

Demonstration of Hybrid Probabilistic Geometric Shaping 64QAM Optical Fiber Transmission Using Optimized Constellation for MAP Detection with Hard Decision Decoding

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Abstract— We propose the optimized HPGS-64QAM constellations for hard decision decoding and experimentally verify the performance with optical fiber transmission. The proposed HPGS-64QAM constellations outperform the regular PS-64QAM in all ranges of entropy.

Keywords— Geometric shaping, probabilistic shaping, coherent optical transmission

I. INTRODUCTION

In modern coherent optical transmission systems, coded modulations (CMs) which is a combination of forward error correction (FEC) and high-order QAM format, has been paid attention to increase a spectral efficiency (SE) and get closer to the Shannon's limit. In particular, constellation shaping (CS) techniques are actively discussed. Two principles of shaping techniques are proposed, the probabilistic shaping (PS) and the geometric shaping (GS), respectively [1]-[2]. Recently, the hybrid PS/GS (HPGS) are also proposed, and the shaping gain is verified [3], although the performance is similar to PS. With the shaping, the constellation is designed to optimize information metrics such as pre-FEC bit error rate (BER) and generalized mutual information (GMI), which are the metrics in systems employ hard-decision (HD) FEC and soft-decision (SD) FEC, respectively [4]. CS with SD-FEC has been commonly used to increase the SE in long-haul transmission systems since it has better net coding gain than HD-FEC [4]. However, it also introduces the increase of the decoding complexity and power consumption [5]. Recently, CS with HD-FEC has experienced a revived attention thanks to the appearance of very powerful HD-FEC schemes, such as staircase codes [5]. Therefore, HD-FEC can be appealing alternative even in long-haul transmission systems.

Considering long-haul transmission systems utilizing CS with HD-FEC, the constellation shape should be designed to

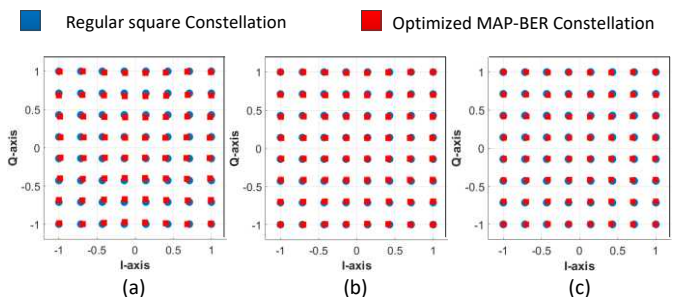


Figure. 1 R-64 and optimized MAP-64 constellations for (a) $H(P) = 3.5$, (b) $H(P) = 4.0$, and (c) $H(P) = 5.0$ bit/symbol.

minimize pre-FEC BER, since it determines the achievable information rate. The optimized GS and PS assuming HD-FEC have been reported [5]. However, to date, there is no reports about the design of the optimized HPGS assuming HD-FEC.

In this paper, we design the optimized HPGS-64QAM constellations for assuming hard decision decoding (HDD) and HD-FEC at the specific given signal to noise ratio (SNR) and entropies $H(P)$. With the optimized constellations, we experimentally verify the performance in the fiber transmission. The performance of the proposed constellations is slightly better than the regular PS-64QAM.

II. DESIGN OF OPTIMUM HPGS-64QAM MAP CONSTELLATIONS

In transmission systems with HD-FEC, transmitted QAM symbols are estimated symbol-by-symbol (i.e., hard decision) from received symbols based on maximum likelihood (ML) estimation [4]. In the ML decision, the symbol which is closest to a received symbol is regarded as the transmitted symbol. On the other hand, in transmission systems utilizing PS with HD-FEC, the decision is made by maximum a posteriori probability (MAP) estimation rather than ML estimation [6]. The MAP decision takes into account a priori probability of the PS, which

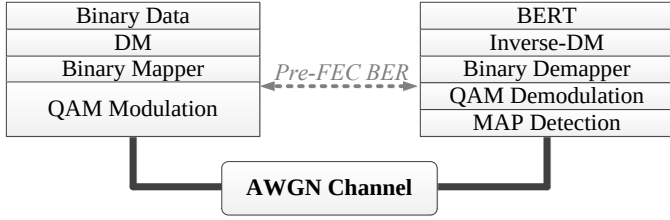


Figure 2 Simulation block diagrams

results in more reliable estimation. Hereafter, we call a pre-FEC BER after the ML and MAP decision as ML-BER and MAP-BER, respectively. Considering the MAP decision, the decision threshold between any 2 symbols x_i and x_j on the QAM constellation can be calculated as

$$TH_{x_i, x_j} = \frac{x_i + x_j}{2} + \frac{\sigma^2 \ln(P_X(X=x_i)/P_X(X=x_j))}{x_i - x_j}, \quad (1)$$

where $P_X(X = x_i)$ is the probability of the transmitted symbol x_i , and σ^2 is the noise variance. Obviously, if the constellation is not probabilistically shaped and the probability of the transmitted symbol are uniform, the second term will disappear, and the MAP decision threshold becomes as same as the ML decision threshold. Then, the MAP-BER is calculated by

$$BER = \sum_{j=1}^N \sum_{i=1}^N \left(P_X(X = x_i) \cdot \frac{1}{2} \operatorname{erfc} \left(\frac{TH_{x_i, x_j}}{\sigma} \right) \right) \times \frac{h(x_i, x_j)}{M}. \quad (2)$$

Note that $h(x_i, x_j)$ is the Hamming distance between x_i and x_j , and M represent total bit in one QAM symbol. The MAP-BER in Eq. (2) becomes ML-BER when we neglect the 2nd term in (1). Similar expressions of Eq. (1) and (2) can be seen in [7]. In this work, we designed the optimized constellations for HPGS-64QAM (MAP-64) at given SNR and $H(P)$ by using the GPO algorithm [8], considering MAP-BER as the cost function. Fig. 1 shows the MAP-64 in comparison with regular squared PS-64QAM constellation (R-64). The MAP-64 constellations were designed to minimize the MAP-BER. Fig. 1 (a)-(c) show different target entropies of $H(P) = 3.5, 4.0$, and 5.0 bit/symbol. All constellations are normalized to have the maximum amplitude equal to 1. These constellations are designed to achieve the maximum shaping gain assuming the 20% of forward-error correction overhead (FEC-OH) threshold at pre-FEC BER = 0.01. We can see that the heavily shaped constellations can be seen when low $H(P)$ is used. Since the shaped constellation are symmetrical in all 4 quadrants, it is able to use the probability governed by two-dimensional Maxwell Boltzmann (2D-MB) distribution and the 2D distribution matcher (DM) based probabilistic fold shaping (PFS) technique to realize HPGS signal generation [3].

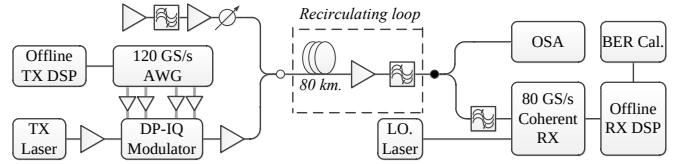


Figure 3 The experimental setup.

TABLE 1. COMPARISON OF PS-64QAM AND HPGS-64QAM

Implementation	Constellation Shaping	
	PS-64QAM	HPGS-64QAM
Constellation diagram	Regular square QAM with uniform grid	Non-square QAM with non-uniform grid
Signal probability	Non-uniform	Non-uniform
Probabilistic shaping scheme	1D-shaping	2D-shaping
Distribution Matcher	1D-MB DM	2D-MB DM

III. SIMULATION AND EXPERIMENTAL DEMONSTRATION

To evaluate the performance of the proposed constellation, we performed the Monte Carlo simulation under AWGN channel using MATLAB. The block diagrams are shown in Fig. 2. The binary sequence was probabilistically shaped by using two-dimensional Maxwell Boltzmann (2D-MB) distribution and the 2D distribution matcher (DM) based probabilistic fold shaping (PFS) technique [3] with a block-length larger than 10,000. The shaped amplitude signals were modulated with QAM modulator using the optimized MAP-64 constellation to obtain HPGS-64QAM signal whereas the conventional QAM modulator with R-64 constellation were used to obtain PS-64QAM signal. The differences between PS-64QAM and HPGS-64QAM are shown in Table 1. All pre-processing HPGS signals were passed through AWGN channel. The transmitted symbols were estimated from received symbols by MAP detectors based on (1) and the pre-FEC BER was calculated over $3 \times 200,000$ symbols. The simulation results will be shown later.

The experimental setup to generate dual polarization (DP) HPGS-64QAM is shown in Fig. 3. The HPGS signal was pre-prepared the same as the simulation. A header of 1024 QPSK pilot symbols was placed before a frame of 65536 HPGS-64QAM symbols. In addition to this, pilots were added at a rate of 1/32 for carrier phase recovery. The sequence was up-sampled and pulse-shaped with a root raised cosine filter with a roll-off factor of 0.01. The electrical 30 GBd HPGS-64QAM signal was generated by a 120 GSa/s arbitrary waveform generator (AWG). Then the signals were fed into DP-IQ modulator with the low linewidth external cavity laser (ECL) to create 30 GBd DP-HPGS-64QAM optical signals. The amplified spontaneous emission (ASE) noise is loaded by using an Erbium doped fiber amplifier (EDFA) to sweep the optical SNR, assuming AWGN channel. For the optical fiber transmission, an optical re-circulating loop which is consisted of

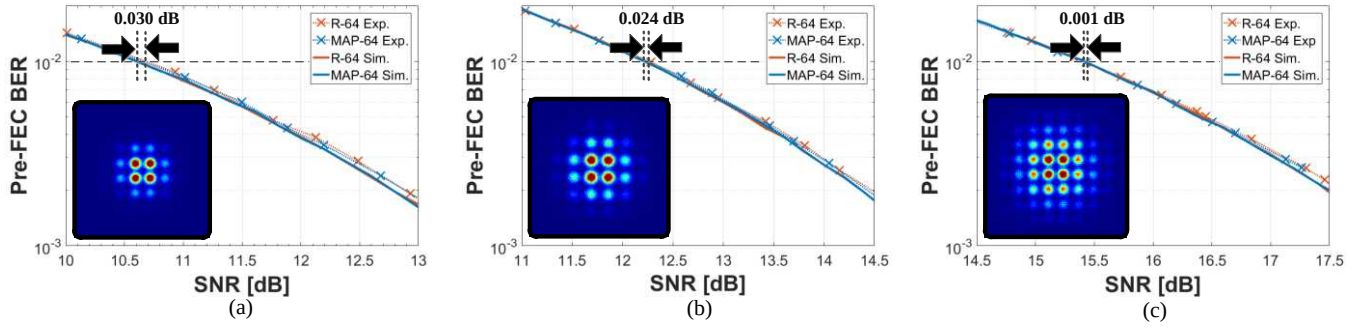


Figure. 4 Simulation and experimental results of the B2B case (a) $H(P) = 3.5$, (b) $H(P) = 4.0$, and (c) $H(P) = 5.0$ bit/symbol.

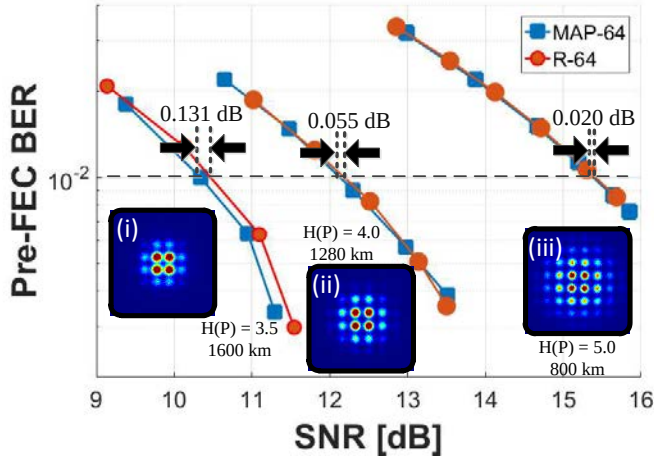


Figure. 5 Experimental comparison between MAP-64 and R-64 constellations in the optical fiber transmission.

an 80 km of a standard single-mode fiber (SMF), EDFA, and the optical band pass filter (OBPF), is used to investigate the performance under the ASE noise and fiber nonlinearity impairments as shown in the dashed box in Fig. 3. At the DP-coherent receiver, another ECL is used as the local oscillator (LO). The detected signals were digitized by an 80 GSa/s oscilloscope. After that, the signal distortions are equalized by using the pilot symbol digital signal processing (DSP) technique [9]. The transmitted symbols were estimated from received symbols by MAP detectors based on Eq. (1) and the pre-FEC BER was calculated over 6 trials with a total 374,976 symbols.

Firstly, we measured back-to-back (B2B) performances. Fig. 4(a)-(c) shows the pre-FEC BER of signal with $H(P) = 3.5$, 4.0, and 5.0 bit/symbol as a function of effective SNR. Both of the simulation and experimental results are shown. For each $H(P)$, the MAP-BER from PS-64QAM and the MAP-BER from HPGS-64QAM are plotted as R-64 and MAP-64, respectively. The simulation results show that the HPGS-64QAM can improve the pre-FEC BER than PS-64QAM. The shaping gains obtained by HPGS-64QAM in comparison with PS-64QAM are measured at 20% FEC-OH threshold. For $H(P) = 3.5$, 4.0, and 5.0 bit/symbol, shaping gains are 0.030, 0.024, and 0.011 dB, and the received signals obtained from MAP-64 are shown as

insets, respectively. The experimental results also confirm the simulation as shown in dashed lines in Fig. 4, respectively. Therefore, under AWGN channel using MAP detection, we can confirm that, the HPGS-64QAM can improve the performance over PS-64QAM, and the shaping gains are increased as the probability distribution function (PDF) is strongly shaped.

We measured the long-haul transmission performance. The pre-FEC BER characteristics are shown in Fig. 5. The received signals of MAP-64 constellations at pre-FEC BER threshold are shown as insets. The numbers of re-circulating loop are 20, 16, and 10 which is corresponding to distance of 1600, 1280, and 800 km, for $H(P) = 3.5$, 4.0, and 5.0 bit/symbol, respectively. For all cases, HPGS-64QAM has the better performance than PS-64QAM with the shaping gain of 0.131, 0.055, and 0.020 dB for $H(P) = 3.5$, 4.0, and 5.0 bit/symbol. As a result, the proposed HPGS-64QAM outperforms conventional PS-64QAM in fiber transmission using MAP detection.

IV. CONCLUSIONS

Constellations to minimize MAP-BER at specific SNR and $H(P)$ for pre-FEC BER at 0.01 with $H(P) = 3.5$, 4.0, and 5.0 bit/symbol for HPGS-64QAM under hard decision decoding with MAP detection were proposed. The Monte Carlo simulations under AWGN channel and experimental demonstration in back-to-back case were in agreement and shaping gain for HPGS-64QAM over PS-64QAM was found for all $H(P)$. The long-haul transmission of all proposed constellations was also conducted and showed that HPGS-64QAM outperformed PS-64QAM with maximum shaping gain of 0.131 dB for $H(P) = 3.5$ bit/symbol.

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