Performance investigation of polar coded IM/DD optical OFDM for short reach interconnection

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Abstract—**In this paper, we design a novel polar coded intensity modulation direct detection (IM/DD) optical orthogonal frequency division multiplexing-based (OFDM) system used in short reach interconnection. The experimental results demonstrate the 9.5-dB net coding gain (NCG) at the BER of 1e-3 after 40-km standard single mode fiber (SSMF) transmission.**

Keywords: polar codes, IM/DD, OFDM

I. Introduction

Recently, to meet the increasing demand of high-rate short reach optical communication system, the advanced modulation format [1-2] with the soft-detection forward error correct (FEC) are proposed and considered as one of promising solution， which can achieve power reduction and cost efficiency in short reach optical interconnection. Meanwhile, the optical orthogonal frequency division multiplexing (OFDM) attracts much attention due to its high spectral efficiency, flexible spectral resource allocation, chromatic and polarization mode dispersion (PMD) robustness [3], especially in the intensity modulation direct detection (IM/DD)-based short reach optical interconnection system due to the advantages of cost and energy efficiency brought by simple structure. While in the practical system, the transmission performance is limited by the the subcarrier-to-subcarrier intermixing interference (SSII) induced by the OFDM [4]. To deal with this issue, some works applying the FEC technique were proposed, such as the Reed–Solomon codes and low density parity code (LDPC) codes [5-7]. Whereas, without the proper design, these FEC techniques would bring the high error floor far above the target BER. The concatenated FEC scheme can suppress the error floor effectively, while inducing latency and implementation complexity increasement which can't be tolerated in short reach interconnection.

The polar codes, which can achieve the symmetric capacity of arbitrary binary-input discrete memoryless channels under a low complexity successive cancellation decoding scheme [8], have been chosen as the future fifth-generation (5G) technology in the enhanced mobile broadband (eMBB) scenario by the 3rd Generation Partnership Project (3GPP). However, to the best of our knowledge, the polar coded IM/DD optical OFDM has not been studied in short-reach optical communication literature yet.

To address this research gap, we design a novel polar coded IM/DD optical OFDM system and study it by experiment and simulation. A method of evaluating the channel signal noise ratio (SNR) is proposed for soft demodulation. The results show that, ~9.5-dB net coding gain (NCG) at the BER of 1e-3 after 10-Gb/s 40-km standard single mode fiber (SSMF) transmission can be achieved. Meanwhile, by simulation, the polar codes can achieve 0.3-dB NCG at the BER of 1e-3 compared to the LDPC codes with the same code length and code rate over 20-Gb/s 40-km SSMF.

II. Principle Of Polar Coded Optical OFDM System

Figure.1 gives the system setup of the polar coded IM/DD optical OFDM system for short reach interconnection. The transmitter of the offline digital signal processing (DSP) procedures is presented in Insert (a) of Fig.1. Here, the user's data are encoded by polar codes firstly. The generator matrix G_N of the polar codes is defined as [8]

$$G_N = B_N \cdot F^{\otimes n}, \quad n = \log_2 N \tag{1}$$

$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \tag{2}$$

Where B_N denotes the bit-reversal permutation and N means the code length of the polar codes. The output sequence of the polar encoding bits X_N is Gray mapping to the 16-quadrature amplitude modulation (QAM) constellation every 4-bits as a group. And then the sequence is mapping to the OFDM data subcarriers. The complex data signal, $X=[X_0,X_1,X_2,\ldots,X_{NSC-1}]$, performs the inverse fast fourier transform (IFFT). NSC denotes the number of subcarriers. Since OFDM signals designed for IM/DD systems must be real, the complex data signal X is constrained to have Hermitian symmetry. Before the IFFT operation, the pilot subcarriers are inserted every 20 OFDM symbols for channel estimation at the receiver. After IFFT and adding the cyclic prefix (CP), signal is then converted from parallel to serial (P/S) and a PN sequence is added for the synchronization at receiver.

The receiver of the offline DSP procedures is presented in Insert (b) of Fig.1. The synchronization operates firstly to find correct symbol start. The OFMD demodulation operation includes removing CP, FFT, channel estimation, subcarrier

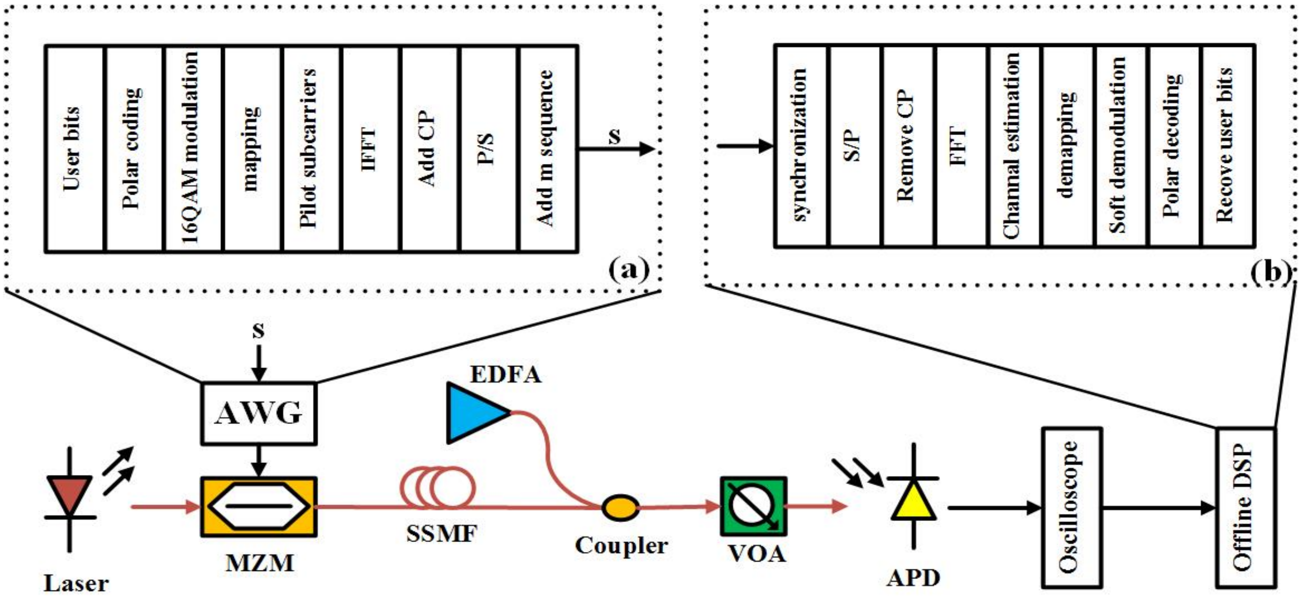

Figure 1. Polar coded IM/DD OFDM System setup (AWG, Arbitrary Waveform Generator; MZM, Mach-Zehnder Modulator; SSMF, Standard Single Mode Fiber; VOA, Variable Optical Attenuator; EDFA, Erbium Doped Fiber Amplifier; APD, Avalanche Photo Diode)

demapping and soft demodulation. The soft-demodulation of 16-QAM is to get the log likelihood ratio (LLR) of every bit that are used for 16-QAM modulation. We assume that four bits, $\{b_1,b_2,b_3,b_4\}$, in the transmitter are mapping to the 16QAM constellation, expressed as a complex value x. And after subcarrier demapping at the receiver, we get the complex value y. The output of LLR in 16-QAM soft demodulator can be expressed as

$$LLR(b_i) = \ln \frac{p(b_i = 0 \mid y)}{p(b_i = 1 \mid y)}, \quad i = 1,2,3,4 \tag{3}$$

The soft demodulation of 16-QAM should have the first knowledge of the noise probability density distribution (PDF). For simplify, we assume the channel of this IM/DD OFDM system as an AWGN channel and the noise follows the zero-mean Gaussian distribution with variance σ^2. However, there have a challenge of getting the knowledge of σ^2 when applying polar codes in IM/DD optical OFDM system. In this paper, we propose a method of evaluating the σ^2 and SNR of the IM/DD optical OFDM channel, and now we will explain it.

At the beginning of the simulation and experiment, we send 16 test sequences $s_k(k=1,2,3\ldots16)$, and every element in the same sequence has the same complex value, which are the value of 16-QAM constellation. At the receiver, we can get 16 test sequences r_k after the subcarriers demapping, the SNR can be calculated as follow

$$SNR = \frac{\sum_{k=1}^{16} E[r_k] \cdot E^*[r_k] / 16}{\sum_{k=1}^{16} E\{r_k - E[r_k]\} \cdot E^*\{r_k - E[r_k]\} / 16} \tag{4}$$

And the σ^2 can be expressed as

$$\sigma^2 = \sum_{k=1}^{16} E\{r_k - E[r_k]\} \cdot E^*\{r_k - E[r_k]\} / 16 \tag{5}$$

Where $E[X]$ denotes the mean of the sequence X. In this way, we can get the SNR of the channel and the LLR of each bit.

In the polar decoding, the successive-cancellation list (SCL) [9] decoding method is adopted to recover the original bit sequence. Parameter L is the number of the path being considering concurrently at each decoding stage, and the computing complexity of the SCL is $O(L*N*\log N)$.

Figure.1 also demonstrates the polar coded IM/DD OFDM system setup. At the transmitter, a continuous-wave laser (Koheras AdjustiK-E15) working at 1550nm is used as the light source. The polar coded OFDM signal is generated in the MATLAB offline and then loaded into the arbitrary waveform generator (AWG, Tektronix AWG7122C) to generate the analog signals. A cost-efficient 10GHz Mach-Zehnder modulator (MZM) is applied to modulate the optical signals. In order to evaluate the polar codes performance at different channel conditions, an erbium doped fiber amplifier (EDFA) is used as the noise source, and use a 2*1 coupler to combine the signals and noise. The variable optical attenuator (VOA) is used to control the receiver power of the optical signals. At the receiver, an avalanche photo diode (APD) is adopted to acquire the electronic polar coded OFDM signals. Subsequently, signals are sampled by the oscilloscope (LeCroy SDA 830Zi-A) for offline processing in MATLAB.

III. RESULTS AND ANALYSIS

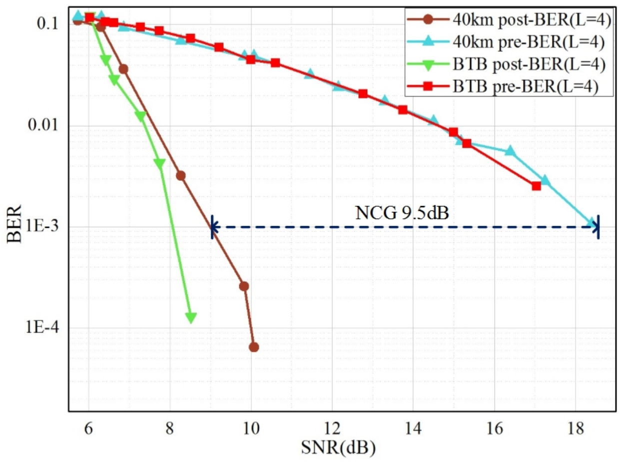

Figure 2. BER versus SNR after BTB and 40 km SSMF transmission in experiment

The experimental results of back-to-back (BTB) and 40-km SSMF transmission are presented in Fig.2. Limited by experimental conditions, the AWG sample rate is set to 10-GS/s. The length of polar codes is 512 and the code rate is 0.5. The IFFT/FFT size of the OFDM signals is 128 and the number of the data subcarriers is 32. So the data rate of polar coded OFDM signal is 10-Gb/s. The parameter L of the SCL decoding method is set to 4. The polar codes obtain the 9.5-dB NCG at the BER of 1e-3 after 40km SSMF transmission. The pre-BER performance of BTB transmission and 40km SSMF transmission are almost the same but the post-BER performance of BTB transmission is better than 40-km SSMF transmission, which has the 1-dB gain at the BER of 1e-3. The reason of this phenomenon is that we assume the channel as an AWGN channel for simplicity and ignore the impact of the chromatic when soft demodulating. However, this degradation of transmission performance can be ignored due to the short transmission distance in short reach optical interconnection.

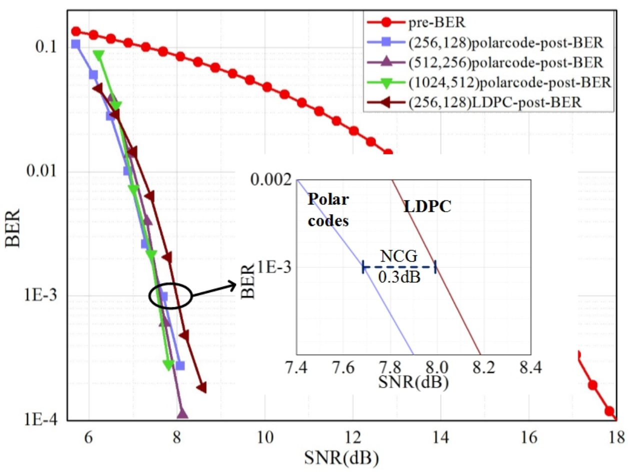

Figure 3. BER versus SNR for polar codes of different code lengths and (256,128)LDPC in simulation

In order to illustrate the superiority of the polar codes performance, we compared with the LDPC codes at the same code length and code rate in simulation. The AWG sample rate is set to 20-GS/s and the other parameters are same as in experiment. So the data rate of polar coded OFDM signal is 20-Gb/s. The decoding method of LDPC is belief propagation (BP) algorithm with the maximum iterations of 50. From the Fig.3, the polar codes have the 0.3-dB NCG at the BER of 1e-3. The BER performance of different code lengths of polar codes are also presented and the impact of code length on the BER performance is negligible.

IV. CONCLUSION:

In this paper, we experimentally demonstrate the polar coded IM/DD optical OFDM-based short-reach transmission system. Also, the method of evaluating the channel SNR proposed is proven to be suitable for soft demodulation. With the proper design of the polar codes, ~9.5-dB NCG can be achieved at the BER of 1e-3 after transmission at 10-Gb/s over 40-km SSMF. Besides, compared to the LDPC codes with the same code length and code rate, ~0.3-dB NCG improvement can be obtained over 20-Gb/s 40-km SSMF. Therefore, owing to its simple structure and excellent transmission performance, the polar coded-based IM/DD optical OFDM techniques would become the promising candidate for future short reach optical interconnection.

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