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Experimental demonstration of polar coded IM/DD optical OFDM for short reach system

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we propose a novel polar coded intensity modulation direct detection (IM/DD) optical orthogonal frequency division multiplexing (OFDM) system for short reach system. A method of evaluating the channel signal noise ratio (SNR) is proposed for soft-demodulation. The experimental results demonstrate that, compared to the conventional case, ~9.5 dB net coding gain (NCG) at the bit error rate (BER) of 1E-3 can be achieved after 40-km standard single mode fiber (SSMF) transmission. Based on the experimental result, (512,256) polar code with low complexity and satisfactory BER performance meets the requirement of low latency in short reach system, which is a promising candidate for latency-stringent short reach optical system.

1. Introduction

Recently, to meet the increasing demand of high-rate short reach optical communication system, the advanced modulation format [1–4] with the soft-detection forward error correct (FEC) [5] are proposed and considered as one of the promising solutions, which can achieve power reduction and cost efficiency in latency-stringent short reach system. As a multicarrier modulation format, 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 [6,7]. At the same time, owing to its simple structure, the intensity modulation direct detection (IM/DD) OFDM has attracts more interest in terms of cost and energy efficiency for short reach system. Compared to the pulse amplitude modulation (PAM) modulation, direct detection OFDM has the larger transmission capacity and higher spectral efficiency [8]. However, the transmission performance is limited by the subcarrier-to-subcarrier intermixing interference (SSII) in IM/DD optical OFDM system [9]. To mitigate the degradation of transmission performance, there are several works focused on applying the FEC technique to the optical OFDM system, including the Reed–Solomon (RS) codes and low density parity code (LDPC) codes [10–13]. Whereas, without the proper design, these FEC techniques would bring the high error floor far above the target bit error rate (BER). The concatenated FEC scheme can suppress the error floor effectively, while will increase latency and implementation complexity which cannot meet the requirement of low latency in short reach system.

In addition, the polar codes, as a novel soft-detection FEC technique which can achieve the symmetric capacity of arbitrary binary-input discrete memoryless channels under a low complexity successive cancellation decoding scheme [14,15], have been chosen as the future fifth-generation (5G) technology in the enhanced mobile broadband (eMBB) scenario by the 3rd Generation Partnership Project (3GPP). In Ref. [5], the authors verified that polar codes are promising candidates for latency-constrained system with short block lengths and the polar codes with list-cyclic redundancy check (CRC) decoding can outperform state-of-the-art LDPC codes in short block lengths. However, to the best of our knowledge, the combining of the polar codes and IM/DD optical OFDM was not yet studied in short reach optical communication literature.

To address this research gap, we proposed and experimentally demonstrate the polar coded-based IM/DD optical OFDM system. To further promote the system performance, we design a novel method of evaluating the channel signal noise ratio (SNR) for soft demodulation. The experimental results demonstrate the net coding gain (NCG) of 9.5 dB at the BER of 1E-3 after 10-Gb/s 40-km standard single mode fiber (SSMF) transmission. Furthermore, (512,256) polar code with low

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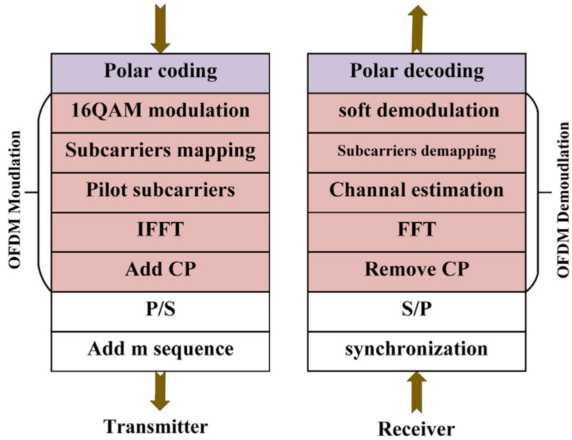

Fig. 1. The block diagram of the polar coded IM/DD optical OFDM.

complexity and satisfactory BER performance meets the requirement of low latency in short reach system. The reminder of this paper is organized as follows. Section 2 discusses the principle of the polar coded IM/DD optical OFDM system and the method of evaluating the SNR. In Section 3, we present the system setup of experiment and discuss the result. Finally, Section 4 gives the conclusions.

2. Principle of polar coded optical OFDM system

Fig. 1 shows the block diagram of the polar coded IM/DD optical OFDM system. At the transmitter, the construction method of polar codes is calculating Bhattacharyya parameters to choose the channels to transmit the information bits [14]. The generator matrix G_N of the polar codes is defined as [14]

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

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

where B_N denotes the bit-reversal permutation and N means the code length of the polar codes. The output sequence of the polar encoder X_N can be expressed as

$$X_N = U_N * G_N. \tag{3}$$

After the polar encoding, the output sequence X_N is Gray mapping to the 16-quadrature amplitude modulation (QAM) constellation every four 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, as

$$X_m = X^*_{NSC-m}, \quad 0 < m < NSC/2. \tag{4}$$

And the two components X_0 and $X_{NSC/2}$ are set to zero, i.e. $X_0 = X_{NSC} = 0$. The subcarriers that not transmitting the information also should be set to zero. So the complex signal X can be denoted as $X = [0, 0, \ldots, X_{start}, X_{start+1}, \ldots X_{start+p-1}, 0, \ldots]$, X_{start} means the first data subcarrier and the p means number of subcarriers used for transmitting data. 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 x is then converted from parallel to serial (P/S) and a PN sequence is added for the synchronization at receiver [16].

At the receiver, the synchronization operates firstly to find correct symbol start. The OFMD demodulation operation includes removing CP, FFT, channel estimation, subcarrier demapping and soft demodulation. The soft-demodulation of 16-QAM is getting the log likelihood ratio (LLR) of every bit that used for 16-QAM modulation. The 16-QAM soft demodulator output the LLR of each bit, which can be expressed as

$$LLR(b_i) = \ln \frac{p(b_i = 0|y)}{p(b_i = 1|y)}, \quad i = 1, 2, 3, 4 \tag{5}$$

where b_i means the coding bit in the transmitter. 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 soft demodulator should use the complex value y to calculate the LLR of each four bit. Since the probabilities of $b_i = 0$ and $b_i = 1$ in polar coded signal are equal, the posterior probability of $p(b_i = 0|y)$ and $p(b_i = 1|y)$ can be expressed as

$$\begin{cases} p(b_i = 0|y) = \dfrac{p(y|b_i = 0)}{p(y|b_i = 0) + p(y|b_i = 1)} \\ p(b_i = 1|y) = \dfrac{p(y|b_i = 1)}{p(y|b_i = 0) + p(y|b_i = 1)} \end{cases} \tag{6}$$

where the $p(y|b_i = 0)$ and $p(y|b_i = 1)$ are the prior probabilities of b_i. For simplicity, we assume the channel from x to y is an additive white gaussian noise (AWGN) channel, so we can calculate the $p(y|b_i = 0)$ as follows

$$\begin{aligned} p(y|b_i = 0) &= \sum_{k=1}^{8} p(y_{re}, s_{re,k,i,0}) \cdot p(y_{im}, s_{im,k,i,0}) \\ &= \sum_{k=1}^{8} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(y_{re} - s_{re,k,i,0})^2}{\sigma^2}\right) \\ &\quad \cdot \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(y_{im} - s_{im,k,i,0})^2}{\sigma^2}\right) \end{aligned} \tag{7}$$

where $y = y_{re} + j^* y_{im}$. When $b_i = 0$, there are eight possible cases of the other three bits. And the $p(y|b_i = 0)$ are the sum of these eight probabilities. In Eq. (7), k means the index of the possible case and s means the constellation value of these possible case. And the σ^2 means the variance of the noise. In this way, we also can calculate the $p(y|b_i = 1)$, so that we can get the LLR of each bit using the Eqs. (5) and (6).

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 in detail. When a signal $s(t)$ transmits to an AWGN channel, the received signal $r(t)$ can be given by

$$r(t) = s(t) + n(t) \tag{8}$$

where $n(t)$ is a zero-mean Gaussian noise process. The noise power can be denoted as $E[n^2(t)]$, and the signal power can be denoted as $E[s^2(t)]$. If we assume the transmitting signal $s(t)$ is constant, which can be denoted as s. The received signal is $r(t) = s + n(t)$. Then we can get that

$$\begin{aligned} D[r(t)] &= E^2\{r(t) - E[r(t)]\} \\ &= E[r^2(t)] - E^2[r(t)] \\ &= E[(s + n(t))^2] - E^2[s + n(t)] \\ &= E[n^2(t)] \end{aligned} \tag{9}$$

$$\begin{aligned} E^2[r(t)] &= E^2[s + n(t)] \\ &= \{E[s] + E[n(t)]\}^2 \\ &= E^2[s]. \end{aligned} \tag{10}$$

From the Eqs. (9) and (10), the noise power can be calculated using $D[r(t)]$ and signal power can be calculated using $E^2[r(t)]$. ($E[X]$ denotes

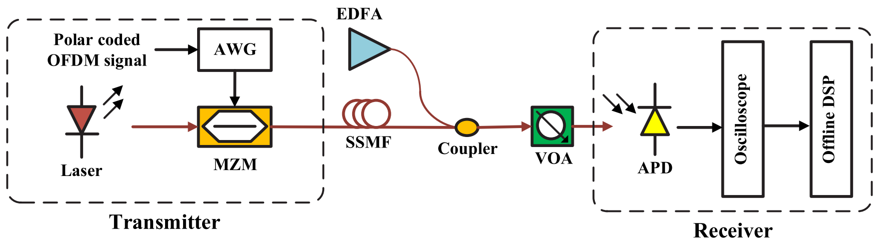

Fig. 2. System architecture of polar coded IM-DD OFDM transmission (AWG, arbitrary waveform generator; MZM, Mach–Zehnder modulator; SSMF, standard single mode fiber; VOA, variable optical attenuator; EDFA, erbium doped fiber amplifier; APD, avalanche photo diode).

the mean of the sequence X, the $D[X]$ denotes the variance of the sequence X). Then the SNR can be expressed as

$$SNR = \frac{E^2[r(t)]}{D[r(t)]}. \tag{11}$$

Due to the 16-QAM modulation, the transmitting signals $s(t)$ have 16 complex values can be set. At the beginning of the experiment, we send 16 test sequences $s_k(k = 1, 2, 3 \ldots 16)$, and every element in the same sequence has the same complex value. At the receiver after the subcarriers demapping, we can get 16 test sequences r_k, and the SNR can be calculated as follow

$$\begin{aligned} SNR &= \frac{\sum_{k=1}^{16} E[r_k] \cdot E^*[r_k]/16}{\sum_{k=1}^{16} E\{r_k - E[r_k]\} \cdot E^*\{r_k - E[r_k]\}/16} \\ &= \frac{\sum_{k=1}^{16} E[r_k] \cdot E^*[r_k]}{\sum_{k=1}^{16} E\{r_k - E[r_k]\} \cdot E^*\{r_k - E[r_k]\}}. \end{aligned} \tag{12}$$

And the σ^2 equals to $D[r(t)]$, and we can calculate it as follow

$$\sigma^2 = \sum_{k=1}^{16} E\{r_k - E[r_k]\} \cdot E^*\{r_k - E[r_k]\}/16. \tag{13}$$

In this way, we can get the SNR of the channel and the LLR of each bit. The SCL [17] 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 $O(L * N * \log N)$.

3. Experiment setup and result discussion

Fig. 2 illustrates the system setup for polar coded IM/DD optical OFDM system. At the transmitter, a continuous-wave laser (Koheras AdjustiK-E15) working at 1550 nm is used as the light source. The polar coded OFDM signal is firstly generated offline in MATLAB and then loaded into the arbitrary waveform generator (AWG, Tektronix AWG7122C) to generate the analog signals. A cost-efficient 10 GHz Mach–Zehnder modulator (MZM) is applied to modulate the optical signals. In order to evaluate the polar codes performance at different channel conditions, we use an erbium doped fiber amplifier (EDFA) 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) based on the direct detection is adopted to acquire the electronic polar coded OFDM signals. Subsequently, signals are sampled by the oscilloscope (LeCroy SDA 830Zi-A) and restored for digital signal processing (DSP) offline in MATLAB.

Fig. 3 demonstrates the experimental results of back to back (BTB) transmission in different code lengths of polar codes. Limited by experimental conditions, the AWG sample rate is set to 10 GS/s. The code rates are all set to 0.5. The IFFT/FFT size of the OFDM signals is 128 and the number of the data subcarriers is 32. Therefore, the data rate of polar coded OFDM signal is 10-Gb/s. The launch power is precisely adjusted for BTB transmission to obtain the best performance and avoid the nonlinear distortions induced by the high peak-to-average power ratio (PAPR). The optimal output power of the laser is 8 dBm.

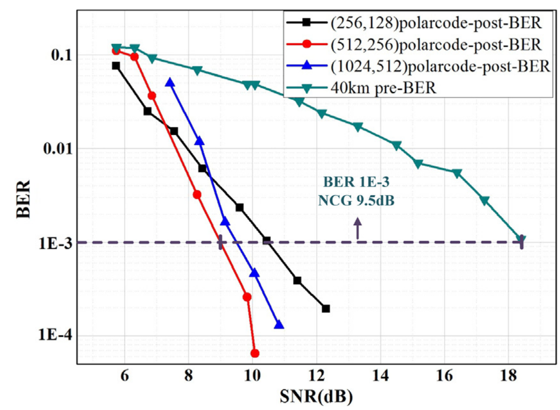

Fig. 3. BER versus SNR after BTB transmission in experiment.

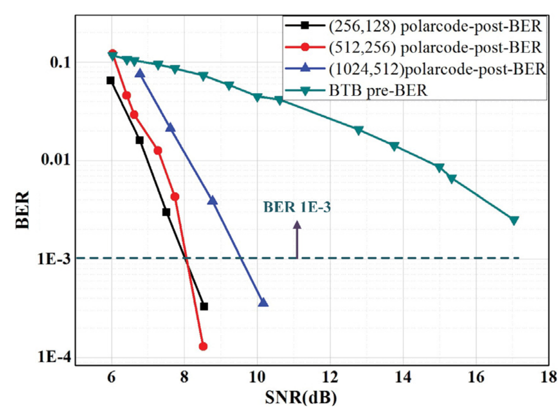

Fig. 4. BER versus SNR after 40-km SSMF transmission in experiment.

Taking into consideration of the low latency requirement in short reach interconnection, the parameter L of the SCL decoding method is set to 4 to reduce the complexity in decoding. Comparing the results of different code lengths, when the SNR is lower than 8 dB, the (256,128) polar code has the best performance while the (512,256) polar code performs better than the (256,128) polar code when the SNR is higher than 8 dB. And the (1024,512) polar code has the worst performance in this BTB transmission experiment.

The experimental results of 40-km SSMF transmission are demonstrated in Fig. 4. The parameters in 40-km SSMF transmission experiment are the same as those in BTB transmission experiment and the laser power is also precisely adjusted to 8 dBm for 40-km SSMF transmission. From the Fig. 4 we can know that (512,256) polar code has the best performance compared with the other two polar codes and the NCG of 9.5 dB is achieved at the BER of 1E-3. The BER curve of (256,128) polar code declines slow when the SNR becoming high. Similar with the BTB transmission, (1024,512) polar code has less NCG than (512,256) polar code at the BER of 1E-3. The results from Figs. 3 and 4 both show that the performance of (1024,512) polar code is worse than the (512,256) polar code. However, in the theory of channel polarization [14], the degree of channel polarization becomes large as the code length N increasing, which contributes to the better BER performance. The results of the experiment do not match this theory. The reason of this phenomenon can be explained as follows. The channel polarization gain brought by code length N can be neglected in the short code length such as (1024,512), (512,256) cases. The SCL decoding method uses successive decision, in which the former estimated bit affects the latter estimated bit in one block of polar code. If the first error estimated occurs in the ith bit ($i = 1, 2, \ldots, N$), $i + 1, i + 2, \ldots, 1024$th bits will be affected for (1024,512) polar code while only $i+1, i+2, \ldots, 512$th bits will be affected for (512,256) polar code, resulting in the worse BER performance for (1024,512) case. The computing complexities for the IFFT and FFT operation are both $O(\mathrm{NSC} * \log \mathrm{NSC})$. The computing complexities for polar encoder and decoder are $O(N * \log N)$ and $O(L * N * \log N)$ respectively. When the L is set to 4 in the SCL polar decoding operation, the computing complexities for the polar en/decoding are quite similar to those for the IFFT/FFT operations. Since the latency induced by the IFFT/FFT operations is tolerable for the short reach optical system, the computing complexity for the proposed IM/DD optical polar coded OFDM system meets the requirement of the short reach optical system. When comparing the performance of different polar codes, (512,256) polar coded IM/DD optical OFDM with SCL ($L = 4$) is a promising candidate for latency-stringent short reach optical interconnection.

4. Conclusion

In this paper, we experimentally demonstrate the polar coded IM/DD optical OFDM transmission system. (512,256) polar code has the NCG of 9.5 dB at the BER of 1E-3 after 10-Gb/s 40-km transmission in the experiment. The method of evaluating the channel SNR is well suitable for the soft demodulation. Compared with different short code lengths of polar codes, (512,256) polar code with low complexity and satisfactory BER performance meets the requirement of low latency in short reach optical interconnection, which can become the promising candidate for future short reach system.

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