Hybrid probabilistic-geometric shaping in optical communication systems

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Abstract— We propose a universal distribution matcher applicable to any two-dimensional signal constellation. We experimentally demonstrate that the performance of the proposed 32-ary quadrature amplitude modulation (QAM), based on hybrid probabilistic-geometric shaping, is superior to probabilistically shaped (PS)-32QAM and regular 32QAM, and comparable to PS-64QAM.

Keywords— *distribution matcher, geometric shaping, probabilistic shaping, QAM.*

I. INTRODUCTION

Geometric shaping (GS) and probabilistic amplitude shaping (PAS) have been extensively studied to bridge the gap to the Shannon limit [1-4]. GS scheme suffers non-Gray mapping penalty when binary forward error correction (FEC) codes are applied [1]. PAS scheme can only be used for square quadrature amplitude modulation (QAM), which greatly limits its application [2]. Although the performance of PAS-64QAM in principle is able to approach the Shannon limit, its implementation penalty is not clear in experiments.

In this invited paper, we describe a two-dimensional (2D) distribution matcher (DM) [5,6], i.e., arbitrary probabilistic shaping (APS). Generalized pair-wise optimization (GPO) algorithm is applied here to obtain an optimized 32-ary signal constellation, named here opti-32QAM, which is enabled by the hybrid PS and GS schemes. In our experiment, we find that the performance of opti-32QAM is comparable to that of the PS-32QAM, and better than regular 32QAM by 0.9 dB, when capacity is 3.33 bits/symbol (b/s). In case of 4 b/s, opti-32QAM outperforms PS-32QAM and regular 32QAM by 0.2 dB and 0.7 dB, respectively. Additionally, the performance the opti-32QAM is comparable to PAS-64QAM.

II. UNIVERSAL PS SCHEMES

Fig. 1 shows the proposed APS-MQAM scheme. The symbols generated by the DM do not yield M-B distribution. The information bits obtained from bit labeling are used to generate the parity-check bits. After the bit-to-symbol mapping, the parity-check bits will be mapped to N -ary QAM (NQAM) symbols, where N is the largest power of 2 to contain the MQAM constellation points with the target probabilities of $> (1 - R)/M$. Assuming the target probability distribution of the MQAM symbols is $P_M(x)$, the distribution of the MQAM symbols after DM is $P_D(x)$, and the NQAM probability distribution is $P_N(y) = 1/N$, so that the overall relationship among them can be represented as,

$$P_M(x) = \frac{RP_D(x)/\log_2(M) + (1-R)P_N(y)/\log_2(N)}{R/\log_2(M) + (1-R)\log_2(N)} \quad (1)$$

If $N = M$, we have that $P_M(x) = RP_D(x) + (1 - R)/M$. Therefore, the target distribution of MQAM can also be achieved after the binary FEC coding.

III. EXPERIMENTAL DEMONSTRATION

The diagram of the experimental setup is depicted in Fig. 2. The GPO algorithm is used for the generation of the hybrid PS/GS 32QAM (opti-32QAM) [7]. The resulting constellation diagram of the opti-32QAM is shown in the inset of Fig. 2(a). At the transmitter, the binary data is mapped to the symbol sequence via the 2D DM. After the bit labeling, low-density parity check (LDPC) encoding, and bit-to-symbol mapping, as described in Fig. 1, the digital symbols are pulse-shaped by a 92 G Sa/s arbitrary waveform generator (AWG) to generate 40G Baud electrical signals. Such signals are modulated by a polarization multiplexed (PM) I/Q

Fig. 1. Universal PS schemes based on APS.

Fig. 2. Experimental setup.

Fig. 3. The measured post-FEC BER versus SNR for various QAM formats, in cases of: (a) $C=3.33$ b/s and (b) $C=4$ b/s.

modulator, and the resulting 40G Baud PM-MQAM optical signal is mixed with the amplified spontaneous emission (ASE) noise, and filtered out by an optical tunable filter (OTF). After coherent detection, the signals are digitized by a real-time oscilloscope for off-line processing. The LDPC decoder performs the sum-product algorithm, followed by the bit-error rate (BER) measurements. The DVB-S2 irregular LDPC codes are used for channel coding. For a fair comparison, the performances of the MQAM formats are compared under the same capacity, which is defined as $C =$

$H(p) - m(1 - R)$, where $H(p)$ represents the entropy of the PS-MQAM, $m = \log_2(M)$, and R is the code rate of the DVB-S2 irregular binary LDPC codes.

Fig. 3 shows the BERs versus SNR performance. When the C is 3.33 b/s, the performance of opti-32QAM is similar to that of the PS-32QAM, and better than regular 32QAM by 0.9 dB in the waterfall region. In case of $C=4$ b/s, opti-32QAM outperforms PS-32QAM and regular 32QAM by 0.2 dB and 0.7 dB, respectively, at the BER of 10^{-4} . In addition, PAS-64QAM is measured to have less than 0.1 dB SNR advantage over opti-32QAM in cases of $C=3.33$ b/s and 4 b/s.

IV. CONCLUDING REMARKS

Two universal DMs have been proposed and used to generate hybrid PS/GS 32QAM and PS-32QAM formats. Our results have shown that the proposed hybrid GS/PS 32QAM could outperform PS-32QAM and regular 32QAM, meanwhile being comparable to PAS-64QAM.

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