Optimization of Probability Mass Function for Complex Modulated Signals by Considering Noise Variance and Errors of the Received Symbols

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***Abstract*—We optimize the probabilistic shaping distribution by reallocating the symbol probability based on the performance of the training sequence constellation. The scheme is experimentally verified in a 40-km transmission system with 24 Gbaud 64-QAM signals.**

Keywords—probabilistic shaping, coherent system, quadrature amplitude modulation, probability mass function

I. Introduction

In recent years, probabilistic constellation shaping (PCS) has drawn extensive attention in optical communications [1, 2], especially for signals in advanced modulation formats such as quadrature amplitude modulation (QAM) signals. In addition to the flexibility of controlling the information capacity, PCS signals also offer a shaping gain. While reducing the entropy of the transmitting symbols, PCS signals can achieve a system performance better than that of uniformly distributed signals [3-5].

In an ideal additive white Gaussian noise (AWGN) channel, the mutual information of the channel will be maximized when the probability mass function (PMF) of QAM signals follows a standard Maxwell-Boltzmann (M-B) distribution [1]. However, the AWGN approximation may not be optimal in practical communication channels which suffer from residual nonlinear distortion, transceiver noise, as well as amplifier spontaneous emission noise. Under this circumstance, the constellation performance appears to be asymmetrical, and the standard M-B distribution is no longer the optimal one [6, 7]. It is unfortunate that asymmetric performance among the constellation points is difficult to model and characterize due to the complexity of its composition and the slightness of the asymmetry. Consequently, it is important to develop an approach to find a PMF with performance superior to that of the M-B distribution. The signal with new distribution should also cope with the asymmetric degradation.

In this paper, we develop a reallocation mechanism to generate a new distribution by utilizing a training sequence with standard M-B distribution. Two different parameters (noise variance and error number of each constellation point) are considered and evaluated during the verification. When compared with standard M-B distribution in a 40-km transmission system, the signal with a newly generated distribution achieved an average GMI improvement of 0.0630 (noise variance) and 0.0597 (error counting).

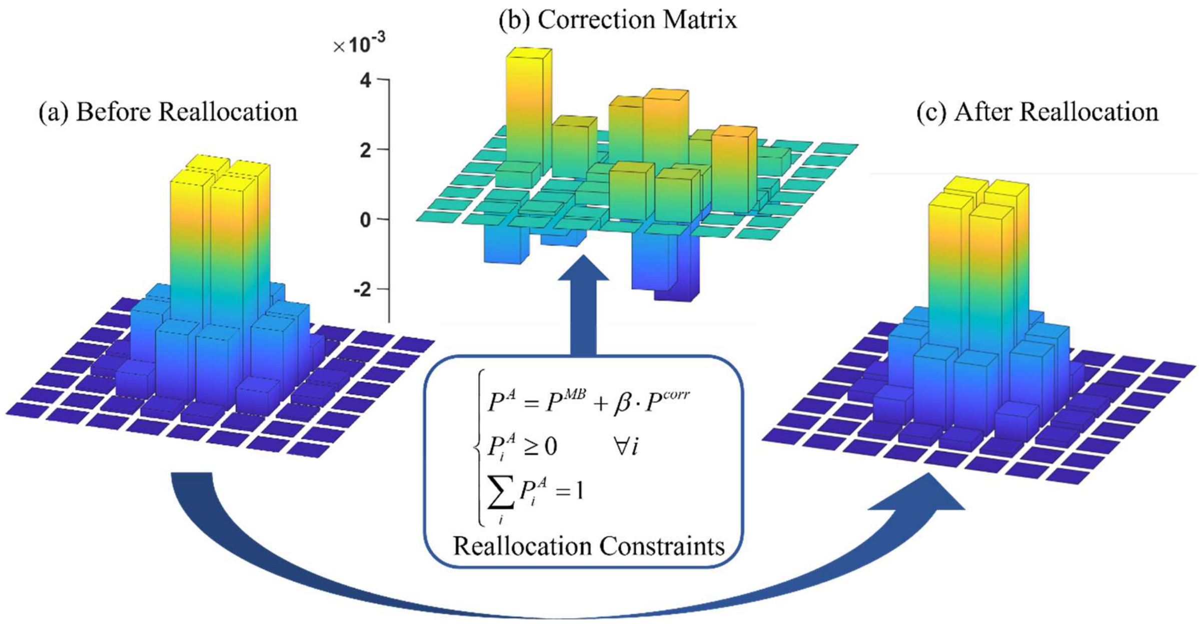

Figure 1. The concept and principle of PMF reallocation. (a) The PS distribution before PMF reallocation. (b) The generated correction matrix based on the reallocation constraints. (c) The PS distribution after PMF reallocation.

The average improvement in the total data rate is 1.5124 Gbit/s (noise variance) and 1.4321 Gbit/s (error counting), respectively. This reallocation mechanism is model-free and iterative-free with very low computational complexity. By characterizing the channel in terms of asymmetrical constellation performance, PMF reallocation provides an effective scheme to supplement the existing equalization algorithm. The proposed reallocation mechanism works jointly with the conventional nonlinear compensation algorithms, and copes with the asymmetric degradation in practical communication systems.

II. Principle and Experimental Setup

The principle of the PMF reallocation mechanism is illustrated in Fig. 1. The PS distribution before PMF reallocation is the standard M-B distribution, as shown in Fig. 1(a). The correction matrix that makes corrections to the M-B distribution is generated through the reallocation constraints, as shown in Fig. 1(b). The PS distribution after PMF reallocation is obtained by adding the correction matrix to the existing M-B distribution, as shown in Fig. 1(c). In the reallocation constraints, we denote P^{MB} as the standard M-B distribution before reallocation, and P^{A} as the PMF matrix after reallocation. P^{corr} is the correction matrix and is obtained through $P_i^{corr} = \bar{V} - V_i$, where V denotes the parameter matrix containing the noise variance or error number of each constellation. The reallocation constraints of P^{A} can be represented as shown in Fig. 1, where P_i^{A} is the probability of each constellation point after reallocation. The first constraint represents that P^{A} is obtained through the standard M-B distribution P^{MB} and the correction matrix P^{corr}. The parameter β is used to adjust the correction level. In the process of reallocation, β is maximized until P^{A} meets the limit of the second constraint. The second constraint ensures that each probability is larger than zero after correction. The third constraint ensures that the sum of all the probabilities is equal to 1. By solving these equations, we can generate new PMF after reallocation. It is worth noting that the generation of the correction matrix P^{corr} is performed ring by ring in the PCS 64-QAM constellation, as shown in Fig. 2. For each ring, different numbers of constellation points are taken into account when performing reallocation. By reallocating independently within each ring, the new PMF is of almost the same entropy and transmitted power as the original distribution.

The workflow of PMF reallocation is split into a few steps. First, we utilize a standard MB-distributed PS signal to conduct transmission and collect 20 sets of data at the receiver side (Rx-side). Based on the received signal, we generate a noise variance/error counting matrix from each set of data and calculate the average. We then perform PMF reallocation within each ring under the above-mentioned constraints. Subsequently, we conduct transmission again and evaluate the performance of the received signal in terms of GMI and NGMI. The reason we utilize GMI and NGMI for evaluation simultaneously is because the entropy of the newly generated PMF is slightly smaller than that of the M-B distribution (3.992 compared to 4.000). Consequently, GMI will reflect the actual improvement more objectively.

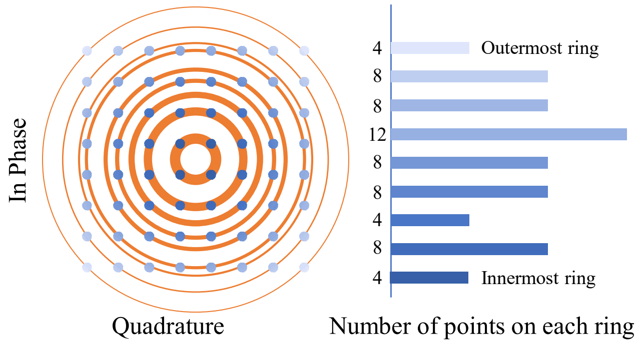

Figure 2. The constellation of the PS 64-QAM signal and the number of constellation points that take into account on each ring. The PMF reallocation within each ring is performed independently.

We build a coherent detection system to evaluate the performance improvement of the PMF reallocation mechanism as shown in Fig. 3. In the transmitter digital signal processing (Tx-DSP) part, we generate a pseudorandom binary sequence (PRBS) and apply PS mapping to the signal. After normalization, we apply the root-raised cosine (RRC) filter to reduce the inter-symbol interference. A 1555-nm optical carrier of 100-kHz linewidth is modulated with 24-Gbaud PS 64-QAM signal obtained from an arbitrary waveform generator (Keysight M8194A). After 40km transmission in a standard single-mode fiber (SMF), a DCF is used to compensate for the dispersion. We add amplified spontaneous emission (ASE) noise to vary the OSNR of the system and utilize a polarization controller to maintain a stable single-polarization state at the receiver (NeoPhotonics ICR). The detected photocurrent is captured by a real-time oscilloscope (Keysight UXR0594A) operating at 256 GSa/s for the following Rx-DSP. The Rx-DSP includes the procedures of resampling, synchronization, RRC pulse shaping, frequency offset estimation (FOE), and power normalization. After blind phase search (BPS) based phase noise compensation, we conduct decision-directed least mean square (DD-LMS) equalization. The system performance was evaluated in terms of GMI and NGMI after demodulation.

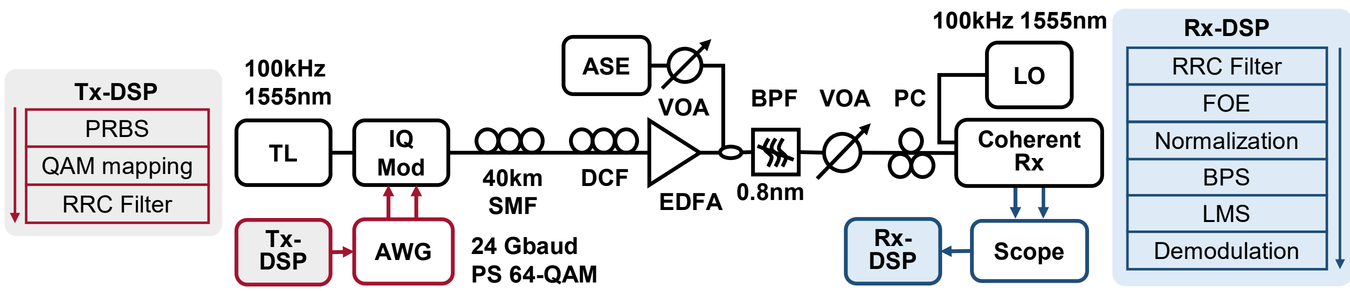

Figure 3. Experimental setup for the 40-km coherent transmission system. TL: Tunable laser; IQ Mod: IQ modulator; AWG: arbitrary waveform generator; SMF: single mode fiber; DCF: dispersion compensating fiber; EDFA: erbium-doped fiber amplifier; ASE: amplifier spontaneous emission; BPF: bandpass filter; VOA: variable optical attenuator; PC: polarization controller; LO: local oscillator.

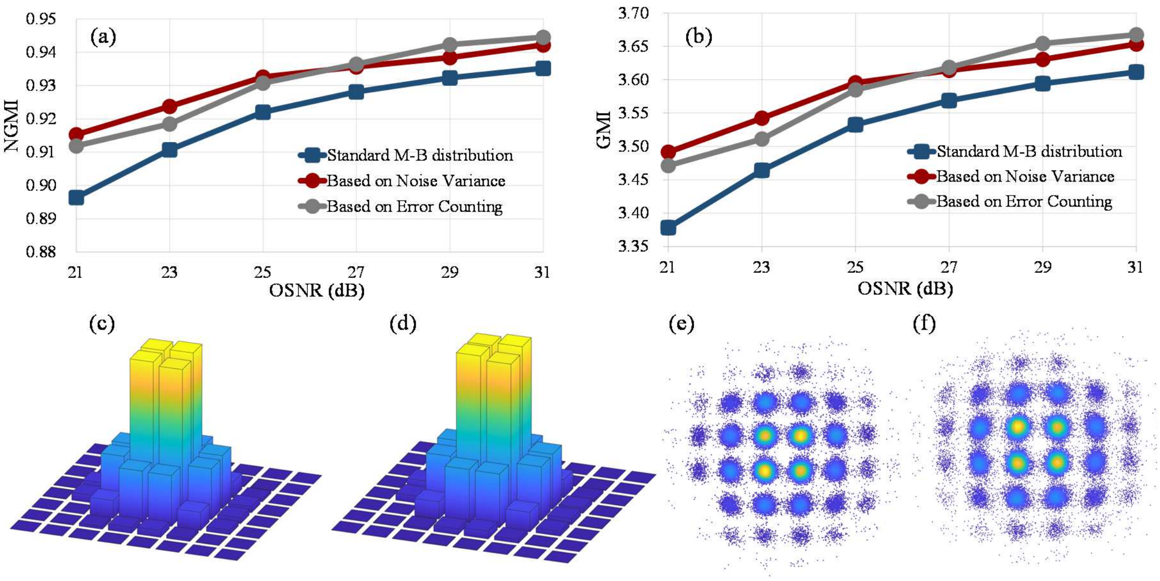

Figure 4. Performance, distribution, and constellation diagram of the PCS 64-QAM signal. (a) The NGMI and (b) GMI performance comparison of the standard M-B distributed signal and the reallocated signal under different OSNR conditions. The PMF after reallocation based on (c) the noise variance and (d) the error number of the standard M-B distributed signals under 25dB OSNR. The constellation of the received signal with reallocated PMF based on (e) the noise variance and (f) the error number under 25dB OSNR.

III. Results and Discussion

We present the experimental results in Fig. 4 after conducting the 40-km transmission under different OSNR conditions. Fig. 4(a) and Fig. 4(b) show the NGMI and GMI performance comparison, respectively, of the standard M-B distributed signal and the reallocated signal under different OSNR conditions. Through reallocation, we have achieved an average GMI improvement of 0.0630 (noise variance) and 0.0597 (error counting). Considering the 24-Gbuad PCS 64-QAM signal, the average total data rate improvement is 1.5124 Gbit/s (noise variance) and 1.4321 Gbit/s (error counting), respectively. The improvement is consistent with previously published simulation results [8]. It is worth mentioning that under low OSNR conditions, the improvement based on noise variance is larger than that of error counting. On the other hand, under high OSNR conditions, the improvement based on error counting is more pronounced. This is because noise variance can better characterize the asymmetrical constellation performance when the ASE noise has larger power, as reflected in the case of low OSNR. Fig. 4 (c) and (d) show respectively the PMF after reallocation based on the noise variance and the error number distribution on each constellation point of the received signals under 25dB OSNR. Fig. 4 (e) and (f) show the constellations of the received signal with reallocated PMF. Our results reveal that both proposed reallocation mechanisms can improve the system performance compared to M-B distribution in practical communication systems.

IV. Conclusion

We optimize the probabilistic shaping distribution by reallocating the symbol probability based on the performance of the training sequence constellation. The effectiveness of this mechanism is experimentally verified in a 40-km transmission system with 24 Gbaud PCS 64-QAM signals. Through reallocation, we have achieved an average GMI improvement of 0.0630 (noise variance) and 0.0597 (error counting) compared to M-B distributed signals. The average total data rate improvement is 1.5124 Gbit/s (noise variance) and 1.4321 Gbit/s (error counting), respectively. Our experimental results show that both reallocation mechanisms can effectively improve the system performance compared to that of M-B distribution in practical communication systems.

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