Experimental evaluation of the BER performance in optical OFDM system based on discrete Hartley transform precoding*

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We experimentally assess the bit error rate (BER) performance of an intensity modulation/direct detection (IM/DD) optical orthogonal frequency division multiplexing (OFDM) system based on discrete Hartley transform (DHT) precoding in single-mode fiber (SMF) link for 2.5 Gbit/s quadrature phase shift keying (QPSK) OFDM symbol rate. The experimental results show that for the optical OFDM system based on DHT-precoding, the receiver sensitivity at the BER of 10^{-4} after 100 km SMF transmission is about 1.5 dBm better than that of the original QPSK OFDM signal, and the DHT-precoded OFDM QPSK signal can achieve approximately 1.3 dB of peak-to-average power ratio (PAPR) reduction.

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In recent years, the orthogonal frequency division multiplexing (OFDM) has been proposed for communication over optical fiber links to combat channel dispersions in fiber media which limit the data rate and length of optical fiber links[1,2]. These efforts can be divided into two different approaches: coherent optical detection and direct detection optical OFDM systems. Intensity modulation/direct detection (IM/DD) systems have lower optical hardware complexity. We focus on IM/DD systems in this work. High peak-to-average power ratio (PAPR) has been recognized as one of the major practical problems for OFDM modulation. Many PAPR reduction techniques have been proposed for wireless OFDM systems, such as clipping, companding, coding and partial transmit sequences[3]. Currently, some precoding techniques have been advanced to reduce the PAPR of the OFDM signals, such as Hadarmad and DCT precoders[4-10]. These methods can not only reduce the PAPR but also improve the BER of the OFDM system. In Ref.[6], the DHT precoding has been applied to the wireless OFDM system. The analysis and simulation results show that the PAPR and BER performance can be improved. However, the experiment research on the optical IM/DD OFDM system based on DHT precoding has not been reported.

In this paper, the BER performance of the DHT precoding optical OFDM system is evaluated by experiment. In our experiment setup, 2.5 Gbit/s QPSK OFDM signal is generated and transmitted over 100-km standard single-mode fiber link. The experiment results demonstrate that the HDT precoding scheme can reduce the PAPR of OFDM signal and can also improve the BER performance of system.

DHT can be defined as[11]:

$$X(k)=\frac{1}{\sqrt{M}}\sum_{n=0}^{M-1}x(n)[\cos(2\pi kn/M)+\sin(2\pi kn/M)]$$
$$k=0,\quad 1,\quad \cdots,\quad M-1. \tag{1}$$

DHT of size M-by-M can be created by using

$$t_{ij}=\operatorname{cas}\left(\frac{2\pi ij}{M}\right)=\cos\left(\frac{2\pi ij}{M}\right)+\sin\left(\frac{2\pi ij}{M}\right), \tag{2}$$

where $i=0,\ 1,\ \cdots,\ M-1$ and $j=0,\ 1,\ \cdots,\ M-1$. The $M\times M$ DHT precoding matrix $\boldsymbol{T}$ is given as

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$$\boldsymbol{T} = \begin{bmatrix} t_{00} & t_{01} & \cdots & t_{0(M-1)} \\ t_{10} & t_{11} & \cdots & t_{1(M-1)} \\ \vdots & \vdots & \vdots & \vdots \\ t_{(M-1)0} & t_{(M-1)1} & \cdots & t_{(M-1)(M-1)} \end{bmatrix}, \tag{3}$$

where t_{ij} means the *i*th row and *j*th column of the DHT precoding matrix.

Fig.1 shows a DHT precoding based on optical IM/DD OFDM system. On the transmitter end, a DHT precoding matrix $\boldsymbol{T}$ with dimension $M \times M$ is applied to the constellation symbols to lower the autocorrelation of input sequence for the inverse fast Fourier transform (IFFT) to reduction the PAPR. The number of subcarriers is N=2M. In the transmitter, the transformed symbols are processed by the IFFT unit.

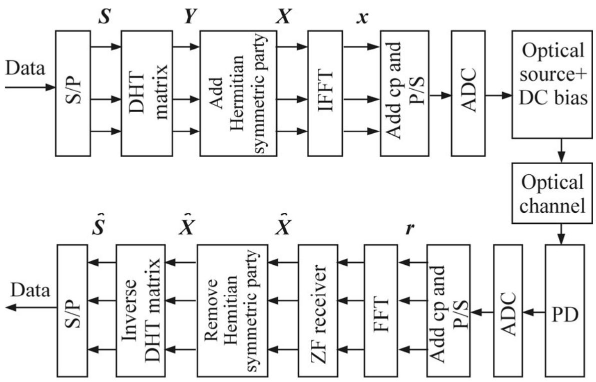

Fig.1 Block diagram of the proposed system

In the DHT precoding based on optical IM/DD OFDM systems, baseband modulation data is passed through S/P converter which generates a complex vector with size *M*, which can be written as follows:

$$\boldsymbol{S} = \left[S_0 \quad S_1 \quad \cdots \quad S_{M-1} \right]^{\mathrm{T}} . \tag{4}$$

The DHT precoding is applied to this complex vector which transforms this complex vector into new vector with the same length *M*, which can be written as follows:

$$\boldsymbol{Y} = \boldsymbol{TS} = \left[Y_0 \quad Y_1 \quad \cdots \quad Y_{M-1} \right]^{\mathrm{T}}, \tag{5}$$

where $\boldsymbol{T}$ is a precoder matrix with size $M \times M$ and Y_l can be written as follows:

$$Y_l = \sum_{j=1}^{M-1} t_{ij} S_j \,, \quad 1 = 0, \quad 1, \quad \cdots, \quad M-1 . \tag{6}$$

Eq.(5) represents the DHT precoded constellation symbols. After the precoding operation, we get the Hermitian symmetric data vector $\overline{\boldsymbol{Y}}$. It is expressed as:

$$\overline{\boldsymbol{Y}} = \left[Y_{M-1}^{*} \quad \cdots \quad Y_1^{*} \quad Y_0^{*} \right]^{\mathrm{T}} . \tag{7}$$

Thus, the OFDM data frame with size *N* can be written as

$$\boldsymbol{X} = \left[\boldsymbol{Y}^{\mathrm{T}} \quad \overline{\boldsymbol{Y}}^{\mathrm{T}} \right]^{\mathrm{T}} . \tag{8}$$

The vector $\boldsymbol{X}$ is transformed by the IFFT unit, so the output of the IFFT is expressed as:

$$\boldsymbol{x} = IFFT\left(\boldsymbol{X}\right) . \tag{9}$$

At the receiver side, the optical domain signal is transformed to electric domain signal by the PD detector. After that, the cyclic prefix is removed and the fast Fourier transform (FFT) function is executed. So the data symbol in the *k*th subcarrier can be written as follows:

$$R_k = H_k X_k + Q_k \,, \; k = 0, \quad 1, \quad \cdots, \quad N-1 , \tag{10}$$

where H_k is the channel discrete frequency response and Q_k is zero-mean Gaussian noise with variance N_0 .

Then the equalization and zero forcing (ZF) receiver is carried out on each obtained signal R_k with size $N \times N$. The output of the ZF receiver is data vector $\hat{\boldsymbol{X}}$ with size $N \times N$.

After removed the Hermitian symmetric data, then the new data vector is expressed as:

$$\hat{X}_k = H_k X_k + Q_k \,, \quad k = 0, \quad 1, \quad \cdots, \quad N/2-1 . \tag{11}$$

Doing the inverse DHT to X_k , then the estimated data symbols can be expressed as:

$$\hat{S}_k = T^{-1} \hat{X}_k = H_k T^{-1} X_k + T^{-1} Q_k = \\ H_k T^{-1} X_k + W_k \,, \; k = 0, \quad 1, \quad \cdots, \quad N/2-1 . \tag{12}$$

Due to the unitary property of T , $W_k = T^{-1} Q_k$ continues to be uncorrelated Gaussian random variables with variance.

Fig.2 shows the experimental setup of an IM/ID optical OFDM system with DHT precoding. The data frame is first precoded by DHT matrix and then mapped into the data modulation symbols (such as BPSK, QPSK, 16QAM). Then the data modulation symbols are modulated by the IFFT unit. The DHT-precoded baseband OFDM signals are generated offline and uploaded into an arbitrary waveform generator (AWG). In the receiver, we use MATLAB program to process waveform, which is recorded by a real-time oscilloscope. The symbols rate of the OFDM signals is 2.5 Gbit/s. In our experiment, the central wavelength of the continuous lightwave (CW) is 1565.350 nm. The Mach-Zehnder modulator (MZM) is biased at 1.9 V.

In experiment setup, there are 256 subcarriers, in which 200 subcarriers are used for data and 56 subcarriers are set to zero as guard interval. The cyclic prefix with 32 symbols is used for avoiding inter block inter block interference. The optical launch power is -2 dBm.

PAPR is defined as the ratio between the maximum peak power and the average power of the transmitted OFDM signals. The PAPR of the OFDM signals $x(n)$ is defined as

$$PAPR = \frac{\max\limits_{0 \le n \le N-1} \left[\left| x(n) \right|^2 \right]}{E\left\{ \left| x(n) \right|^2 \right\}} . \tag{13}$$

The PAPR performance of an OFDM system can be evaluated using the complementary cumulative distribution function (CCDF) to measure the PAPR. The CCDF of PAPR can be expressed as

$$P_{\mathrm{c}} = \Pr\left\{ PAPR > \zeta_{\mathrm{P}} \right\}. \tag{14}$$

P_{c} indicates the probability that PAPR exceeds a particular value $k = 0,\ 1,\ \cdots,\ N-1$.

The PAPR of the DHT precoded OFDM signal can be calculated by Eq.(14). In experiment setup, the 50000 OFDM data frames are used to measure the PAPR of the OFDM signal. Fig.3 shows the CCDF comparison of the PAPR of the DHT-precoded system with that of the conventional system at CCDF of 10^{-3}.

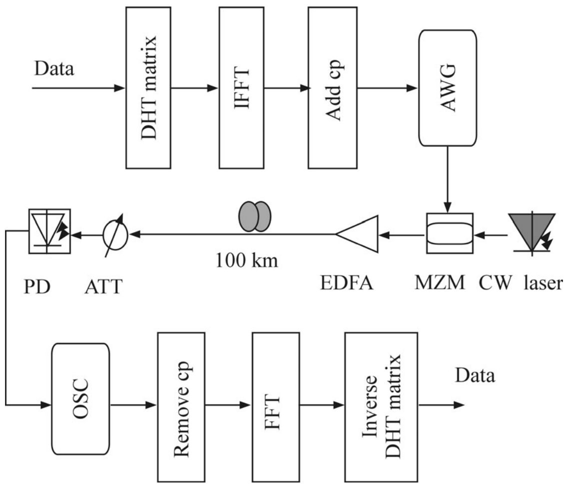

Fig.2 Experimental setup (AWG: arbitrary waveform generator; MZM: Mach-Zehnder modulator; EDFA: erbium doped fiber amplifier; ATT: attenuator; PD: photodiode; OSC: oscilloscope)

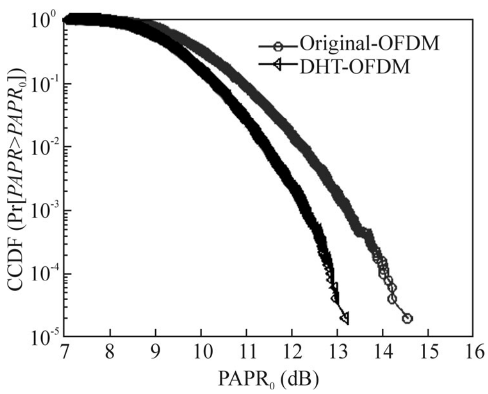

Fig.3 Comparison of the PAPRs of the OFDM signals

In this section, we evaluated the BER of the optical IM/DD OFDM system based on DHT precoding scheme. The symbol rate of the QPSK OFDM signal is fixed at 2.5 Gbit/s. Fig.4 shows that the received sensitivity of the DHT precoded system at the BER of 10^{-4} after 100 km SMF transmission is about 1.5 dB better than that of the original OFDM signal. The experimental results are consistent with the previously reported results in Refs.[12,13].

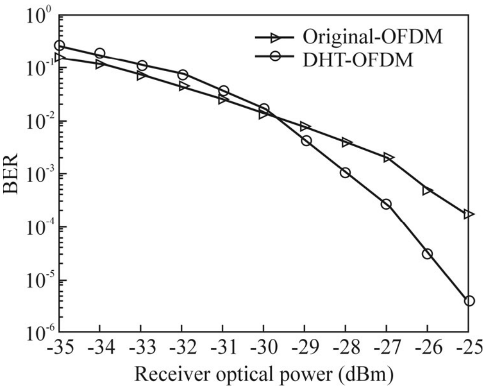

Fig.4 Measured BER vs. received optical power

We measure the constellation diagrams of the transmission signals. Figs.5 and 6 show the constellations of the original and DHT-precoded QPSK OFDM signals at receiver optical power of -27 dBm, respectively. From the measured constellation graphs of the received signals, we can see that the quality of the modulated symbols with precoding in Fig.6 is better than that of the original symbols in Fig.5.

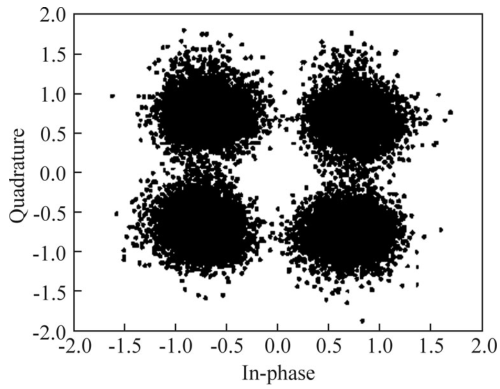

Fig.5 Constellation of the original OFDM signal with the received optical power of -27 dBm

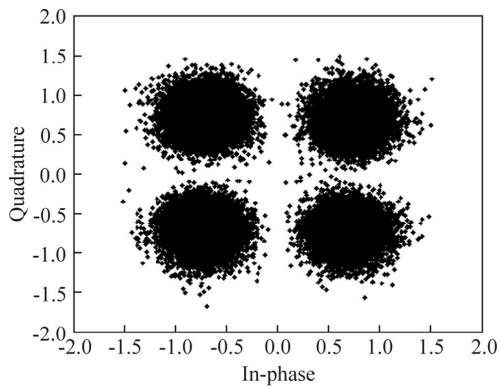

Fig.6 Constellation of the DHT-precoded OFDM signal with the received optical power of -27 dBm

We have shown a DHT-precoding scheme for an optical IM/DD OFDM system. The BER performance of the proposed scheme was evaluated in optical OFDM transmission experimental platform. The experimental results show that the sensitivity of the system based on DHT-precoding is about 1.5 dBm better than that of the conventional OFDM system at the BER of 10^{-4} after 100 km SMF transmission. The PAPR of the proposed DHT-precoded optical OFDM system can achieve approximately 1.3 dB reduction compared with that of the conventional system.

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