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Eight-Dimensional Modulation for Coherent Optical Communications

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Abstract. We propose several 8-dimensional modulation formats for coherent fiber-optic communications. For spectral efficiencies of 1.75 and 2 b/s/Hz/pol, the proposed modulations offer up to 1 dB gain over DP-QPSK.

1. Introduction

Since 4-dimensional (4D) modulation was investigated by Betti *et al.*[1] and more rigorously by Agrell and Karlsson[2,3], 4D formats have been extensively studied over the last few years. The 4D signal constellation can achieve substantial gains compared with conventional formats such as dual-polarization quadrature phase-shift keying (DP-QPSK) and 16-ary quadrature amplitude modulation (DP-16QAM). For example, polarization-switched QPSK (PS-QPSK)[4] and set-partitioned 128-ary QAM (SP-128QAM)[5] asymptotically achieve 1.76 dB and 2.43 dB gains, respectively. Even experimental studies have verified that the 4D formats can achieve up to 1 dB gain in the forward-error correction (FEC) limit regimes[6,7].

Although higher-dimensional modulations have been investigated for years[8,9], its application to optical communications has been limited to 4D case. In this paper, we are motivated to focus on evaluating the performance of 8D modulations because of their significant gain and their relative simplicity. We propose two different types, i) hyper-sphere diamond lattice E_8, which is the densest lattice[10] in 8D, and ii) hyper-cube lattice with parity. We show that both types can achieve up to 1 dB gain. We also discuss mapping 8D constellations onto 4D optical carriers. Through optical fiber link simulations of 50 spans, we show a significant advantage of our proposed 8D formats against conventional DP-QPSK or PS-QPSK.

2. Mapping high-dimensional constellations onto a 4D carrier

We first need to map the 8D orthogonal signal vector[8–10] onto the 4D optical carrier for practical use. We consider in-phase, quadrature, polarization, and time as orthogonal dimensions to do so. Some examples of

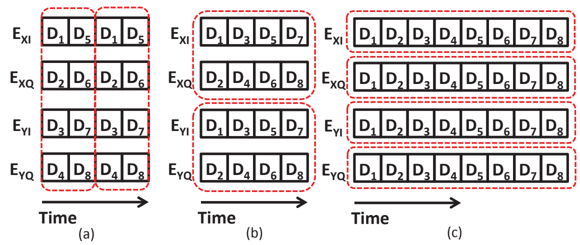

Fig. 1. Different mapping of 8D basis to 4D carrier using time domain.

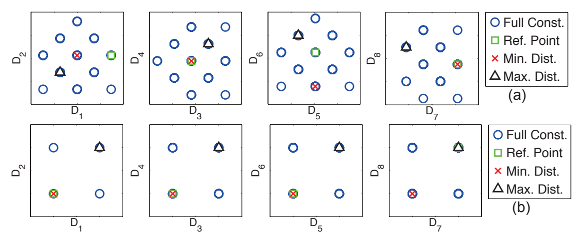

Fig. 2. 8D constellations: (a) 7b-8D sphere and (b) 7b-8D parity. Minimum and maximum Euclidean distance points compared to a reference point are also shown.

mapping are illustrated in Fig. 1. It is of course possible to use other orthogonal bases, such as different frequency domain subcarriers or spatial modes, to map multi-dimensional constellations.

As an example in this paper, we map eight-dimensional basis onto two adjacent 4D symbols in time, as shown in Fig. 1(a). Although different mappings may have different performance over nonlinear fiber channels, we leave the exhaustive study of mapping effects for future works.

3. Eight-dimensional modulation formats

To demonstrate the benefits of 8D modulations, we propose three different 8D constellations, and compare them with conventional DP-QPSK and PS-QPSK. Two modulations are based on spherical cutting[9] of the diamond E_8 lattice in 8D with 128 and 256 points, achieving 1.75 and 2 b/s/Hz/pol spectral efficiencies, respectively. These formats are referred

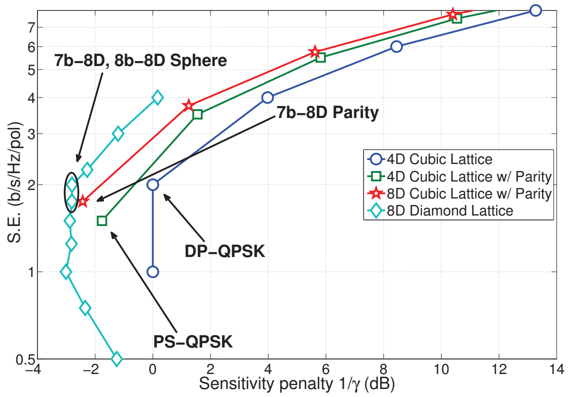

Fig. 3. Spectral efficiency and sensitivity penalty of 4 and 8-dimensional lattice constellations.

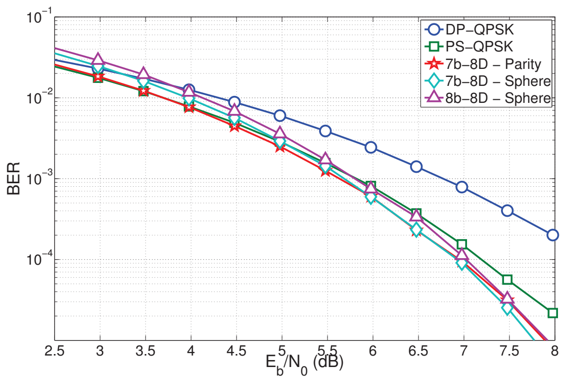

Fig. 4. BER performance of 8D and 4D formats in terms of E_b/N_0.

to as 7b-8D sphere modulation and 8b-8D sphere modulation. We also propose a 128-ary format based on 8D hypercube lattice, where 1 redundant bit is parity (this is analogous to SP-128-QAM and PS-QPSK), achieving 1.75 b/s/Hz/pol. This format is referred to as 7b-8D parity modulation.

Fig. 2 shows the proposed 7b-8D sphere and 7b-8D parity constellations. Constellations over time and polarizations are dependent such that the number of possible points is limited to 128. It is worth noting that the 7b-8D sphere constellation has 4 or 5 levels per quadrature, and would be relatively simple to generate in hardware. Similarly, 7b-8D parity modulation shown in Fig. 2(b) has only two levels per quadrature and could be generated using binary signals.

The asymptotic power efficiency[2] of these modulations is listed in Table 1. We also plot the asymptotic power efficiency of 8D lattice modulations[9] in Fig. 3 along with conventional 4D formats. Asymptotic power efficiency is a good indicator for block error rate performance, but not necessarily for BER performance, which relies on labeling[2]. The BER performance in additive white Gaussian noise (AWGN) channels are presented in Fig. 4. The results of gain over DP-QPSK are summarized in Table 1.

In general, the number of multipliers required for maximum-likelihood (ML) decisions is exponential with the spectral efficiency and dimensionality. However, study of demodulating high-dimensional lattices has yielded several low-complexity algorithms for ML decisions, some of which are multiplier-free[11].

4. Transmission simulation setup

For simulating transmission over fiber, we consider a 5-channel wavelength-division multiplexing (WDM) system with a channel spacing of 50 GHz and a data rate of 112 Gb/s per channel. Tx and Rx use 5^{th} order Bessel filters with 0.6 times signal bandwidth. The transmission link is 50 spans of standard single mode fiber (SSMF) with parameters of $D = 17$ ps/nm/km, $\gamma = 1.3$ /W/km, $\alpha = 0.2$ dB/km, and $S = 0$ without polarization mode dispersion. Nonlinear propagation was simulated using an adaptive step-size split-step Fourier method with the Manakov model. We assume either no inline optical dispersion compensation, or 95 % compensation per span before amplification using an ideal linear and lossless compensator. Noise loading was performed at the receiver assuming 50 inline amplifiers each with a noise figure of 5 dB. We use a data-directed adaptive equalizer with least-mean-square updating.

For evaluations, we use a performance metric of span-loss budget given by Poggiolini *et al.*[4] since sufficient error counting at the received optical signal-to-noise power ratio (OSNR) would not be possible due to the low BER regimes. A span-loss budget is calculated by a linear fit of Q-factor vs. span loss for a given target BER.

5. Simulation results and discussion

Fig. 5 shows the performance of the 5-channel WDM system over a 50-span link without inline dispersion compensation. Target BERs of 10^{-3} and 10^{-2} are shown, respectively corresponding to the BER limit of 7% overhead hard-decision and 20% soft-decision FEC. In the linear region, all 8D formats are comparable to PS-QPSK even though spectral efficiency increases from 1.5 to 1.75 or 2 b/s/Hz/pol. Comparing to DP-QPSK, one can see $0.2 \sim 1$ dB gains. In the

Table 1. Summary of performance for modulation formats considered in this work.

	DP-QPSK	PS-QPSK	7b-8D Parity	7b-8D Sphere	8b-8D Sphere
Number of modulation dimensions	4	4	8	8	8
Asymptotic power efficiency $1/\gamma$ (dB)	0	−1.76	−2.43	−2.81	−2.79
Spectral efficiency (b/s/Hz/pol)	2	1.5	1.75	1.75	2
E_b/N_0 gain vs DP-QPSK @ BER=10^{-3} (dB)	0	1.0	1.2	1.1	1.0
E_b/N_0 gain vs DP-QPSK @ BER=10^{-2} (dB)	0	0.6	0.6	0.3	0.2

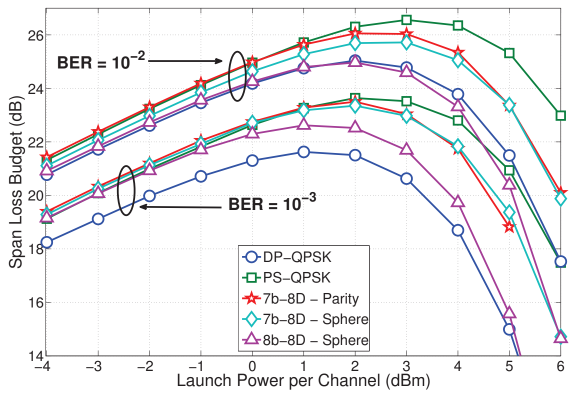

Fig. 5. Span loss budget for 50-span transmission link without inline dispersion compensation for target BERs of 10^{-3} and 10^{-2}.

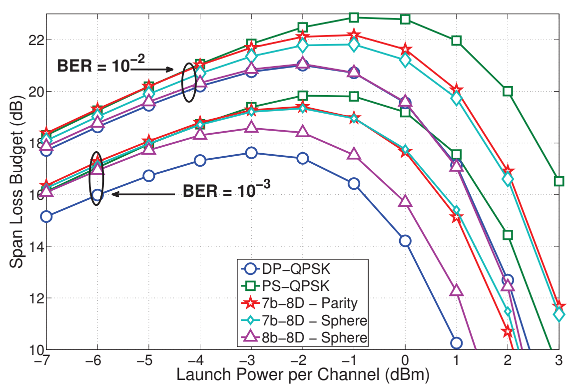

Fig. 6. Span loss budget for 50-span transmission link with 95% optical dispersion compensation per span for target BERs of 10^{-3} and 10^{-2}.

nonlinear region, the performance is better for modulations with broader spectra. 8b-8D sphere modulation has the same optimal launch power as DP-QPSK albeit with 1 dB higher margin, while 7b-8D sphere modulation and 7b-8D parity modulation offers approximately a 1 dB increase in optimum launch power, which is comparable to that of PS-QPSK. We speculate that this is due to the higher effective dispersion seen by the broader spectra[12], which in turn reduces signal auto-correlation and thus nonlinearity.

Fig. 6 shows the performance in 95% dispersion compensation per span. Although the optimal launch power is reduced for all modulation formats by approximately 4 dB, the comparative performance of the different formats remains the same. Note that in Figs. 5 and 6, the higher target BER results in an increase of optimum launch power by approx. 1 dB.

An attractive feature of the proposed modulations is the increased spectral efficiency compared to PS-QPSK. For a 112 Gb/s system, 7b-8D formats require 32 GHz of bandwidth, whereas PS-QPSK requires 37.3 GHz. At 124 Gb/s 7b-8D formats require 35.4 GHz whereas PS-QPSK requires 41.3 GHz. This reduction in bandwidth may be highly attractive in networks with reconfigurable optical add-drop multiplexers (ROADM), where improved performance at 100 Gb/s is desired, but filtering penalties reduce or even negate the advantages of PS-QPSK.

6. Conclusions

We have proposed 8-dimensional lattice modulations and compared them with DP-QPSK and PS-QPSK over a 50-span link with and without inline optical dispersion compensation. The proposed modulations outperform DP-QPSK in noise tolerance, with a slight or no loss in spectral efficiency. More importantly, the 8D constellations can offer almost comparable performance to PS-QPSK with higher spectral efficiency. This is particularly encouraging for their use at 100 Gb/s over ROADM networks, where filtering penalties are significant for PS-QPSK.

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