Coded Modulation for Next-Generation Optical Communications

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Abstract

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1. Introduction

As coherent optical communcation systems have moved beyond 100 Gb/s interface rates, strategies for coding and modulation have become increasingly sophisticated. The emerging fourth generation of coherent systems utilize complex digital signal processing (DSP) at both the transmitter and receiver [1], a wide variety of modulation formats [2], and SD-FEC with high gain [3]. In this environment, designers must find the remaining marginal performance gains as systems begin to approach their information-theoretic limits [4]. One such method for approaching the information-theoretic bounds is coded modulation: the joint-design of coding and modulation strategies for a given channel.

In this paper, we discuss different coded modulation strategies, with particular attention to constellation shaping. We examine the performance of numerically optimized geometric shaping with different optimization criteria and channels, and show that significant gains may be achieved by geometric shaping without significant increase in complexity compared with conventional square QAM systems.

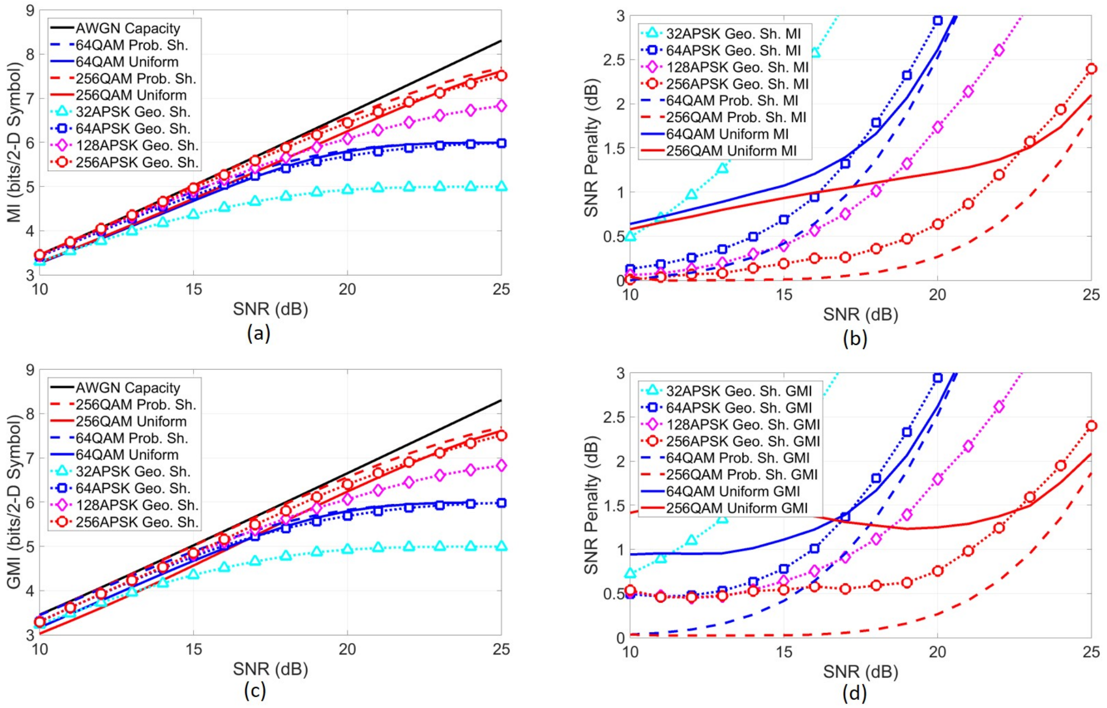
2. Coded Modulation

Coded modulation is considered to be the joint optimization of the coding and modulation schemes employed in a communcations system, for a given channel. While multi-dimensional modulation [5], optical nonlinearity tolerant modulation [6] and other topics have been of significant interest in the optical communications literature recently, constellation shaping is currently the topic of much study [7–11]. The fundamental principal of constellation shaping is quite simple: for a given channel, there is a signal distribution which maximizes the achievable information rate. By optimizing the constellation, we are able to ‘shape’ the signal distribution in useful ways. The most commonly used channel for optical communications is the additive white Gaussian noise (AWGN) channel, which has an optimal signal distribution which is also Gaussian. In the asymptotically high SNR regime, the Gaussian distribution can achieve approximately 0.5 bits/2-D symbol (equivalent to a 1.53 dB SNR gain) more than a uniformly distributed signal, which may be considered an upper bound on square QAM formats with symbol metric decoding.

Probabilistic shaping is one technique that has seen a significant interest recently. This technique requires that the equally probable source bits are mapped onto a set of un-equally probable symbols. As this means that different points in the constellation carry different amounts of information, bit mapping and demapping is a significant challenge. This is often achieved by mapping a sequence of bits into a sequence of symbols, which contains the correct probability distribution of symbols per sequence. Until recently, the demapping part of this system was considered prohibitively complex, due to the need to estimate sequence likelihoods with thousands of elements. ‘Reverse concatenation’ [13] enables the use of an FEC decoder before the shaped symbol sequences are demapped into bits, therefore solving the crisis of complexity in symbol demapping. However, hardware implementation of the distribution matcher remains a significant challenge [14].

3. Geometric Constellation Shaping

Geometric shaping involves un-equally distributing a number of equally probable constellation points in the signal space such that the overall distribution approaches the desired one. While this technique has also been of some interest in the optical communications literature recently [9–11], it is widely considered to have inferior performance compared to probabilistic shaping at equal cardinality and complexity. In order to maintain low complexity, we require that the



(a)

(b)

(c)

(d)

Fig. 1. AWGN performance of square QAM and shaped formats showing (a) MI vs SNR; (b) SNR penalty compared to the Shannon bound for MI optimized formats; (c) GMI vs SNR; (d) SNR penalty compared to the Shannon bound for GMI optimized formats.

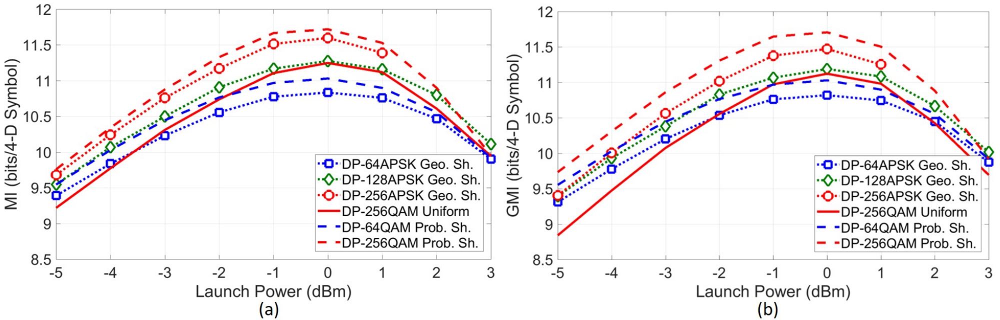
cardinality of the modulation format be as low as possible, therefore reducing coding overhead. Symmetry in the constellation can also be used to reduce the number of parameters to be optimized in the design process.

In this work, we use a constellation based on amplitude and phase shift keying (APSK) [12], and numerically optimize the distribution of the amplitude levels to maximize performance given a channel and some performance metric such as mutual information (MI) – which bounds performance for a code with cardinality equal to that of the modulation (symbol metric decoding), or generalized mutual information (GMI) – which bounds performance with a binary code without decoder–demapper iteration (bit metric decoding). We assume a constant number of phase levels on each of the amplitude rings, and a Gray labeling in the amplitude and phase domains when bit metric decoding is considered.

4. Simulation Results

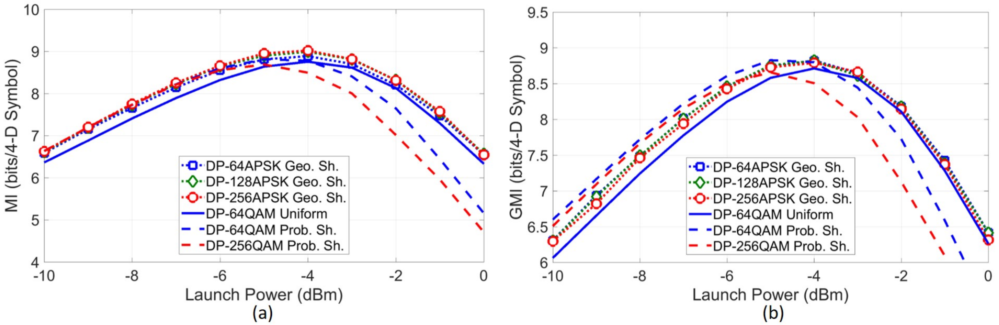
We compare the MI performance over the AWGN channel for uniformly distributed square QAM formats, square QAM formats probabilistically shaped with Maxwell-Boltzmann distributions, and geometrically shaped APSK formats in Fig. 1. We note from Fig. 1(a), that both probabilistically and geometrically shaped constellations approach the AWGN capacity, although for a given cardinality and SNR, probabilistic shaping can achieve a higher rate than that of geometric shaping, while uniform QAM is inferior at all but the highest SNRs. Fig. 1(c) shows the GMI performance of the shaped and uniform QAM constellations. We note from Fig. 1(c) that the performance of probabilistically shaped QAM can closely approach the AWGN capacity, even with bit metric decoding. In fact, the penalty for bit metric decoding compared with symbol metric decoding is extremely small – less than 0.05 bits/2-D symbol in all cases. As can be seen from Fig. 1(d), the performance of the geometrically shaped constellations is reduced by around 0.5 dB compared with the AWGN capacity. While this is a significant impairment, we note that over the range of SNR and cardinality considered, gain over square QAM is at least 0.5 dB.

Fig. 2 shows the performance of the shaped formats when transmitted over an optical link consisting of 20×80 km of standard single mode fiber (SSMF), with Erbium doped fiber amplifiers (EDFAs) showing (a) MI, and (b) GMI. A single channel was transmitted, at a symbol rate of 34 GBd, and detected using an ideal receiver without DSP. To optimize the performance of probabilistically shaped QAM, we use the estimated SNR from the transmission of uniform QAM at the same cardinality and power to select the optimal Maxwell-Boltzmann distribution. We note that for MI optimized modulation, at the optimal launch power, geometric shaping can achieve a gain of 0.35 bits/4-



(a) (b)

Fig. 2. Transmission performance over a 20 × 80km SSMF only link of square QAM and shaped formats showing (a) MI performance; (b) GMI performance.



(a) (b)

Fig. 3. Transmission performance over a 20 × 80km NZ-DSF link with 95% inline CD compensation, of square QAM and shaped formats showing (a) MI performance; (b) GMI performance.

D symbol compared with DP-256QAM while probabilistic shaping can achieve 0.5 bits/4-D symbol. For the GMI optimized modulation, probabilistic shaping exhibits a gain of 0.55 bits/4-D symbol, while the geometrically shaped constellation shows a gain of 0.35 bits/4-D symbol. These results fall broadly inline with previously reported results on the achievable performance gains from probabalistic shaping [7].

Fig. 3 shows the performance of the shaped formats when transmitted over an optical link consisting of 20 × 80 km of non-zero dispersion shifted fiber (NZ-DSF), with EDFA amplification and 95% inline optical compensation of chromatic dispersion showing (a) MI, and (b) GMI. We note from (a) that MI optimized probabilistic modulation shows no gain over uniformly distributed DP-64QAM, while geometrically shaped modulation exhibits a gain of 0.25 bits/4-D symbol. From (b) we note that both probabilistically and geometrically shaped constellations achieve a GMI gain of 0.15 bits/4-D symbol compared with DP-64QAM. While the use of Maxwell-Boltzmann distributions derived from SNR estimates from uniform QAM transmission may be pessimistic for this transmission scheme, [15] showed that the use of such a scheme could be suboptimal by only a small amount in an unrepeated link with low total accumulated dispersion.

5. Conclusions

We have compared the performance of geometrically and probabilistically shaped constellations with that of regular square QAM modulation. We have noted that while probabilistic shaping has superior performance, geometric shaping can also achieve good performance gains. We note in particular that geometric shaping with bit metric decoding can achieve at least half of the gain available, while maintaining low complexity.

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