High Spectral Efficiency Probabilistically Shaped PDM 1024-QAM Transmission System

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***Abstract*—We demonstrate experimentally the 80-km standard single-mode fiber transmission of probabilistically shaped polarization-division multiplexed 1024-QAM signals. The spectral efficiency of 16.19 bit/s/Hz has been achieved with the probabilistic shaping data of 17-bit/symbol information entropy.**

Keywords—Coherent optical communication, digital signal processing, probabilistic shaping, polarization-division multiplexing.

I. INTRODUCTION

The enormous growth in communications traffic arises from rapid development of distributed cloud data centers and 5G technologies. Thus, data center interconnect (DCI) needs to accommodate multiple point-to-point capacities over medium to long distance fiber. One way to meet the DCI demand is to strike the right balance between modulation and demodulation complexity, system bandwidth for wavelength division multiplexing (WDM), and the number of parallel spatial paths. Therefore, a highly accurate, tightly integrated digital coherent receiver become a key device for high-capacity DCI systems [1,2].

In order to achieve high spectral efficiency (SE) of a single carrier, it is straightforward to increase the order of the signal modulation format in addition to polarization-division multiplexed (PDM) techniques. Meanwhile, digital-to-analog converters (DACs) with high effective number of bits (ENOB) and bandwidth periods have been fabricated, which can be used to effectively improve the transmitter ground signal-to-noise ratio (SNR) and increase the noise tolerance of the modulation format. On the other hand, probabilistic shaping (PS) techniques can be used to improve noise tolerance by modifying the probability of the symbols.

Recently, the single carrier-based PDM-64QAM module has been basically commercialized, and the PDM-256QAM experimental system of high baud rate transmission also has been reported, while the performance of higher-order modulation signals such as 1024-QAM and 4096-QAM highly relies on the device noise tolerance and receives limitations in terms of transmission distance and net-rate [3-8].

In this work, we demonstrate experimentally the 80-km standard single-mode fiber (SSMF) transmission of probabilistically shaped PDM-1024-QAM signal. The tradeoff between high optical signal-to-noise ratio (OSNR) and nonlinear impairment is investigated by adjusting the input voltage of the modulator. Exploiting a root-raise-cosine (RRC) filter with the roll-off factor of 0.05, we yield a high SE of 16.19 bit/s/Hz by transmitting a 2-GBd signal while achieving a net bit rate of 32.38 Gb/s.

II. EXPERIMENTAL SETUP

The experimental schematic of PS-PDM-1024-QAM transmission for high SE is shown in Fig 1. At the transmitter side, a single frequency laser with a center frequency of 1550.112 nm is exploited, which has a linewidth of less than 100 Hz. Then, the PS can be achieved based on the probabilistic amplitude shaping (PAS), where the pseudo-random binary sequence (PRBS) is first encoded by constant component distribution matcher (CCDM) to convert a uniformly-distributed sequence into a desired non-uniformly-distributed sequence, and then its output is used as amplitude bits [9]. Here, 0.05% pilot-symbol is interpolated in front of 10,000 symbols with a symbol entropy of 8.5 bits/symbol to assist in depolarization-division multiplexing and phase recovery. After that, the generated PS pulse amplitude modulation (PAM-32) signals are passed through an RRC filter with a roll-off factor of 0.05 and an up-sampling multiplier of 4. Next, the filtered signals are loaded into an 8-GSa/s 14-bit arbitrary waveform generator (AWG) to drive the in-phase/quadrature (I/Q) modulator. Thus, we yield a PS PDM-1024-QAM optical signal.

In the transmission link, the signal from the modulator is first amplified by an erbium-doped fiber amplifier (EDFA) and subsequently enters a variable optical attenuator (VOA) to adjust the launched power into the transmission link. The link uses a G.652D standard single-mode fiber (SSMF) of 80 km with an average loss of 0.18 dB/km and a dispersion of 16.09 ps/nm/km. The received OSNR is 40.57 dB and 36.03 dB after back-to-back (BTB) and 80 km transmission, respectively, with a noise reference bandwidth of 0.1 nm.

At the receiver side, the PS PDM-1024-QAM signal is received by a polarization-diversity coherent receiver and then acquired by a 50-GSa/s real-time oscilloscope for analog-to-

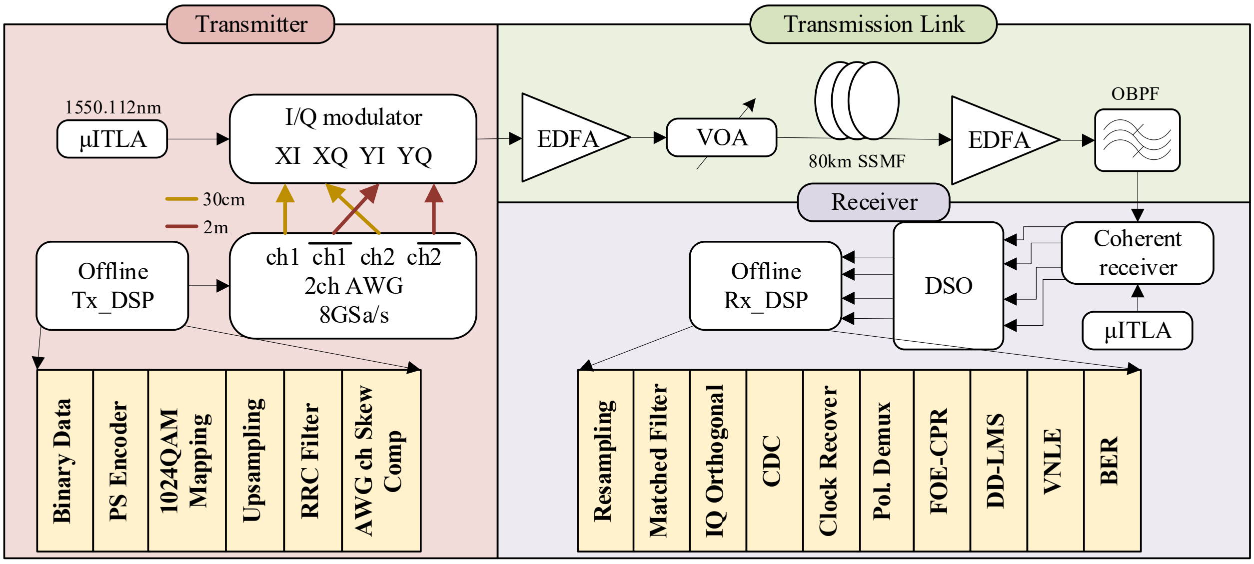

Fig. 1. Experimental setup of PS PDM-1024-QAM signal transmission

digital conversion. Then, the off-line DSP algorithms are implemented, where the received signal is first resampled to 2 samples/symbol and then matched filtered using the RRC filter with the same roll-off coefficient at the transmitter. After that, Gramm-Schmidt orthogonalization process (GSOP) is utilized to compensate impairments caused by I/Q imbalance. Next, the chromatic dispersion of 80-km SSMF is compensated based on frequency domain dispersion equalization. After the clock is recovered by Gardner algorithm, the polarization-division de-multiplexing is pre-converged by using a pilot-assisted minimum-mean-square equalization with a radius-directed equalization (RDE) algorithm [10,11]. Then, Fourier-transform-based frequency offset estimation and blind phase search algorithms are applied for the carrier recovery [12]. Furthermore, Volterra nonlinear equalizer (VNLE) is utilized to compensate nonlinear impairments from nonlinearities of components and link transmission [13,14]. Finally, the signal is demodulated and bit error ratio (BER) is calculated.

III. Measured Results and Discussion

Generally, the BER performance highly relies on the OSNR of the signal. Higher the driving voltage of the modulator, higher the OSNR of the generated signal. However, the nonlinear impairment also plays an important role in the BER performance. Therefore, the BER performance can't be improved consistently with the increase of driving voltage of the modulator. In order to optimize the driving voltage of the modulator, we measured the OSNR of the output optical modulated signal as well as the BER versus the voltage value of input electrical signal in the modulator, as shown in Fig. 2. It is obvious that with the increase of the input voltage, the OSNR increases first fast and then slowly. The BER curve has similar tendency, and the OSNR of fast increase corresponds to the BER of fast decrease. For an input voltage of 350 mV, the OSNR of PS PDM-1024-QAM signal is 45.01dB in the BTB transmission. Although a higher input voltage can increase the OSNR of the modulated signal, it will also induce stronger nonlinear impairments from the modulator, which will seriously deteriorate the BER of decoding bits.

Then, we evaluated the PS PDM-1024-QAM signal performance in back-to-back experiments with an input voltage of 350 mV in the modulator. We exploited a VOA and an EDFA prior to the coherent receiver, to control the noise level for OSNR variation. Fig. 3 plots the experimentally measured and calculated in theory BERs versus various OSNR values. Under the condition of low OSNR, the experimental and theoretical results are close. When the OSNR rises to a certain tolerance, the signal is affected by the components' noise and the BER performance can no longer continually be improved. Fortunately, the error floor is lower than the soft-decision forward-error-correction (SD-FEC) BER threshold.

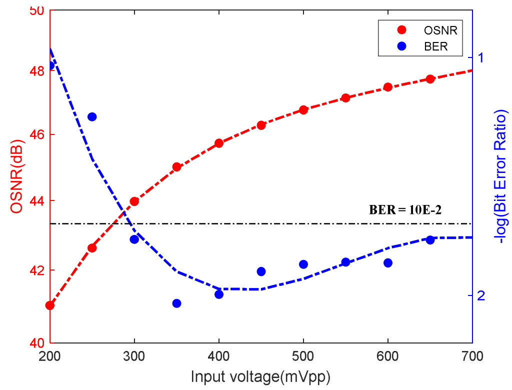

Fig. 2. Measured OSNR and BER vs. input electrical signal's voltage of the modulator

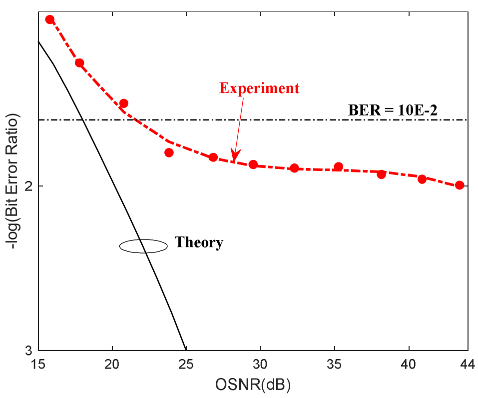

Fig. 3 Measured BER vs. OSNR in the BTB transmission

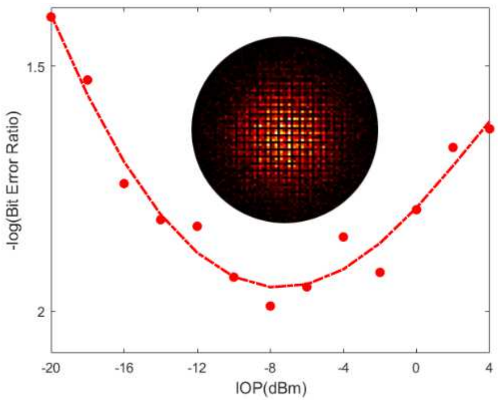

Fig. 4 Measured BER vs. input optical power (IOP) of fiber, the inset shows constellation scatter heatmap of x-polarization PS 1024-QAM signal with the IOP of -8dBm

Finally, we verified the transmission performance of PS PDM-1024-QAM signal over 80-km SSMF. Here, a PS PDM-1024-QAM signal with a dual polarization information entropy of 17 bits/symbol is used, and its SE is calculated by $SE = H\,/\,(1+\alpha)$ to be 16.19 bit/s/Hz. We measured the BER curve as a function of input optical power (IOP) in Fig. 4. The input power into the 80-km SSMF varies between -20 dBm and 4 dBm. We observe that the best performance of the transmission system can be achieved at an input optical power of -8 dBm.

IV. Conclusion

In this work, we demonstrated experimentally the transmission of 2-GBd PS PDM-1024-QAM signal over 80-km SSMF with an assist from ultra-high resolution AWG and ultra-narrow linewidth laser. The driving voltage of the modulator and the input power of the fiber are optimized to achieve the SE of 16.19 bit/s/Hz.

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