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Blind Shaping Rate Identification for Probabilistic Shaping Quadrature Amplitude Modulation Formats

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Abstract: We experimentally demonstrate a blind scheme enabled by a frequency offset loading technique to identify the shaping factor and modulation format of probabilistically shaped 16/64/256QAM signals with various entropies.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communications; (060.4080) Modulation.

1. Introduction

Ever since probabilistic shaping (PS) technique was first put forward in fiber optical transmission systems [1], it has shown great potential to approach Shannon limit [2, 3]. Meanwhile, rate-adaptive transmission can be also realized by the PS technique. Transmission rate can be adjusted by changing entropy under the condition of fixed forward error rate (FEC) code rate. Recently, the rate/reach adaptation transmission has been realized by probabilistically shaped quadrature amplitude modulation (QAM) across from 80 km to 12,000 km using the same 32-GBaud transponder [4]. Therefore, PS has the potential to play a vital role in future flexible optical networks with the capability to timely adjust the data traffic and fulfill different transmission conditions. By adjusting the modulation format and its entropy, the fiber optical transmission system can achieve both high generalized mutual information (GMI) and flexible bit rates. The normalized GMI (NGMI) of those rate-adaptive transmission systems can satisfy the threshold of fixed rate FEC as well. Meanwhile, the locations of constellation points stretch or shrink after normalization process, due to the variation of average power. Many receiver-side digital signal processing (Rx-DSP) modules need the constellation information, such as radius directed equalization (RDE), decision-directed least mean square (DD-LMS) equalization, and blind phase search (BPS) algorithm [5, 6]. Those Rx-DSP algorithms require the QAM template to calculate the cost function. If the constellation size and the locations of constellation points are not accurate, there may exist error during the decision and the calculation of cost functions. Consequently, the performance is degraded. When the transmission rate is adjusted according to traffic or customer demands, it is necessary to identify both the entropy and modulation format which we define as the shaping rate, for the ease of Rx-DSP implementation.

In this paper, we propose a blind shaping rate identification scheme enabled by a frequency offset (FO) loading technique for future optical networks assisted by PS-QAM. We experimentally verify that, under the condition of almost no generalized mutual information (GMI) loss, the proposed scheme can correctly identify multiple shaping rates.

2. Operation principle

The proposed scheme encodes the shaping rate information by digital FO loading at the transmitter side (Tx) and decodes the corresponding information by FO estimation (FOE) at Rx. The codebook for encoding and decoding can be defined in advance. Once we know the entropy and modulation format, the probabilistic mass function (PMF) of the constellation points can be calculated according to the Maxwell-Boltzmann (MB) distribution [1, 7]. Since the average power of signals can be calculated, the point positions of constellations can be determined after the normalization. If PS-QAM is realized by a LUT based DM, the average power and PMF can be secured by a mapping from the LUT [8, 9].

1.1. Digital FO loading

At Tx, We first divide the shaped signal sequence into blocks. The codeword bits are carried by the frequency value of each block. If the codeword bit is “1”, the symbols in this block are multiplied with a phase item, which is induced by the digital FO and shown in Eq. (1). And other blocks keep unchanged.

$$t(k) = m(k)\exp(j\bullet\Delta\omega kT) \quad k = 0,1,2,...,n \tag{1}$$

where m(k) is one initial data symbol, j is the imaginary unit, the $\Delta\omega$ is the loaded angular FO, T is the duration of one sample, k is the number of this symbol within this block, n is the data block length. The code book we used in this demonstration is presented in Table.1 and can be modified as needed.

Table 1. Code book

codeword	Shaping rate
0000	PS-16QAM with entropy 3.72 bit/sym
0001	PS-16QAM with entropy 3.82 bit/sym
0010	PS-16QAM with entropy 3.92 bit/sym
0011	PS-64QAM with entropy 5.75 bit/sym
0100	PS-64QAM with entropy 5.90 bit/sym
0101	PS-64QAM with entropy 5.97 bit/sym
0110	PS-256QAM with entropy 7.69 bit/sym
0111	PS-256QAM with entropy 7.87 bit/sym
1000	PS-256QAM with entropy 7.96 bit/sym

1.2. Shaping rate identification

At Rx, we perform FOE for each block. The FO values of each block is obtained through fast Fourier transform based FOE (FFT-FOE) which is shown in Eq. (2), and then the bits carried by every block is obtained through the decision of its FO value. And the shaping rates of the shaped sequence can be identified by the decoded codeword.

$$f_{FO} = \frac{1}{4} \arg\max_{f} \left| \sum_{k=0}^{n-1} r^4(k) e^{-j(2\pi f)kT} \right| \tag{2}$$

where f_{FO} is the estimated FO, r(k) is the k^{th} received symbol, and T is the sample duration. We set a threshold for the decision of estimated FO values as shown in Eq. (3).

$$threshold = \frac{1}{2}(FO_{loaded} + FO_{laser}) \tag{3}$$

where FO_{loaded} is the loaded FO at Tx and FO_{laser} is the FO between the transmitter laser and the local oscillator (LO).

3. Experimental setup

To verify the feasibility of our proposed scheme for PS-QAM with various entropies, we conduct an experiment for 2 Gbaud B2B coherent fiber optical rate-adaptive transmission. The proof-of-concept setup is shown in Fig.1 (a). At Tx, a free-running external cavity laser (ECL) with a linewidth of less than 100-kHz is used to generate a 1550 nm continuous-wave (CW) light wave. The CW light is then modulated by an IQ modulator which is driven by an arbitrary waveform generator (AWG, Tektronix AWG7122B) operated at 2 GSa/s. Tx-DSP is schematically shown in Fig.1 (b). Bit stream is transformed into PS sequence through constant composition distribution matching (CCDM) and PS-QAM signals are generated by the PAS architecture and QAM mapping [1, 10]. A 100 MHz FO is digitally loaded to signal blocks with bits “1”. Meanwhile, we divide every 2048 symbols as one block. Then all signals are loaded into the AWG. An amplified spontaneous emission (ASE) loading module is used to adjust the OSNR from 20 dB to 25 dB. At Rx, another tunable ECL is used as a local-oscillator (LO) to realize coherent detection. Then, electrical signals are digitized by a 50 GSa/s digital sampling oscilloscope (Tektronix DPO73304D) for subsequent offline DSP, as shown in Fig.1 (c). After the frame synchronization, resampling and I/Q balance, signals are first divided into blocks. The FO value of each block is estimated by FFT-FOE and then decided according to the pre-set threshold. Meanwhile, the estimated FO values can be used for subsequent FOC. We can also obtain the information of the modulation format directly and the entropy and then calculate the point positions of constellation, which is helpful to guide subsequent DDLMS. We use BPS within DDLMS to realize carrier phase recovery (CPR). Then signals are de-mapped into log-likelihood ratio (LLR) and the GMI of each frame is calculated.

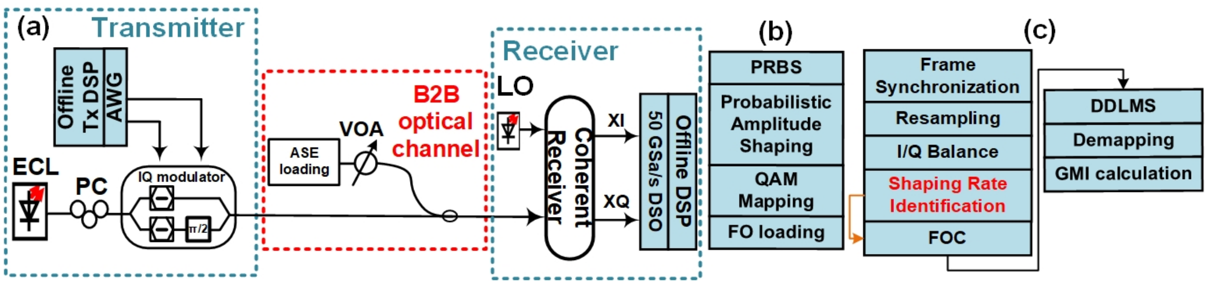

Fig. 1: (a) Proof-of-concept experimental setup, (b) corresponding Tx DSP flow, and (c) corresponding Rx DSP flow

4. Results and discussions

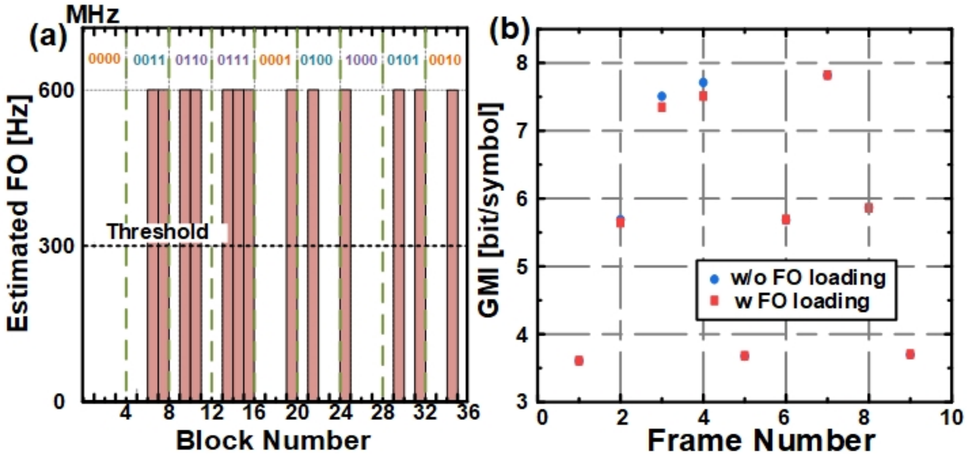

Fig. 2 Experimental results: (a) the estimated FO value of each block and corresponding decoded bit, (b) the GMI of each frame with and without using FO loading

Rate-adaptive transmission is successfully demonstrated. Shaping rates are switched from 9 options in table.1, and the entropies of each modulation format are switched among 3 different options. Experimental results are shown in Fig.2. The decided bits are shown above the histogram of estimated FO values of Fig.2 (a). All 9 shaping rates are correctly identified. The GMI of shaped sequence with different shaping rates using the FO loading or not is calculated, as shown in Fig.2 (b). The maximum GMI loss due to the FO loading is 0.07 bit/symbol, in comparison with the case without using the FO loading.

5. Conclusions

We propose a blind shaping rate identification scheme enabled by digital FO loading for PS-QAM based rate-adaptive transmission. The proposed scheme can identify the shaping rate for PS-QAM formats with various entropies. We conduct an experimental verification for the proposed scheme, under the condition of 2 Gbaud B2B rate-adaptive transmission of PS-16/64/256QAM with 3 different entropies. The maximum GMI loss induced by the digital FO loading is only 0.07 bit/symbol, in comparison with that without using the digital FO loading.

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References

[1] G. Böcherer, P. Schulte and F. Steiner, "Bandwidth efficient and rate-matched low-density parity-check coded modulation," *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4651-4665, 2015.

[2] F. Buchali, W. Idler, L. Schmalen, G. Boecherer, P. Schulte and F. Steiner, "Probabilistically shaped QAM for independent reach, spectral efficiency and bit-rate adaptation," in *Proc. ECOC*, Düsseldorf, Germany, 2016, pp. 1-3，paper

[3] S. Chandrasekhar, B. Li, J. Cho, X. Chen, E. Burrows, G. Raybon and P. Winzer, "High-spectral-efficiency transmission of PDM 256-QAM with parallel probabilistic shaping at record rate-reach trade-offs," in *Proc. ECOC*, Düsseldorf, Germany, 2016, pp. 1-3，paper

[4] J. M. Gené, X. Chen, J. Cho, S. Chandrasekhar and P. Winzer, "Experimental Demonstration of Widely Tunable Rate/Reach Adaptation From 80 km to 12,000 km Using Probabilistic Constellation Shaping," in *Proc. 2020 Optical Fiber Communications Conference and Exhibition (OFC)*, 2020, pp. 1-3，paper

[5] H. Louchet, K. Kuzmin and A. Richter, "Improved DSP algorithms for coherent 16-QAM transmission," in *Proc. 2008 34th European Conference on Optical Communication*, 2008, pp. 1-2，paper

[6] T. Pfau, S. Hoffmann and R. Noe, "Hardware-Efficient Coherent Digital Receiver Concept With Feedforward Carrier Recovery for M-QAM Constellations," *J. Lightwave Technol.*, vol. 27, no. 8, pp. 989-999, 2009.

[7] F. R. Kschischang and S. Pasupathy, "Optimal non-uniform signaling for Gaussian channels," *IEEE Trans. Inf. Theory*, vol. 39, no. 3, pp. 913-929, 1993.

[8] J. Cho and P. J. Winzer, "Multi-rate prefix-free code distribution matching," in *Proc. OFC*, San Diego, CA, USA, 2019, pp. 1-3，paper

[9] T. Yoshida, M. Karlsson and E. Agrell, "Hierarchical distribution matching for probabilistically shaped coded modulation," *J. Lightwave Technol.*, vol. 37, no. 6, pp. 1579-1589, 2019.

[10] P. Schulte and G. Böcherer, "Constant composition distribution matching," *IEEE Trans. Inf. Theory*, vol. 62, no. 1, pp. 430-434, 2015.