Compensation of FEC induced Distribution Distortion based on Distribution Detuning in a 36-Tb/s (45×800-Gb/s) 2100-km Polar Coded PS-64QAM system

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Abstract: In this paper, a detuned distribution enabled polar coded probabilistic shaped 64-QAM is proposed and experimentally investigated over a 36-Tb/s (45×800-Gb/s) 2100-km transmission system at the spectral efficiency of 8-bit/s/Hz.

1. Introduction

Driven by the growing requirements of data services, large-capacity and cost-effective optical transmissions with digital coherent transceivers have become essential, which promotes the developments of wavelength division multiplexing (WDM) technique [1]. In terms of WDM based large-capacity transmissions, 800-Gb/s per lane based WDM transmission schemes are regarded as effective solutions for achieving large-capacity transmission with low cost per bit [2, 3], whose performance could be further enhanced by the combination of probabilistic shaping (PS) technique and forward error correction (FEC) technique owing to the inherent abilities on providing near Shannon-limit transmission [4]. However, in terms of the coding after shaping structure shown in Fig. 1(a), decreased shaping gains would occur owing to that the shaped symbols distribution would be distorted by the uniformly distributed parity bits.

In this paper, a novel detuned distribution enabled polar coded probabilistic shaped 64-ary quadrature amplitude modulation (PS-64QAM) is proposed and experimentally investigated over 2100-km fiber links, which could effectively address the distribution distortion problems induced by the uniformly distributed frozen bits of polar code for the coding after shaping structure. Experimental results show that about 1.0-dB OSNR sensitivity improvement and 350-km maximum-reach improvement could be introduced by the proposed scheme. Besides, the 100-GHz spaced WDM transmission operating with 800-Gb/s/lane demonstrates that all the 45 tested channels could fulfill the bit error ratio (BER) requirement, indicating that the capacity and capacity-distance product could be about 36-Tb/s and 75.6-Pb/s×km respectively.

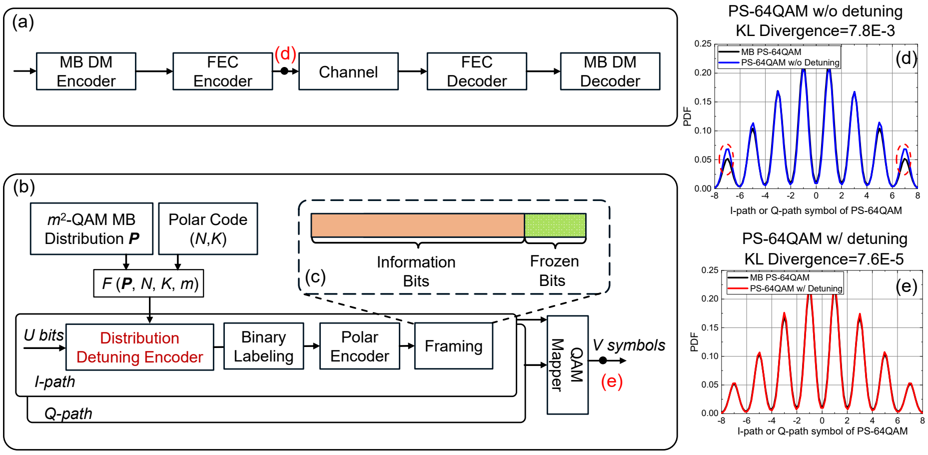

Fig. 1. (a) Coding after shaping structure. (b) The novel distribution detuning enabled scheme. (c) Framing structure. The probability function density (PDF) of I- or Q-path symbols of PS-64QAM (d) without and (e) with distribution detuning and the KL divergence between that of MB-distributed PS-64QAM.

2. Principle of the proposed scheme

The principle of the proposed scheme has been illustrated in Fig. 1 (b). Assuming that the distribution of the in-phase path (I-path) or quadrature path (Q-path) symbols of PS-64QAM with a target Maxwell-Boltzmann (MB) distribution is $\boldsymbol{P} = (p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8)$. And a systematic polar code [5] with the code length of N and information length of K is utilized. Hence, aiming to avoid distribution distortion, symbol sequences following the detuned distribution $\boldsymbol{Q} = (q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8)$ should be provided by the distribution detuning encoder with U input bits, which could be calculated by the target distribution $\boldsymbol{P}$ and the parameter of polar code as Eq. (1).

$$q_i=F(\boldsymbol{P}, N, K, m)=(mK)^{-1}(mNp_i-N+K),\quad i\in[1,2,3,4,5,6,7,8] \tag{1}$$

where m denotes the bit numbers of one 64-QAM symbol used. Then, binary labeling operations would be executed and the bit sequences would be encoded by systematic polar encoder, whose code length and code rate are 2048 and 5/6 (20% overhead) respectively. Afterward, the information bits and frozen bits of polar codewords would be separated and framing as the structure shown in Fig. 1 (c) to execute QAM mapping following binary reflected gray code (BRGC) mapping rules [6], and the PS-64QAM with distribution detuning with the length of V could be obtained. Hence, the actual transmission rate R_{actual} could be calculated as $2U/V$.

As mentioned above, if the coding after shaping scheme shown in Fig. 1(a) is utilized, the final distribution of I- or Q-path symbols of PS-64QAM would deviate from the that of MB distribution, which could be verified by the probability density function (PDF) shown in Fig. 1(d). It could be observed that the *Kullback-Leibler* (KL) divergence between the PS-64QAM without distribution detuning and the MB-distributed PS-64QAM is about 7.8E-3 due to the significant differences marked by red dashed circles in Fig. 1(d). In terms of the proposed scheme, its PDF labeled by red solid lines in Fig. 1(e) is approximately coincident with that of MB-distributed PS-64QAM and the divergence between the two schemes would be about 7.6E-5, suggesting that the distribution deviation problem of the coding after shaping schemes could be effectively compensated by the proposed distribution detuning enabled scheme. And experiments would be executed to further investigate the performance of the proposed scheme comprehensively in the following sections.

3. Experimental Setup and Results

The experimental setup and the Tx- and Rx-side DSP are illustrated in Fig. 2. In terms of emulated channels, spectrally shaped amplified spontaneous emission noise (SS-ASE) loading scheme [1] is utilized to provide 44 adjacent channels with 100-GHz grid to emulate full-loaded WDM system under the assistance of amplified spontaneous emission noise (ASE) source, erbium-doped fiber amplifier (EDFA) and wavelength selective switch (WSS). In terms of the channel under test (CUT), four pseudo random bit sequences (PRBS) are generated and processed by detuned distribution enabled polar coded PS-64QAM generator to provide dual-polarized (DP) signals, whose actual transmission rate is about 4.437-bit/symbol per polarization. Afterwards, it would be resampled and sent to the arbitrary waveform generator operating at 120-GSa/s sampling rate to output 91-GBaud electrical signals, contributing to a net data rate of 807.54-Gb/s/lane. Then, the electrical signals would be utilized to drive the silicon-based DP IQ modulator [7], and the continuous waveform (CW) of the modulators is provided by a tunable laser source (Southern Photonics, TLS150-20) with a linewidth less than 300-kHz. Before coupling the optical signal into the recirculating loop, signals from emulated channels and CUT would be combined by WSS and amplified by an EDFA, and an attenuator is deployed to adjust the launch power of the full-loaded system. Finally, WDM signals are launched into the recirculating loop, consisting of seven spans of 50-km backward-pumped Raman amplified ultra-large effective area fiber. Besides, another WSS is deployed in the recirculating loop to flatten the gain slope. For fair comparisons, the polar coded PS-64QAM without distribution detuning operating at 88- GBaud and polar coded

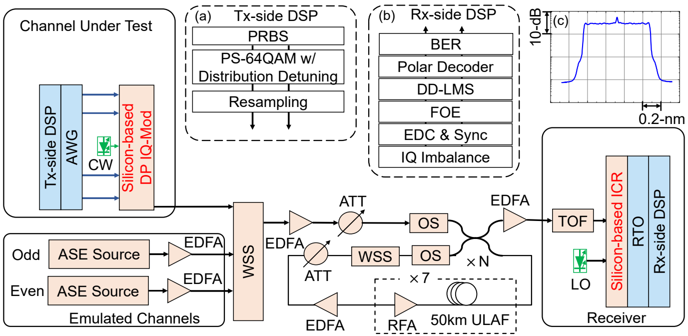

Fig. 2. The experimental setup together with (a)Tx-side DSP, (b)Rx-side DSP and (c) The optical spectra.

UD-64QAM operating at 80-GBaud with the consistent net data rate of 800-Gb/s/lane are utilized. At the receiver side, optical signals would be amplified by EDFA and then filtered by a tunable optical filter (TOF). Subsequently, it would be captured by the silicon-based integrated coherent receiver (ICR) [7] and sent to a 59-GHz bandwidth real-time oscilloscope (RTO) with 256-GSa/s. Finally, offline digital signal processing (DSP) is executed as shown in Fig. 2 (b), including IQ imbalance compensation, electrical chromatic dispersion compensation (EDC), frequency offset estimation (FOE), decision-directed least mean square (DD-LMS) based equalization and carrier phase recovery [5] and polar decoding.

The performance under optical back-to-back (OBTB) cases is measured first as shown in Fig. 3 (a). Here, owing to the limitation of offline experiments that low BER values could not be reliably estimated, such as 1E-15, an outer low-complexity code having a BER threshold of 1E-3 to achieve the final BER of 1E-15 is assumed here [8]. Therefore, the post-BER of PS-64QAM with distribution detuning could reach the BER threshold of 1.0E-3 at the OSNR of 28-dB. However, in terms of PS-64QAM without distribution detuning, the required OSNR to fulfill the BER requirement would be increased to about 29-dB, indicating that the proposed distribution detuning scheme could provide better OSNR tolerance. Then, launch power optimizations over 2100-km transmissions are executed under full-loaded cases, and results show that the optimal launch power of the three signals over 2100-km transmission is consistently 20-dBm as shown in Fig. 3(b), corresponding to about 3.47-dBm per lane. Fig. 3(e) and Fig. 3(f) illustrate the pre-BER and post-BER versus the distance. As shown, the maximum-reach is 700-km for UD-64QAM and 1750-km for PS-64QAM without distribution detuning respectively, while it would be 2100-km for PS-64QAM with distribution detuning, suggesting about 1400-km and 350-km transmission distance improvements could be introduced by the proposed distribution detuning scheme. Finally, Fig. 3 (g) shows the WDM 2100-km transmission results of PS-64QAM with distribution detuning. As shown, the post-BER of all tested channels could agree with the BER requirement of 1.0E-3, contributing to the capacity and capacity-distance product of 36-Tb/s (45×800-Gb/s) and 75.6-Pb/s×km (36-Tb/s×2100-km) respectively.

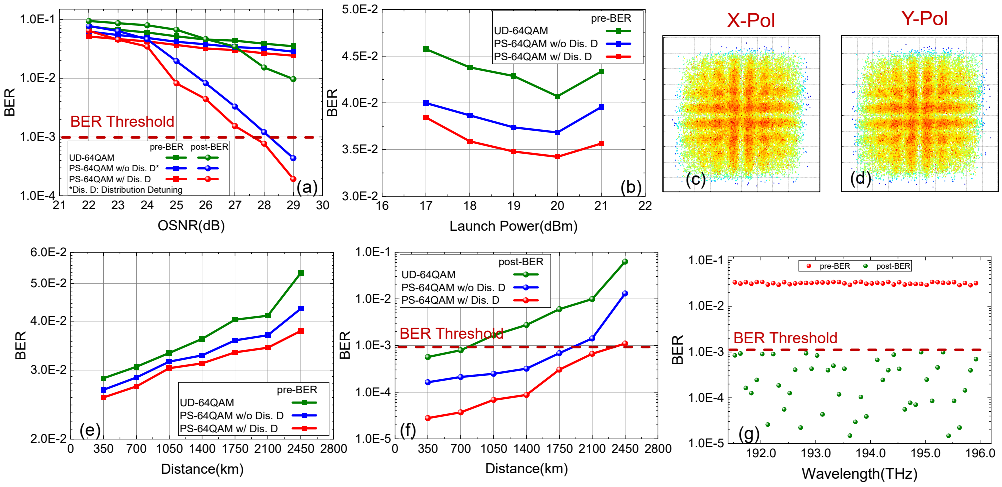

Fig.3. (a) The experimental results under OBTB cases. (b) The pre-BER versus launch power over 2100-km under full-loaded cases and (c-d) the constellations of PS-64QAM with distribution detuning scheme over 2100-km at the optimal launch power. The (e) pre-BER and (f) post-BER versus transmission distance. (g) The BER of all 45-channels for PS-64QAM with distribution detuning over 2100-km transmission.

4. Conclusions

In this paper, a novel detuned distribution enabled polar coded PS-64QAM scheme is proposed and investigated over 800-Gb/s/lane based large-capacity long-haul transmission system, which shows powerful abilities on addressing distribution deviation problems of coding after shaping schemes. Employing this novel technique, a 36-Tb/s (45×800-Gb/s) WDM coherent transmission is successfully demonstrated over 2100-km fiber links with a post-BER lower than 1.0E-3.

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