Transmission of 36-Gbaud PAM-8 Signal in IM/DD System Using Pairwise-Distributed Probabilistic Amplitude Shaping

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Abstract: We experimentally demonstrate the transmission of 36-Gbaud probabilistically-shaped PAM-8 signal over 10-km link. The performance measured after FEC decoding and inverse distribution matcher shows that the receiver sensitivity is improved by >1 dB compared to uniform-distributed signals.
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1. Introduction

As the demand for data traffic increases in unabated and exponential manners, various technologies such as multi-level modulation formats, channel equalization, and advanced forward error correction (FEC) techniques are required to approach the Shannon limit in optical communication systems. However, there still exists a non-negligible signal-to-noise (SNR) gap between the achievable performance of modern fiber-optic system and the Shannon limit for a given capacity. The probabilistic constellation shaping (PCS) technology has recently drawn considerable attention since the probabilistic amplitude shaping (PAS) architecture was introduced to provide a systematic way to combine the FEC technique with the PCS [1]. This technology is capable of closing the gap by changing the kurtosis of the signal amplitude distribution, and thus adjusting the information rate (IR) adaptively to the channel capacity [2,3].

Intensity modulation (IM)/direct-detection (DD) system is the simplest of optical transmission schemes. Thus, it has long been the transmission system of choice for short-haul, cost-sensitive applications. However, it is not straightforward to apply the PCS technology based on PAS architecture to IM/DD systems. This is because a symmetric *M*-PAM distribution is created in the PAS architecture by multiplying each of the half-PAM symbols with a uniformly-distributed (UD) parity bit acting as a sign bit [1,3]. This symmetric distribution can be used for the coherent transmission systems where *bipolar* signals (such as *M*-ary QAM signal) are utilized. However, in the IM/DD systems where the data information is carried over *unipolar* optical intensity, it is necessary to modify the PAS architecture to have *asymmetric* single-sided Gaussian-like amplitude distribution. The previous works on the use of PCS technology for IM/DD systems sidestep this problem, without implementing the FEC encoding and decoding. For example, it was assumed that the amplitude distribution of IM signal followed the desired distribution [e.g., Maxwell-Boltzmann (MB) or exponential distributions] without taking into account the fact that the parity bits have a uniform distribution [4,5]. It was only mentioned in [4] that the UD parity bits can be transmitted in a time-shared fashion such as using the time-division hybrid modulation at the expense of performance degradation.

We have recently proposed a new mapping method for applying the PCS technology to IM/DD system [6]. In this method, we first convert the probabilistically-shaped (PS) half-PAM symbols to bits, append a parity bit as a least significant bit (LSB), and then map it onto the *M*-PAM symbols for transmission. Since the UD parity bit is assigned to the LSB (instead of a sign bit), we have an asymmetric distribution where the two adjacent symbols have the same distribution. We call this distribution a pairwise distribution. Even though the pairwise Maxwell-Boltzmann (MB) distribution deviates slightly from the optimum MB distribution, we showed that the SNR penalty caused by this discrepancy is negligible.

In this paper, we experimentally demonstrate the transmission of 36-Gbaud PS PAM-8 signal over a 10-km long standard single-mode fiber (SSMF) link. To demonstrate the efficacy of the proposed method, we evaluate the performance of the PS signal after inverse distribution matcher (IDM) in terms of frame-error ratio (FER). We show that the PS PAM-8 signal improves the receiver sensitivity by >1 dB in comparison with the UD signals.

2. Experimental setup

Fig. 1(a) shows the experimental setup. First, UD binary data are fed to the constant composition distribution matcher (CCDM), which generates MB-distributed PAM-4 symbols, as shown in the inset. The block length of the CCDM's output is 400. After binary labeling, we send the signal to the FEC encoder. We employ an FEC coding specified in DVB-S2, which is composed of an outer BCH code and an inner low-density parity-check (LDPC) code [7]. The systematic FEC encoder outputs the PS data bits together with UD parity bits. For the PAM-8 mapping, the ratio

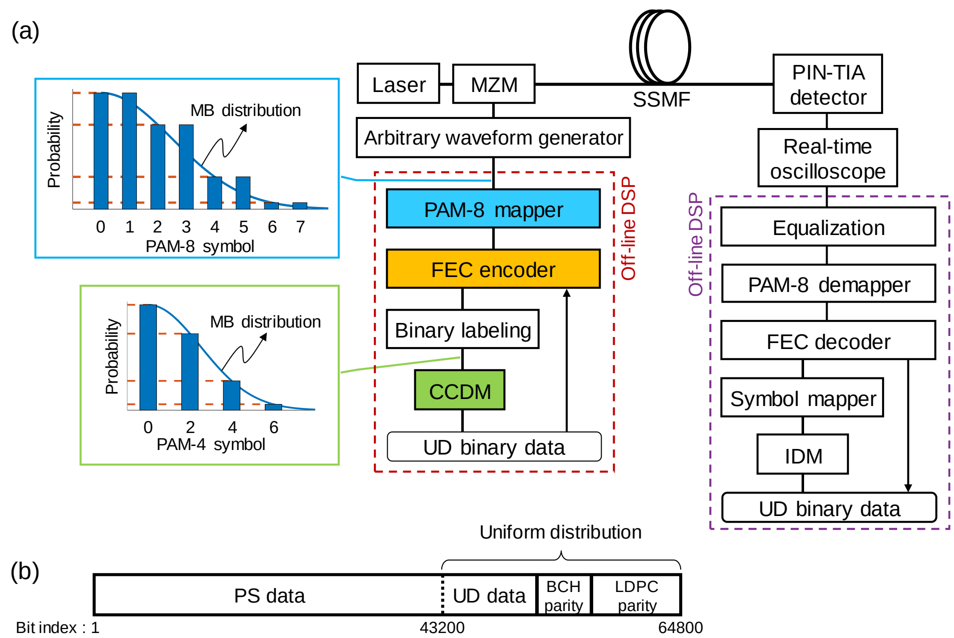

Fig. 1. (a) Experimental setup. (b) Frame structure of FEC encoder output.

between the PS bits and UD bits should be 2:1. Since this ratio might not be satisfied after FEC encoding, we add some UD data bits in the frame, as shown in Fig. 1(b). The PAM-8 mapper converts the 3-bit input to a PAM-8 symbol. For this purpose, we assign the first two significant bits to PS data and the LSB to UD data. Since the PS data (appearing in the first two bits at the mapper's input) follow the MB distribution, we have a pairwise MB distribution after the mapper, as shown in the inset. It was shown that the performance degradation induced by this pairwise distribution is negligible [6]. We port this PS signal to an arbitrary waveform generator (AWG) running at 72 Gsample/s for data modulation. We utilize a Mach-Zehnder modulator (bandwidth = 25 GHz). The optical signal at 1310 nm is transported over 10-km SSMF and directly detected by using a PIN-TIA receiver (bandwidth = 36 GHz). The received signal is sampled and digitized by a real-time oscilloscope (sampling rate = 80 Gsample/s). In the offline signal processing, we first compensate for the waveform distortions (caused by non-flat frequency response of components) using a 10-tap feed-forward linear equalizer. Then, we perform the bit-metric decoding at the PAM-8 demapper. We next perform the FEC decoding. The PS signal is finally sent to the IDM to recover the original UD binary data. We count the FER for the performance evaluation of PS PAM-8 signal. For comparison, we also transmit the UD PAM-8 signals. The performance of UD PAM-8 signals is evaluated in terms of bit-error ratio (BER).

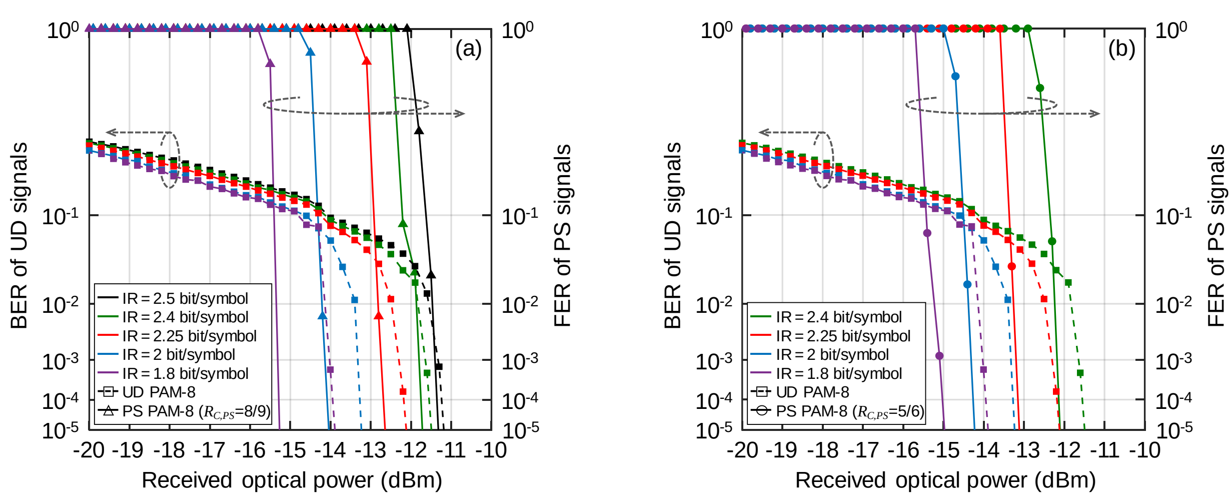

Fig. 2. Measured back-to-back performance when the FEC rates for PS signals ($R_{C,PS}$) are (a) 8/9 and (b) 5/6.

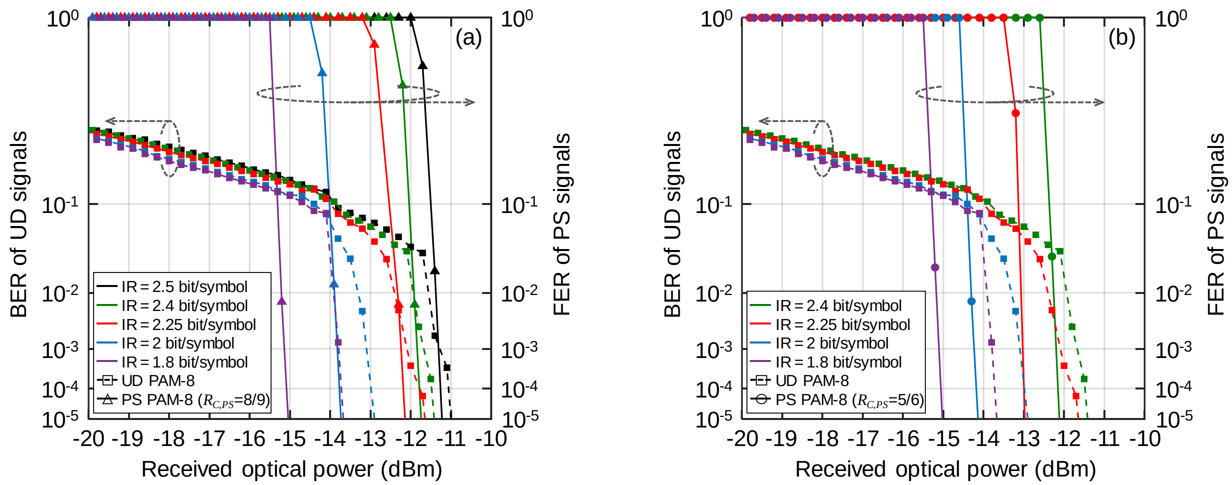

Fig. 3. BER and FER performance measured after 10-km long transmission when the FEC rates for PS signals ($R_{C,PS}$) are (a) 8/9 and (b) 5/6.

3. Results

In our experimental demonstration, we select five FEC rates for UD PAM-8 signals: 5/6, 4/5, 3/4, 2/3, and 3/5. These FEC rates yield IRs of 2.5, 2.4, 2.25, 2.0, and 1.8 bit/symbol, respectively. For fair comparison between PS and UD signals, we adjust the kurtosis of distribution such that the PS signals have the same IR as the UD signals since the IR of PS signal can be adjusted independently of the FEC rate. Fig. 2(a) shows the back-to-back performance when the FEC rate of PS signal (denoted as $R_{C,PS}$ in the legend) is set to be 8/9. The results show that the receiver sensitivity gain increases as the IR decreases. For example, we achieve a 0.2-dB gain at an IR of 2.5 bit/symbol, but it is increased to 1.5 dB when IR is 1.8 bit/symbol. This is because as the IR decreases, the Euclidian distance of the PS signal in the signal space increases for a given received optical power. Even though the UD signal utilizes a stronger FEC (as the IR decreases), the sensitivity gain achieved by the PS signal exceeds that of the UD signal. Fig. 2(b) shows the BER and FER performance when we increase the FEC rate of PS signal to 5/6. In this case, we cannot achieve an IR of 2.5 bit/symbol for PS signal. The results show that we achieve the sensitivity gain of 0.6 dB at an IR of 2.4 bit/symbol. The net data rate is 86 Gb/s in this case.

Fig. 3 shows the performance measured after 10-km transmission. The results exhibit the similar tendency to the back-to-back case. We achieve the receiver sensitivity gains of 1.4 and 0.3 dB for IRs of 1.8 and 2.5 bit/symbol, respectively, when the FEC code rate of PS signal is 8/9. The sensitivity gain of >1 dB is retained after transmission when the IR is less than 2.25 bit/symbol and the $R_{C,PS}$ is 5/6.

4. Conclusions

We have experimentally demonstrated the transmission of 36-Gbaud probabilistically-shaped PAM-8 signal over 10-km SSMF in IM/DD system. We modify the conventional probabilistic amplitude shaping architecture to be applicable to IM/DD system and utilize the pairwise Maxwell-Boltzmann distribution. The experimental results show that the probabilistically-shaped PAM-8 signal exhibits >1-dB sensitivity improvement compared to the uniformly-distributed signals.

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