Demonstration of Polar Coded Truncated Probabilistic Shaped 64-QAM Transmission over 2000-km G.654E Fiber

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Abstract: In this paper, a polar coded truncated probabilistic shaped 64-QAM (PTPS-64QAM) scheme is proposed and investigated over the G.654E fiber. Results show that about 2000-km transmission could be achieved aided by the novel proposed scheme.

1. Introduction

The rapid increase of internet traffic has made the research and application of coherent optical communication more appealing, whose performance could be further improved by the combination of the state-of-the-art probabilistic shaping (PS) technology and excellent channel coding technology [1]. Aiming to reach the requirement of high data rates, high order modulation could be a potential candidate to release the requirement of crucial components, such as the 64-ary quadrature amplitude modulation (64-QAM). However, high order modulation would deteriorate the system optical signal-to-noise ratio (OSNR) tolerance and higher OSNR is required, which could be partly relaxed by probabilistic shaping technology with large shaping depth for providing better OSNR tolerance. Nevertheless, the large shaping depth would incur more severe error convergency of constant modulus algorithm inevitably owing to the decreased probability of the outermost constellations for 64-QAM, degrading the system sensitivity ultimately [2]. Therefore, to make a trade-off between the shaping depth and DSP performance, truncated probabilistic shaped (TPS) technology could be utilized owing to its inherent advantages for supporting suitable shaping depth and relaxing the difficulties of some DSP algorithms induced by the large shaping depth [3].

As for the TPS achieving schemes, although the constant composition distribution matcher (CCDM) based schemes could provide feasible spectral efficiency adaption, high complexity of the matcher and error propagation induced by the de-matcher are still great challenges [4], which could be alleviated by many-to-one (MTO) based scheme [5]. MTO scheme achieves probabilistic shaping by introducing some ambiguous bits, and these ambiguous bits always are distinguished by iterative operations on the information exchange between the soft-decision forward error correction decoder and MTO de-mapper at the receiver side, which introduces considerable complexities. To depress the effect of ambiguous bits and avoid iterative operations, polar code with low encoding and decoding complexities is a candidate to deploy in the MTO-based PS scheme, which could avoid iterative operations assisted by the puncturing aided successive cancellation (SC) decoding or successive cancellation list (SCL) decoding algorithms as demonstrated in our previous work [5].

Therefore, in this paper, a polar coded truncated probabilistic shaped 64-QAM (PTPS-64QAM) scheme is proposed and experimentally investigated over G.654E fiber links. The PTPS-64QAM signal could be obtained by combing the in-phase path (I-path) and quadrature path (Q-path) components following the dyadic distribution, which are generated by different polar encoders and mapped with the same mapping rules. At the receiver side, MTO de-mapper is utilized to recover the original transmitted binary sequences by puncturing aided SC or SCL decoding algorithm. Experimental results show that about 2000-km transmission with a post bit error ratio (post-BER) lower than 1.00×10^{-3} could be achieved for the PTPS-64QAM scheme.

2. Principle of PTPS-64QAM

The principle of PTPS-64QAM is shown in Fig. 1. In order to achieve the polar coded truncated probabilistic shaping, a systematic polar encoder should be utilized [5]. After the interleaver, binary bits are sent to the MTO mapper to generate I- and Q-path symbols following the designed mapping rules as illustrated in the inset (I) of Fig. 1. The least significant bit (LSB) is controlled by the frozen bits and the other two bits are controlled by the information bits, which could be obtained from the frozen induces and information induces of polar encoders according to the capacities of bit channels estimated by Gaussian approximation algorithm respectively [6]. Based on the MTO rules, 3-bits sequences are mapped to six-level signals. For instance, symbol '1' could be obtained from two codewords, '110' and '111', where the LSB of symbol '1' are labeled by 'X' to indicate this bit is an ambiguous bit in Fig.1 (I). After QAM mapper, the I-path and Q-path symbols are combined into PTPS-64QAM symbols. At the receiver side, aiming to avoid iterative operations to recover ambiguous bits, puncturing aided decoding algorithm is used as a trade-off between the complexity and performance, which has been elaborated in detail in [5].

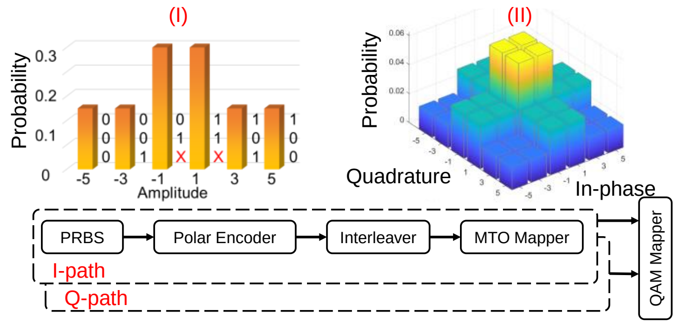

Fig. 1 The principle of PTPS-64QAM. (I) MTO mapping rules for I-path and Q-path. (II) The distribution of PTPS-64QAM.

3. Experimental Setup and Results

The experimental setup together with the Tx and Rx DSP is illustrated in Fig. 2. At the transmitter side, four pseudo random bit sequences (PRBS) with different length are generated and fed to the polar encoder for generating four individual binary bit sequences, which would be sent to MTO mapper to obtain four PS sequences following the designed distribution respectively as illustrated in Fig. 1(I). The dual polarization (DP) PTPS-64QAM symbols could be obtained after QAM mapper. Afterwards, two polarization signals are resampled and ported to arbitrary waveform generator (AWG, Keysight M8196A) operating with 92-GSa/s sampling rate and the output 60-GBaud signals would be amplified by electrical amplifiers (EA, SHF S807B). The continuous waveform (CW) at 193.4-THz from tunable laser source (Keysight N7714A) with a linewidth less than 100 kHz is fed into the I/Q modulator (Fujitsu FTM7977 HQA) and driven by the pre-processed DP PTPS-64QAM signal. Before coupling the optical signal into the recirculating loop, an erbium-doped fiber amplifier (EDFA) is inserted to amplify the signal, which is cascaded by an attenuator to adjust the launch power. Finally, the signals are launched into the recirculating loop, consisting of eight spans of 50-km ultra large effective area fiber (ULAF, G.654E) together with backward-pumped Raman amplifiers (RFA). Besides, in order to flatten the gain slope in the recirculating loop, a wavelength selective switch (WSS) is deployed.

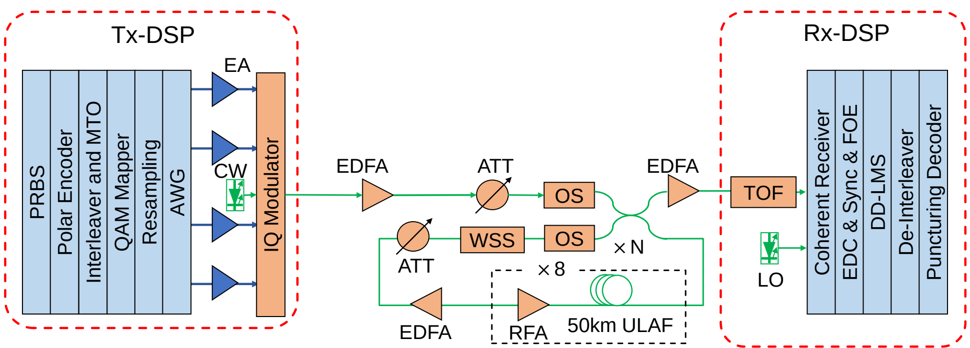

Fig. 2 The experimental setup.

At the receiver side, the optical signal is amplified by another EDFA and the out-of-band noise is removed by the tunable optical filter (TOF) inserted before coherent receiver. Subsequently, the filtered signals are sampled by the 80-GSa/s digital sampling oscilloscope with 36-GHz 3-dB bandwidth, and the DSP is carried out offline. The electrical chromatic dispersion compensation (EDC) and frequency offset estimation (FOE) are performed orderly. Then, a decision-directed least mean square (DD-LMS) based finite-impulse-response filter is utilized to execute compensation for the phase noise and linear time-varying impairments simultaneously [7]. Finally, about 10 million symbols are utilized for performance comparisons and the puncturing aided SCL decoding algorithm with the list size of L =32 is utilized for recovering the original PRBS. Besides, a polar coded uniform distributed (UD) 64-QAM with the same net data rates is also demonstrated for comparison.

Here, owing to the limitation of offline experiments that low BER values could not be reliably estimated, such as 1.00×10^{-15}, an outer low-complexity code having a BER threshold of 1.00×10^{-3} to achieve the final BER of 1.00×10^{-15} is assumed here [8]. The optical back-to-back (OBTB) results are investigated firstly as illustrated in Fig. 3(I). The post-BER of PTPS-64QAM could reach the BER threshold @OSNR=24-dB, while the UD-64QAM fails to reach the BER threshold over the measured OSNR range, indicating that the proposed PTPS-64QAM scheme could provide higher OSNR tolerance compared to UD-64QAM. Besides, the constellations of two polarizations of UD-64QAM and PTPS-64QAM are shown in Fig. 3 (a)-(d) @ OSNR=24-dB respectively. Then, transmission experiments are carried out. The pre-BER of PTPS-64QAM and UD-64QAM versus the launch power after 2000-km links are demonstrated in Fig. 3 (II) and (III), and the constellations with the corresponding optimal launch power are given in the inset (e)-(h) of Fig. 3 respectively. Results show that about 1-dB optimal launch power improvement could be obtained for PTPS-64QAM compared to UD-64QAM, suggesting that a better nonlinear tolerance could be achieved by the proposed scheme. Fig. 3 (IV) illustrates the BER of PTPS-64QAM and UD-64QAM with different transmission distances and results show that the PTPS-64QAM could achieve a pre-BER about 2.00×10^{-2} after 2000-km transmission, which could be lower to 3.34×10^{-4} assisted by the puncturing aided SCL decoding with the list size of L=32. However, the transmission distance of UD-64QAM is limited to 1600-km owing to its high requirement of OSNR. Finally, 5-channels WDM transmissions of PTPS-64QAM in 75-GHz grid over 2000-km links are conducted. Results show that the five channels show similar performance and the post-BER of all the channels could be lower than the BER threshold of 1.00×10^{-3} as demonstrated in Fig. 3 (V).

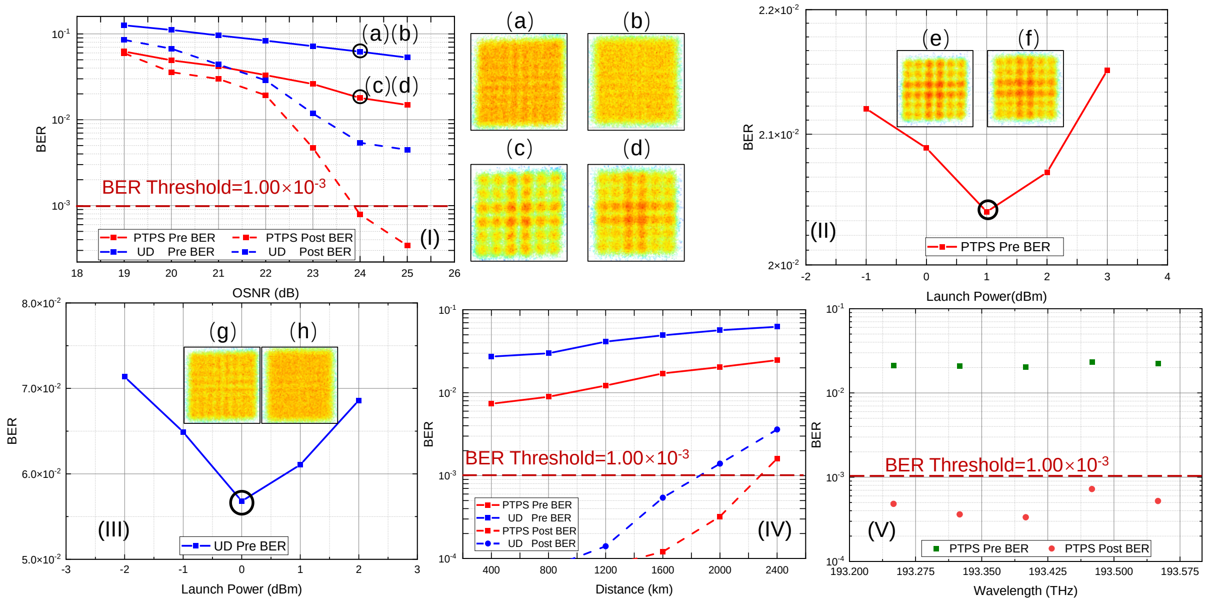

Fig.3 The experimental results: (I) The BER of PTPS-64QAM and UD-64QAM. The Pre-BER versus launch power after 2000-km transmission of (II) PTPS-64QAM and (III) UD-64QAM. (IV) The BER of PTPS-64QAM and UD-64QAM versus different distances with the optimal launch power. (V) The BER of five channels after 2000-km transmission of PTPS-64QAM with optimal launch power. (a)-(b): The constellation of two polarizations of UD-64QAM @OSNR=24-dB; (c)-(d): The constellation of two polarizations of PTPS-64QAM @OSNR=24-dB; (e)-(f): The constellations of two polarizations of PTPS-64QAM after 2000-km transmission @ Launch power =1-dBm. (g)-(h): The constellations of double polarizations of UD-64QAM after 2000-km transmission @ Launch power =0-dBm.

4. Conclusions

In this paper, to the best of our knowledge, polar code is utilized in truncated probabilistic shaping coherent optical communications for the first time and its performance is experimentally evaluated over 2000-km links. Results show that the post-BER of all channels are under the BER threshold of 1.00×10^{-3} after 2000-km transmission aided by the proposed PTPS-64QAM scheme.

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