further (without resorting to improved hardware), and they all involve increasing the dimensionality of the constellation. 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 generalized pulse-position modulation (PPM). PPM was discussed for optical lines already in [6] and more recently in [7, 8], and it is known to have good (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. [7]. In that work, it was demonstrated that 16-PPM combined with polarization-multiplexed QPSK (PMQPSK) can obtain an APE of $\gamma = 3$ dB of increased sensitivity over regular QPSK and PMQPSK. For quantum-limited coherent receivers, the sensitivity in photons per bit can then be directly obtained from the APE and the known sensitivity for QPSK. The purpose of this paper is to evaluate and compare the APE of known power-efficient 2-dimensional (2d) and 4d formats together with PPM. There are a few surprises, e.g., that QPSK and PMQPSK will no longer have equal performance under PPM. The PSQPSK format will again show better sensitivity than other 2d and 4d formats with PPM.

2. Modulation with PPM

The comparison of modulation schemes involves in general two main parameters; the spectral efficiency $SE$ and the APE $\gamma$, which equals the (low-BER) sensitivity gain over QPSK, transmitting the same data rate. In general, these
An attractive way of improving K-PPM is, as suggested in [7], by combining it with a more efficient modulation format $\mathcal{C}$. Specifically, a symbol from a $n$-dimensional $m$-ary constellation is 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 $SE = 2\log_2(mK)/(nK)$. The APE requires a bit more careful evaluation, as the minimum distance in the format can be given by the smallest of the distance within $\mathcal{C}$ and the “PPM distance,” which is $\sqrt{2E_s}$ for the smallest $E_s$ in $\mathcal{C}$. We have evaluated the $SE$ and the APE for some of the most straightforward generalizations of PPM, namely with QPSK, PSQPSK, and PMQPSK (which were demonstrated in [7]). 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 [4]. Just as in the conventional case without PPM, the PSQPSK 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” due to a constellation point near the origin [9].
We also acknowledge inspiring discussions with colleagues within the Chalmers FORCE center.

2.4 dB improvement over PMQPSK when used with 16-PPM.

Table 1: Parameters of PPM and generalized PPM.

<table>
<thead>
<tr>
<th>Format</th>
<th>Dimensionality $N$</th>
<th>Nbr. levels $M$</th>
<th>SE [b/symb/pol]</th>
<th>APE $\gamma$</th>
</tr>
</thead>
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<tr>
<td>$K$-PPM</td>
<td>$K$</td>
<td>$K$</td>
<td>$2\log_2(K)/K$</td>
<td>$\log_2(K)/2$</td>
</tr>
<tr>
<td>$K$-PPM-QPSK</td>
<td>$2K$</td>
<td>$4K$</td>
<td>$\log_2(4K)/K$</td>
<td>$\log_2(4K)/2$</td>
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<tr>
<td>$K$-PPM-PSQPSK</td>
<td>$4K$</td>
<td>$8K$</td>
<td>$\log_2(8K)/(2K)$</td>
<td>$\log_2(8K)/2$</td>
</tr>
<tr>
<td>$K$-PPM-PMQPSK</td>
<td>$4K$</td>
<td>$16K$</td>
<td>$\log_2(16K)/(2K)$</td>
<td>$\log_2(16K)/4$</td>
</tr>
</tbody>
</table>

3. Discussion and Conclusions

The paper confirms analytically the observation recently made in [7], 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 APE, are possible by replacing PMQPSK with a more power-efficient format. 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. The specific example of $16$-PPM at a PPM rate of $312.5$ Mbaud investigated in [7] illustrates this: PMQPSK gives $8$ bits per PPM symbol, thus in total $8 \times 0.3125 = 2.50$ Gb/s. If instead PPM-QPSK were used independently in both polarizations, one would have $6$ bits per polarization ($2$ QPSK and $4$ PPM) and thus $12$ bits per PPM symbol and a net bit rate of $12 \times 0.3125 = 3.75$ 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. As shown in [7], $16$-PPM-PMQPSK would require a bandwidth of $40$ GHz, and gain $3$ dB in sensitivity. Basic $16$-PPM would require $10$ GHz (or using polarized PPM, $5$ GHz would do), while gaining $3$ dB in sensitivity. For $16$-PPM-QPSK the bandwidth requirement is $20/3 = 6.67$ GHz, with a sensitivity gain of $4.8$ dB. Finally, the most sensitive format would be $16$-PPM-PSQPSK, with the best sensitivity gain of $5.4$ dB but also with the highest bandwidth requirement of $20/7 = 11.4$ GHz. These trade-offs are clearly illustrated in Fig 1 (a).

It should be noted that these sensitivity values are asymptotic, which means that slightly less improvement (especially for basic PPM which have many neighbors in signal space) can be expected at a finite BERs, such as the commonly used $10^{-3}$.

In conclusion, we have demonstrated and discussed the spectral efficiency vs. sensitivity trade-offs given by using PPM together with some standard 4d modulation formats. The most sensitive 4d format with PPM is PSQPSK, giving $2.4$ dB improvement over PMQPSK when used with 16-PPM.

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References