Revisiting Probabilistic Constellation Shaping in Unamplified Coherent Optical Links

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Abstract: Considering an unamplified 400ZR-compatible system, we experimentally demonstrate that the reverse Maxwell-Boltzmann distribution significantly enhances PCS performance. With bit-rate adaptation down to 250 Gbps, we find power budget gains of more than 2 dB. © 2023 The Author(s)

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1. Introduction

With the increasingly higher data rate demands being imposed on optical links, the search for cost- and power-efficient systems intensifies. In short-reach applications, such as datacenter interconnects, the power-hungry optical amplifiers can be removed to achieve these goals. Recently, coherent unamplified links have been standardized in 400ZR [1], in which probabilistic constellation shaping (PCS) is also included. In the recent years, PCS has seen a boost in its popularity due to its data rate flexibility and shaping gain [2]. However, its use in unamplified systems (which are governed by a peak-power constraint) is still problematic, both in coherent [3] and intensity modulation and direct-detection (IM-DD) systems [4], due to its increased peak-to-average power ratio (PAPR). We have previously demonstrated that PCS based on a Maxwell-Boltzmann (MB) distribution is beneficial to unamplified coherent systems only if low shaping is applied [3]. However, PCS can be achieved through a wide range of probability distribution functions (PDF). A particularly interesting PDF is the reverse MB (rMB) distribution, which is achieved by substituting the exponential argument with its symmetric in [2, (4)], and can still be implemented through probabilistic amplitude shaping (PAS) [5]. By implementing an rMB-based PCS, we can take advantage of the data rate flexibility, while reducing the impact of the increased PAPR inherent to MB-based PCS, since higher probability is allocated at higher-amplitude symbols. In [5], both MB and rMB distributions are experimentally compared in an optically pre-amplified IM-DD system, and [6] demonstrates a gain of 0.05 bits/channel use in 4-PAM with an optimized PCS targeted at unamplified IM-DD systems. The question then remains on whether PCS achieved through a rMB distribution can indeed be beneficial to unamplified coherent optical systems.

In this work, we experimentally compare the performance of MB and rMB-based PCS to uniform quadrature amplitude modulation (QAM) formats in a coherent unamplified link at 60 Gbaud. Starting from a baseline 400ZR-compatible configuration (uniform 16QAM at 60 Gbaud), we show that the rMB distribution can indeed provide the bit-rate adaptability feature of PCS without the high penalty caused by the MB distribution in peak-power constrained systems.

2. Experimental Setup, Digital Signal Processing and Performance Metrics

Figure 1 shows the experimental setup. The 60 Gbaud signals are generated at the transmitter-side digital signal processing (DSP) block using a root-raised cosine (RRC) filter with a roll-off of $\alpha = 0.1$. The signal is sent

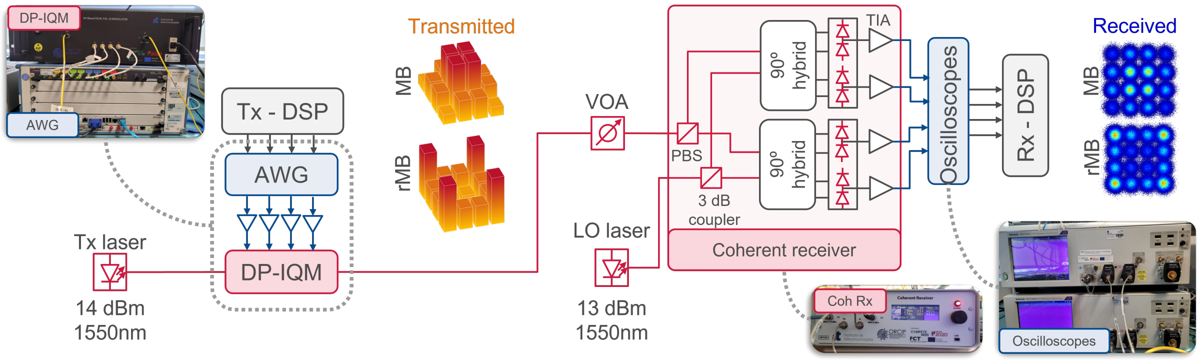

Fig. 1: Diagram of the experimental setup and transmitted and received MB and R-MB 16QAM constellations 380 Gbit/s at 1 dB link loss.

to the 120 Gsa/s arbitrary waveform generator (AWG) with ∼45 GHz analog bandwidth. The electrical signal is then amplified by four radio-frequency (RF) drivers with 23 dB gain and sent to a dual-polarization IQ modulator (DP-IQM), with 35 GHz bandwidth. The optical carrier is generated by a tunable laser source (TLS) operating at 1550 nm and 14 dBm with 100 kHz linewidth. Assuming unamplified single-span transmission (and perfect chromatic dispersion compensation at the receiver), we emulate the practical link loss by using a variable optical attenuator (VOA). At the coherent receiver with a bandwidth of 40 GHz, a TLS is used as local oscillator (LO) at 1550 nm with 100 kHz linewidth and 13 dBm. Four 33 GHz bandwidth oscilloscope channels digitize the signal at 100 Gsa/s. The receiver-side DSP applies the Gram-Schmidt orthonormalization algorithm, constant modulus algorithm (CMA), frequency recovery and a first stage of pilot-based carrier phase estimation (CPE), followed by a 4×4 least-mean squares (LMS) equalizer and a final stage of CPE. We define the net bit rate as $R_b = 2\times R_{\text{FEC}}\times R_{\text{s}}\times\log_2(M)$, where R_{FEC} represents the forward error correction (FEC) rate, R_{s} represents the gross symbol rate, which is 60 Gbaud, and M is the constellation size. Unless otherwise specified, $R_{\text{FEC}} = 5/6$. The system performance is primarily evaluated through the normalized generalized mutual information (NGMI). Then, by sweeping the optical attenuation imposed by the VOA, we estimate the maximum supported link loss that allows to achieve a given threshold NGMI, which assuming ideal FEC is directly given by $\text{NGMI}_{\text{th}} = R_{\text{FEC}}$ [2]. We refer to this maximum supported link loss as the power budget of the unamplified coherent system.

3. Experimental Results

For the experimental assessment, we will consider 3 different modulation options: i) a baseline uniform 16QAM yielding a net bit-rate of 400 Gbps, ii) a PCS-16QAM solution that provides bit-rate adaptability towards lower bit-rates, i.e. in the range of [250, 400[Gbps, and iii) a PCS-36QAM solution that provides bit-rate adaptability over a wider range of bit-rates in the interval of [250, 500] Gbps. In addition, for all PCS-modulated signals we consider two variants: i) the regular MB distribution that is optimal and widely used in amplified (average power constrained) AWGN systems and ii) the reverse MB (rMB) distribution, aimed at improving the PCS performance in the unamplified (peak power constrained) system under test. In all cases, the symbol-rate will be fixed at 60 Gbaud.

Figures 2a – 2d show the probability distribution of the transmitted MB-based and reverse MB-based constellations at a given 300 Gbps net bit-rate, for both 16QAM (a and b) and 36QAM (c and d). Since, in rMB, higher probability is attributed for higher amplitude symbols, its peak-to-average power ratio (PAPR) is lower than that of MB-based PCS. For the illustrated constellation examples at 300 Gbps, it is worth noting a reduction of 3.3 dB and 4.6 dB for the 16- and 36QAM constellations, respectively. Because there is no optical amplification, the transmitted optical power increases proportionally to this PAPR reduction. On the other hand, the rMB distributions are also less power efficient (the average energy of the constellation is higher), which will lead to a tradeoff between SNR improvement due to PAPR reduction and SNR degradation due to the average energy increase.

In order to settle the debate of whether the rMB produces an overall gain for unamplified links, we now proceed with the experimental performance analysis of these different PCS options. The NGMI performance of the system is shown in Figs. 2e and 2f for 8 and 10 dB link loss, respectively, for constellation sizes of 16 and 36, and for both distributions, and also depicting the performance for uniform 16QAM at 400 Gbit/s, as a reference. Owing to its lower PAPR, and consequent higher average energy, the rMB outperforms the legacy MB distribution. For the same reason, it is also critical to always use the smallest possible constellation template that optimizes the PAPR/energy tradeoff of the transmitted signal, and thus we observe that for the range of 250–400 Gbps, PCS-16QAM is the preferred choice. Nevertheless, if some bit-rate adaptability is desired above the 400G nominal bit-rate, rMB-PCS36QAM provides a viable solution.

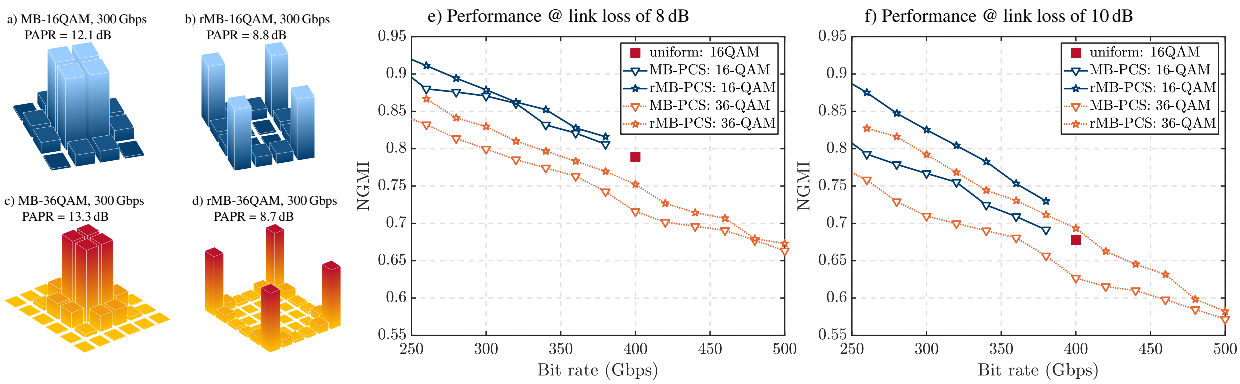

Fig. 2: PCS symbol probabilities of a), c) MB and b), d) reverse MB distributions, for a), b) 16QAM and c), d) 36QAM at 300 Gbps. Performance at varying bit rate for PCS- 16QAM and 36QAM, at a link loss of e) 8 dB and f) 10 dB.

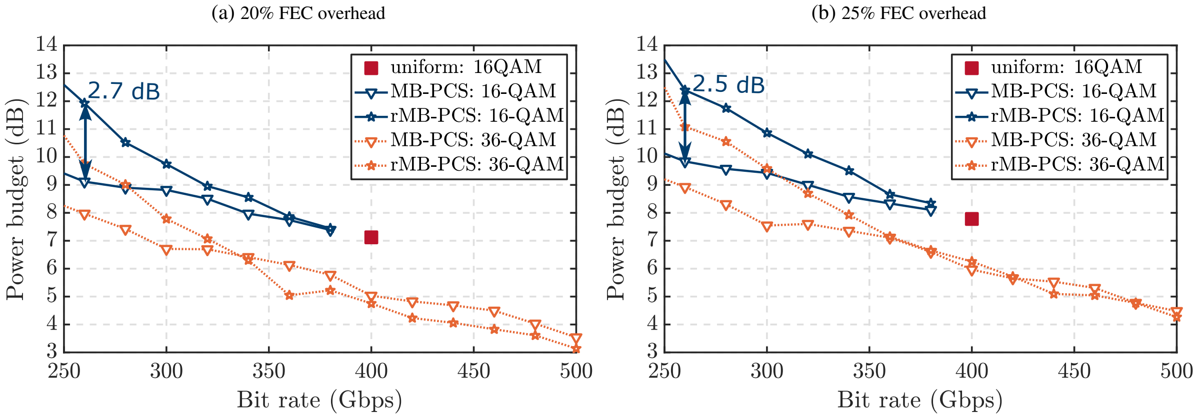

Fig. 3: Achievable power budget with varying bit rate, for 16 and 36QAM, considering a) 20% FEC overhead and b) at 25% FEC overhead.

By repeating the analysis of Figs. 2e and 2f while sweeping the optical link loss from 1 dB up to 15 dB (roughly corresponding to SMF span lengths of 5 km to 75 km) in steps of 1 dB, we have then estimated the maximum supported link loss (i.e. power budget) of the unamplified system, considering two FEC rate options: i) $R_{\mathrm{FEC}} = 5/6$, corresponding to 20% overhead and ii) $R_{\mathrm{FEC}} = 4/5$, corresponding to 25% overhead. The obtained results are shown in Figs. 3a and 3b, respectively. Therein, we can observe that, at lower bit rates, i.e., higher shaping, rMB largely surpasses the MB distribution due to its lower PAPR, e.g. yielding a power budget increase exceeding 2 dB at 260 Gbps between rMB-16QAM and MB-16QAM for 20% FEC overhead. This power budget gain decreases as we move towards uniform constellations, since both probability distributions are converging to the same solution. Similarly to the previous NGMI-based analysis, we generally find that, for a given desired bit-rate, we should always design the PCS signal with the lowest possible template size (16QAM for bit-rates below 400 Gbps and 36QAM above), together with the rMB distribution in detriment of the standard MB distribution. Despite some 0.5–1 dB performance offset, the same general trends and conclusion can be extracted for the two considered FEC overheads of 20% and 25%.

4. Conclusions

Triggered by the need to minimize power consumption and cost, unamplified coherent transmission is currently being considered for the next generation of high-capacity short-reach transceivers. Whereas uniform modulation has been found to be adequate for this kind of systems [7], the bit-rate adaptability provided by PCS is threatened by its high PAPR, severely limiting the performance of unamplified coherent transmission, which is governed by a peak-power constraint. Following this challenge, in this work we have demonstrated that the feature of bit-rate adaptability can still be preserved for these low-power systems provided that the PCS distribution is properly adjusted. Using a low-PAPR reverse MB distribution, we have shown that it is possible to achieve a wide range of bit-rate adaptation (from 250 Gbps up to 500 Gbps in this work) while avoiding the inherent penalty of the standard MB distribution. When adapting the system towards lower bit-rates, we have found power budget gains in excess of 2 dB, which validate the benefit of the reverse MB distribution for flexible unamplified coherent optical systems.

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