IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 11, Number 2, April 2019

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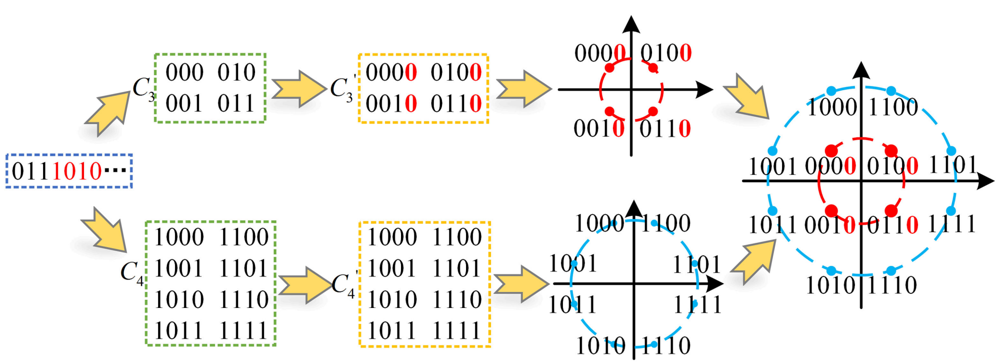

DOI: 10.1109/JPHOT.2019.2899882

A Probabilistically Shaped CAP Modulation Method Employing Multiple Subsets Mapping With Symbol Classification for a Short Reach Communication

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DOI:10.1109/JPHOT.2019.2899882

Manuscript received January 13, 2019; revised February 10, 2019; accepted February 13, 2019. Date of publication February 18, 2019; date of current version March 4, 2019. This work was supported in part by the National Natural Science Foundation of China under Grants 61835005, 61822507, 61522501, 61475024, 61675004, 61705107, 61727817, 61775098, 61720106015, and 61875248; in part by the National High Technology 863 Program of China under Grants 2015AA015501 and 2015AA015502; in part by the Beijing Young Talent under Grant 2016000026833ZK15; and in part by the State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications. Corresponding author: Bo Liu (e-mail: bo@nuist.edu.cn).

Abstract: This paper proposes a novel probabilistically shaped carrierless amplitude/phase (CAP) modulation method employing multiple subsets mapping with symbol classification for a short reach communication. This method can classify the original data into multiple subsets of symbols carrying different amounts of bits, and then, map the symbols with different probabilities in the subsets to the different regions of the constellation to reduce the average signal power, thus improving the system bit error rate (BER) performance. An experiment demonstrating 21.8 Gb/s PS-CAP-12 data transmission employing the proposed method over 25 km standard single-mode fiber is successfully carried out. Experiment results show that the proposed scheme outperforms the traditional CAP-16 modulation by 2 dB improvement in receiver sensitivity at a BER of 1×10^{-3}, which suggests the superiority of our proposed scheme for a future short reach communication.

Index Terms: Probabilistic shaping, CAP modulation, multiple subsets mapping with symbol classification, short reach communication.

1. Introduction

With the ever-growing development of high-end applications (e.g., cloud computing, augmented/virtual reality (AR/VR), and Internet of Things (IoT)), high-speed optical interconnects have played a more and more important role in intra- and inter-data centers (DC) communications [1]. According to a recent Cisco report, 86% of the global Internet traffic will be DC related in which 77% will be within a DC by 2020 [2]. As an effective and future-proof technology, short reach optical network is considered to be a favorable solution, which has been substantially investigated worldwide. Wherein carrier-less amplitude/phase (CAP) modulation is considered as an attractive technique due to its low system cost, easy implementation and low complexity in data processing. A novel N-dimensional CAP filter is designed, which significantly decreases the required iteration steps and maintains the orthogonality between CAP filters with lower cutoff frequency [3]. A multi-dimensional CAP passive optical network (PON) based on non-orthogonal transceiver filters is proposed to improve the spectral efficiency (SE), which utilized a novel inter-symbol interference (ISI) and cross-channel interference (CCI) cancellation algorithm to eliminate the induced interferences. And based on this novel architecture, a 10 Gb/s four-dimensional with four levels/dimension and non-orthogonal CAP data transmission is successfully demonstrated over 20 km standard single mode fiber (SSMF), in which a promising SE gain from 3.85 to 4.35 bits/s/Hz is obtained [4]. Recently, a joint processing algorithm for CAP including traditional Volterra filter and MIMO Volterra filter is designed, which can substantially mitigate both the nonlinearity penalty and IQ imbalance, thus paving the way for mature CAP technique in both short-reach and metro network [5].

Besides, the ability of enlarging the channel capacity to approach the Shannon limit in communication system has always been an unswerving pursuit. Wherein probabilistic shaping (PS), as an outstanding and effective technique, has gained ever-increasing interests among researchers. Compared with conventional constellation mapping schemes, in which constellation points are uniformly-distributed, PS takes into account the different energy costs of constellation points and reduces the transmitting probabilities of the outer points with larger energy, while in turn increasing the chances of the inner points being transmitted. Such an approach can reduce the average transmitted energy to a large extent, and the ultimate shaping gain of 1.53 dB can be achieved theoretically by employing a Maxwell-Boltzmann (MB) distribution in the constellation [6]. A PS-64QAM single-carrier 400G transmission over SSMF is demonstrated, which outperformed the regular 64QAM by 300% reach enhancement [7]. A PS-1024-QAM OFDM fiber transmission in a low-cost intensity modulation combined with direct detection (IM/DD) system is demonstrated, which obtained higher achievable-information-rate performance and stronger nonlinearity robustness [8]. Also, PS-4096QAM is transmitted experimentally in an all-Raman amplified 160 km transmission, which achieved a power margin of 1.4 dB improvement compared with uniformly-shaped 1024QAM in the case of the same spectral efficiency [9]. In addition, aimed at nonlinear channel, a new probabilistic shaping distribution that outperforms Maxwell-Boltzmann distribution is proposed and illustrated to optimize the higher order QAM constellations, which is verified by the mutual information (MI) gain of 0.1 bit/symbol or 0.2 dB signal noise ratio (SNR) gain in a simulation of DP-256QAM and DP-1024QAM transmission [10]. However, current probabilistic shaping schemes are mainly aimed at signal shaping and mapping between regular constellations, such as 16QAM, 64QAM, 1024QAM and so on. What's more, probabilistic shaping implementations are mostly based on conventional approaches, including probabilistic amplitude shaping (PAS) with constant composition distribution matching (CCDM) [11], run-length code based distribution matching with a uniformalizer [12], and turbo coded bit interleaved coded modulation system relied on many-to-one labeling [13].

In this paper, to our best knowledge, we firstly propose a probabilistically shaped CAP modulation method employing multiple subsets mapping with symbol classification for short reach communication. This method classifies the original bits sequence into multiple subsets composed of symbols with different amounts of bits. These symbols are of different probabilities and mapped to the different regions of the constellation in such a manner that the symbols with higher probability are mapped to the inner parts, thus reducing the average signal power and improving the system BER performance. The proposed method is of low digital signal processing (DSP) complexity and is capable of the implementation of various orders modulation formats to acquire flexible information entropies. Moreover, an experiment demonstrating 21.8 Gb/s PS-CAP-12 data transmission employing the proposed method over 25 km SSMF is successfully carried out.

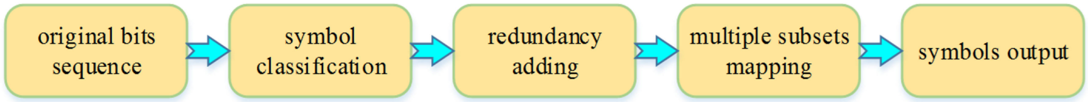

Fig. 1. The principle of proposed probabilistically shaped method employing multiple subsets mapping with symbol classification.

TABLE 1
Parameters of Proposed Probabilistically Shaped Method Employing Multiple Subsets Mapping With Symbol Classification

Subset	Amount of bits carried by each symbol	Probability of each symbol	Amount of symbols
C_1	1	$\frac{1}{2}$	n_1
C_2	2	$\frac{1}{2^2}$	n_2
…	…	…	…
C_i	i	$\frac{1}{2^i}$	n_i
…	…	…	…

2. Principle of Probabilistically Shaped CAP Modulation Method Employing Multiple Subsets Mapping With Symbol Classification

By means of reducing the probabilities of the constellation points with higher energy and increasing the probabilities of those with lower energy, probabilistic shaping can significantly reduce the average signal power and improve the constellation figure of merit (CFM), thus improving the system BER performance. In communication systems, the bits sequence is randomly generated in the source with uniform distribution of “0” and “1”. When m bits are grouped together to form a symbol, a uniform distribution of 2^m symbols can be obtained in the constellation. In our paper, a probabilistically shaped method employing multiple subsets mapping with symbol classification is proposed so as to achieve the non-uniform distribution of the constellation points. Such a method can obtain the shaping gain of the constellation and improve the system performance.

Fig. 1 shows the principle of proposed probabilistically shaped method employing multiple subsets mapping with symbol classification. The original bits sequence with uniform distribution of “0” and “1” is first classified in the form of variable length coding to generate multiple subsets, which distinguishes from one another according to the amount of bits carried by the symbols. In this way, all the symbols in certain subset carry the same number of bits, while in different subsets the numbers are different from one another. The detailed parameters are shown in Table 1, where i denotes the amount of bits carried by the symbols in every subset and m is the maximum amount of bits carried by the symbols. C_i represents the corresponding subset and P_i is the corresponding probability of the symbol. n_i stands for the amount of symbols in the C_i. Due to the uniform distribution of “0” and “1” in the original bits sequence, the following formula can be deduced:

$$\sum_{i=1}^{m} \frac{n_i}{2^i} = 1. \tag{1}$$

Then the redundant bits are added appropriately to achieve the goal that all the symbols are of the same amount of bits, thus resynchronization in the receiver can be easily realized. Finally, in the process of multiple subsets mapping, the distribution of the symbols in the constellation are formed in a pattern that the symbols with large probabilities are mapped to the area with low energy, while those with small probabilities are mapped to the area with high energy. The proposed probabilistic

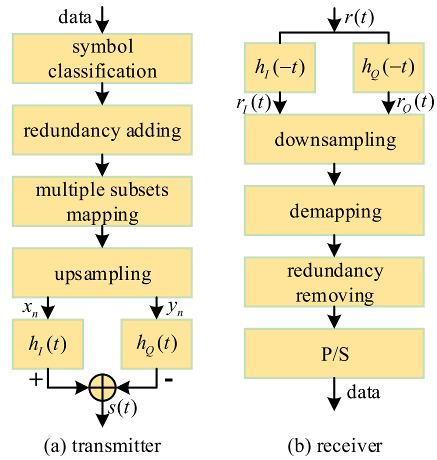

Fig. 2. The schematic diagram of PS-CAP-12 signal (a) transmitter and (b) receiver.

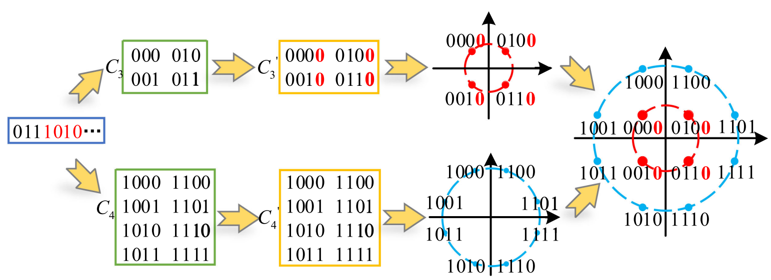

Fig. 3. The schematic diagram of multiple subsets mapping with symbol classification.

shaping scheme can alter the distribution pattern of constellation points to significantly reduce the average signal power in a manner of easy-to-implement and low-complexity.

Based on the proposed method of multiple subsets mapping with symbol classification, a novel probabilistically shaped CAP-12 modulation is designed in this paper, which will be demonstrated below in a comprehensive and elaborate manner. Fig. 2 illustrates the schematic of the proposed PS-CAP-12 modulation. In the transmitter, the original bits sequence firstly undergoes the process of classification to generate multiple subsets with different probabilities. To be specific, as illustrated in Fig. 3, during the serial-to-parallel (S/P) conversion, when the "0" appears first, the consecutive three bits are chosen as a symbol, while the consecutive four bits are chosen as a symbol in the case that "1" appears first. In this way, the original information source can be separated into two subsets, namely C_3 and C_4. C_3 is composed of $\{000,001,010,011\}$, where every symbol carries three bits with the probability of $\frac{1}{2^3} = \frac{1}{8}$. Similarly, C_4 is composed of $\{1000,1001,1010,1011,1100,1101,1110,1111\}$, where every symbol carries four bits with the probability of $\frac{1}{2^4} = \frac{1}{16}$. The total probability of all the symbols in these two subsets can be summed up as $4 \times \frac{1}{8} + 8 \times \frac{1}{16} = 1$, which coincides with the Eq. (1). Then the redundancy of "0" is added to the symbols in C_3 to ensure that all the symbols have a same bits length of four, thus avoiding the error bursts or resynchronization at the receiver. A new subset C_3' is generated in the form of $\{0000,0010,0100,0110\}$, while C_4' remains the same as C_4. Finally, the four symbols in C_3' with higher probabilities are mapped to the four constellation points in the inner ring, while the eight symbols in C_4' with lower probabilities are mapped to the corresponding eight constellation points in the outer ring as illustrated in Fig. 3. Fig. 4 shows the probability distribution of the newly-generated constellation points.

After the process of the proposed probabilistically shaped method, the newly-generated symbols undergo the procedure of upsampling by zero-padding to match the system sampling rate, where

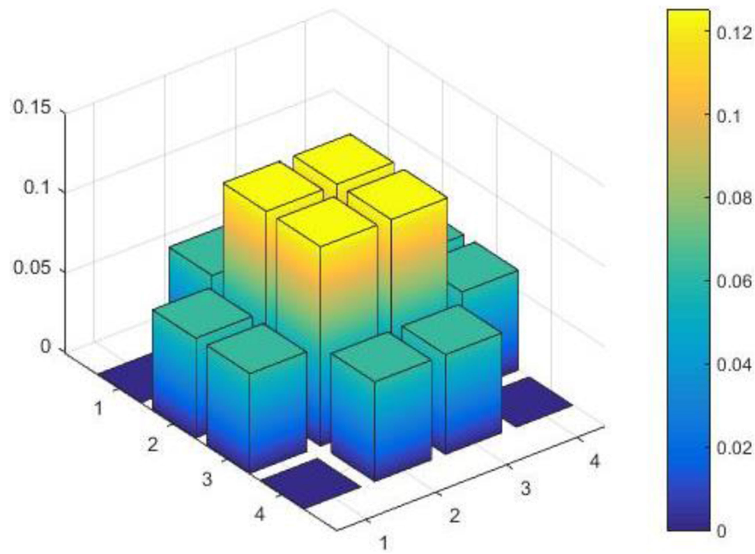

Fig. 4. The probability distribution of the novel PS-CAP-12 modulation.

the number of samples per symbol is given by the radio between the sampling frequency and the symbol rate. At least three samples per symbol are required for a CAP signal to be sampled without losing spectral information [14]. The real and imaginary components of the up-sampled signal are then separated and sent into two orthogonal shaping filters $h_I(t)$ and $h_Q(t)$, respectively. The impulse responses of the two filters form a Hilbert transform pair, which can be expressed as [2]

$$h_I(t) = g(t) \cdot \cos(2\pi f_c t), \tag{2}$$

$$h_Q(t) = g(t) \cdot \sin(2\pi f_c t), \tag{3}$$

where $g(t)$ is a square-root-raised-cosine shaping filter with a roll-off factor of α, and f_c is the carrier frequency. The electrical PS-CAP-12 signal will be generated as the two orthogonal signals are added together, which can be expressed as [15]

$$s(t) = \sum_{n=-\infty}^{\infty} [x_n h_I(t - nT) - y_n h_Q(t - nT)]. \tag{4}$$

where x_n and y_n denote the real and imaginary components of the up-sampled signal, n is the symbol index, and T is the symbol period.

At the receiver, the in-phase and quadrature components are firstly separated with the two matched filters which are time reverse of the shaping filters at the transmitter [15]

$$r_I(t) = r(t) * h_I(-t), \tag{5}$$

$$r_Q(t) = r(t) * h_Q(-t). \tag{6}$$

where $r(t)$ denotes the received signal after photodetector (PD). The two orthogonal signals are combined to re-construct the complex signal before downsampling. After the constellation demapping, the redundant bit of "0" is removed from the symbols, followed by a parallel-to-serial (P/S) conversion, in order to recover the original bits sequence, which will be used for further analysis in terms of BER performance.

3. Experiment and Results

An experiment is conducted to evaluate the performance of proposed scheme and the experimental setup is illustrated in Fig. 5, where IM/DD is adopted for demonstration. At the transmitter, the

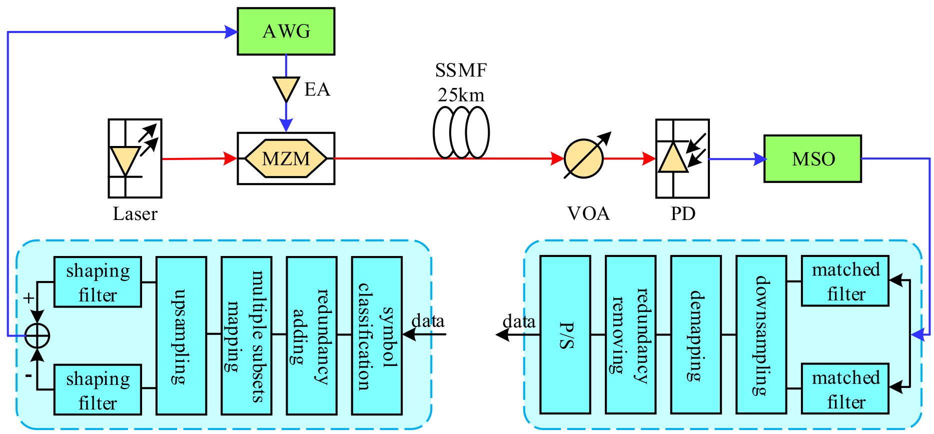

Fig. 5. The experimental setup (AWG: arbitrary waveform generator; EA: electrical amplifier; MZM: Mach-Zehnder modulator; VOA: variable optical attenuator; PD: photodiode; MSO: mixed signal oscilloscope).

PS-CAP-12 signal is generated offline with digital signal processing. To be specific, the raw bits sequence with length of $2^{15} - 1$ firstly undergoes the process of symbol classification in the form of variable length coding to generate two types of subsets, namely C_3 carrying three bits and C_4 carrying four bits. After the redundancy adding, the newly-generated symbols in all the subsets are mapped to the constellation, followed by the quadruple upsampling. The real and imaginary components of the signal are split and sent for corresponding shaping filtering, where the roll-off factor of the shaping filters is set as 0.2. After the combination of the outputs of the two shaping filters in the form of subtraction, the signals are sent into an arbitrary waveform generator (Tektronix, AWG70002A) with 25 Gs/s sampling rate to generate the corresponding electrical waveform, which will drive the Mach-Zehnder modulator (MZM) after the amplification of electrical amplifier (EA). Due to the information entropy of 3.5 bits/symbol in the proposed PS-CAP-12 modulation, a 21.8 Gb/s data transmission can be achieved in the experiment. A continuous wave (CW) laser operated at 1550 nm with an optical power of 10 dBm serves as the light source, which is fed into a Mach-Zehnder modulator (MZM) to achieve the intensity modulation. The output optical signal from the MZM is then injected into a 25 km SSMF for transmission.

At the receiver, a variable optical attenuator (VOA) is adopted to adjust the received optical power. The received optical signal is detected by a 40 GHz photodiode (PD). And a mixed signal oscilloscope (Tektronix, MSO73304DX) is used to sample the detected signal for further digital signal processing. After the resampling of the data coming from MSO, the newly-generated data are split into the real and imaginary components for matched filtering corresponding to the transmitter. After the procedures of downsampling, demapping, redundancy removing, and parallel-to-serial (P/S) conversion, the binary bits sequence is recovered for further BER performance analysis.

Fig. 6 shows the measured BER as a function of received optical power for back to back (b2b) and after 25 km transmission. It can be seen that the required received optical power at a BER of 1×10^{-3} is -17.9 dBm in b2b case, and the power penalty is less than 0.3 dB after 25 km transmission. The constellation diagrams of the received signal are also shown as insets in Fig. 6.

We have also measured the performance of PS-CAP-12 signal under different data rates, and the BER curves are depicted in Fig. 7. By adjusting the sampling rate of the AWG, the signals with Baud rate of 25 GBaud, 12.5 GBaud, 6.25 GBaud and 3.13 GBaud can be obtained, and their corresponding data rates are 21.8 Gb/s, 10.9 Gb/s, 5.5 Gb/s and 2.7 Gb/s, respectively. The transmission distance is set as 25 km during measurement. It can be observed that the BER performance will be degraded as the data rate increases. Specifically, as the data rate doubles, there is an about 1.5 dB drop in received optical power.

Moreover, at the same symbol rate of 6.25 Gbaud, the BER performances among the traditional CAP-16, square CAP-8 and star CAP-8, as well as our proposed PS-CAP-12 have been compared

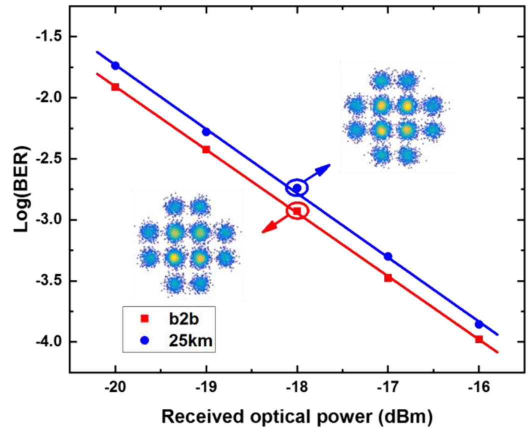

Fig. 6. The measured BER curves of PS-CAP-12 signal before and after 25 km transmission (b2b: back to back).

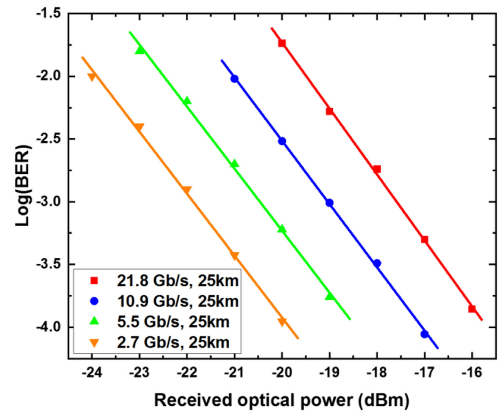

Fig. 7. The measured BER curves of PS-CAP-12 signal under different data rates after 25 km transmission.

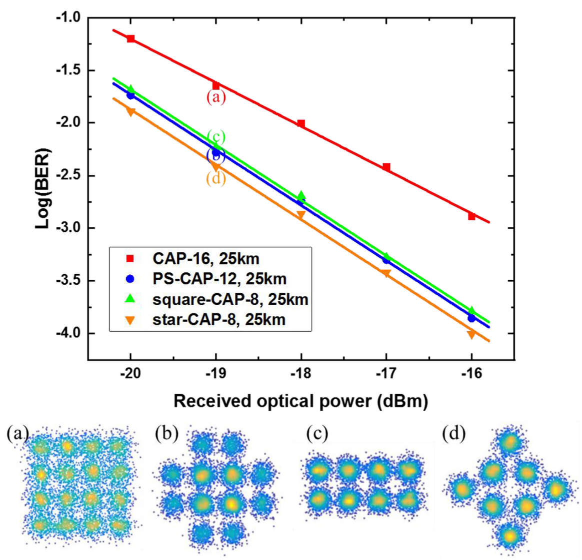

Fig. 8. The measured BER curves with different modulation formats at the same symbol rate.

comprehensively, as shown in Fig. 8. Also, the demodulated constellation diagrams of the different modulation formats are shown in Fig. 8 when the received optical power is -19 dBm. As can be seen, when the PS is introduced, our proposed PS-CAP-12 outperforms the traditional CAP-16 by about 2 dB receiver sensitivity improvement at a BER of 1×10^{-3}, which verifies the superiority of the proposed modulation. What's more, the BER performance of our proposed PS-CAP-12 is similar or even a little superior to that of the square CAP-8, while the former possesses larger information entropy. At the same symbol rate of 6.25 Gbaud, the data rate of PS-CAP-12 is 21.8 Gb/s while square CAP-8 can only have a data rate of 18.8 Gb/s. In addition, due to a certain advantage of the geometrical constellation design, the BER performance of the star CAP-8 is slightly better than the proposed PS-CAP-12 by 0.3 dB at a BER of 1×10^{-3}.

4. Conclusion

We have proposed a novel probabilistically shaped CAP modulation method employing multiple subsets mapping with symbol classification for short reach communication. The proposed method is of low complexity in digital signal processing and is capable of the implementation of various orders modulation formats to acquire flexible information entropies. An experiment demonstrating 21.8 Gb/s PS-CAP-12 data transmission employing the proposed method over 25 km standard single mode fiber (SSMF) is successfully carried out to verify the system performance. Compared with the traditional CAP-16, the proposed PS-CAP-12 can improve the received optical power by about 2 dB at a BER of 1×10^{-3}. The experiment results suggest the proposed scheme a promising technique for future short reach communication.

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