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Grouped DCT precoding for PAPR reduction in optical direct detection OFDM systems*

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A new grouped precoding technique based on discrete cosine transform (DCT) is presented for peak to average power ratio (PAPR) reduction of optical intensity modulated/direct detection (IM/DD) orthogonal frequency division multiplexing (OFDM) system. The computational complexity of the scheme is reduced by at least about 15% compared with that of the ordinary DCT precoding scheme when the number of groups is 2. The PAPR with this method can be reduced by about 0.8 dB. Meantime, compared with original OFDM, the bit error rate (BER) performance of system is improved. So the proposed scheme for reducing PAPR is very effective in optical IM/DD OFDM systems.

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Orthogonal frequency division multiplexing (OFDM) has been widely used in modern wireless communications. In recent years, OFDM has been used in optical communications, because it can combat fiber chromatic dispersion and polarization mode dispersion[1]. As our purpose is to apply peak to average power ratio (PAPR) reduction techniques in intensity modulated/direct detection (IM/DD) systems, we must transmit a real signal. To generate real OFDM signals, Hermitian symmetry (HS) must be forced when using the fast Fourier transform (FFT). However, the high PAPR of OFDM signals is the main problem for optical OFDM system. A large PAPR gives rise to signal impairments through the nonlinearity of modulator, and fiber thus degrades the transmission performance[2,3]. For reducing the PAPR of OFDM signals, many methods are proposed for wireless communication and optical OFDM systems, which can introduce distortion to the signal, reduce the available bandwidth and increase the power. In Ref.[4], the Hadamard precoding is applied to optical OFDM systems based on IM/DD channel, and the performances of the PAPR and bit error rate (BER) are both improved. In Ref.[5], PAPR reduction using discrete cosine transform (DCT) is proposed in OFDM system, but the impact of the proposed scheme on the BER of optical system has not been researched.

The main advantage of precoded PAPR reduction techniques is that there is no degradation in BER of system. However, the complexity of system with precoding is increased compared with that of the system without precoding. In precoding, the modulated data of each OFDM block is multiplied by a precoding matrix before inverse FFT (IFFT) block, and the inverse precoding matrix is applied after FFT block to recover the modulated data.

In this paper, we propose a new grouped DCT precoding to reduce the PAPR of real OFDM signals for IM/DD optical systems. The grouped precoding based on grouped DCT reduces the computational complexity of precoding and inverse precoding. Both the PAPR and BER of optical system are researched based on grouped DCT. The performance of optical OFDM system with grouped precoding is evaluated over plastic optical fibers (POFs) by computer simulation. The experiment results show that the grouped DCT precoding can reduce PAPR compared with the conventional optical OFDM IM/DD system. Meantime, the performance of optical OFDM system is also improved. It is observed that precoding takes advantage of the frequency selectivity of the communication channel, and improves the system performance considerably, which is consistent with previously reported results[6,7].

The IM/DD optical system has lower complexity and cost, so it is used in a broad range of applications. In this paper, we only consider the IM/DD optical OFDM system. In an IM/DD optical system, the information is carried on

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the intensity of the optical signal, which can only be positive and real-valued. The optical system is the required direct current (DC) bias to make the OFDM signal non-negative.

An OFDM symbol obtained by the IFFT can be written as

$$x(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}X(k)\exp(2\pi jkn/N)\,,\quad k=0,\ 1\ \cdots\ N-1, \tag{1}$$

where $X(k)$ (k=0, 1 ⋯ N-1) is input symbols modulation data, n is the discrete time index, and N is the number of subcarriers. To generate real OFDM symbols, the elements $x(n)$ of the input vector must satisfy the HS property, so that only half of the vector supports independent data[8]. In order to produce real-valued OFDM signal of $x(n)$, the input data vector $\boldsymbol{X}=\{X_k, k=0,\ 1\ \cdots\ N-1\}$ of IFFT must satisfy HS of $X_k=X_{N-k}^{*}$.

High PAPR is one of the major drawbacks of OFDM signals. For IM/DD optical OFDM system, the PAPR is also considered as the main problem. The PAPR is defined as the ratio between the maximum peak power and the average power of the transmitted OFDM signal. In the discrete time domain, the PAPR of OFDM signals $x(n)$ is defined as

$$PAPR(x)=10\log_{10}\frac{\max\left[|x(n)|^2\right]}{E\left[|x|^2\right]},\ 0\le n\le N-1\,, \tag{2}$$

where $E[.]$ denotes the average value over the time duration of OFDM symbol.

The complimentary cumulative distribution function (CCDF) of PAPR is commonly used to measure the performance of PAPR reduction techniques[2,8]. The CCDF is the probability of the PAPR exceeding the certain threshold $PAPR_0$, which is expressed as

$$CCDF\{PAPR[x(n)]\}=\Pr\{PAPR>PAPR_0\}=1-(1-\mathrm{e}^{PAPR_0})^N\,. \tag{3}$$

We present the grouped DCT precoding technique for PAPR reduction. The main purpose of grouped precoding is to reduce the computational complexity of precoding matrix, while maintaining both diversity gain and PAPR reduction. The basic idea behind this approach is that the N/2 data is divided into M groups and every group data is firstly transformed by a DCT matrix. The obtained new N/2 data and its N/2 HS data are modulated by IFFT with N points.

Fig.1 is the transmitter schematic diagram of an optical OFDM system for PAPR reduction with grouped DCT precoding. Then complexity of the system with the group precoding is reduced compared with that of the conventional DCT precoding[5].

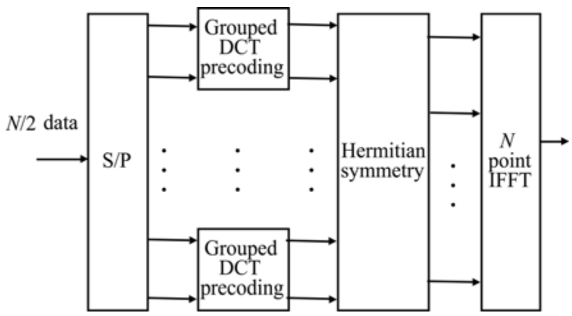

Fig.1 Transmitter diagram of the grouped DCT precoding

Referring to the transmitter model shown in Fig.1, let $S[k]$ (k=0, 1 ⋯ MP) denote MP data symbols, which are modulated by binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or any other quadrature amplitude modulation (QAM) format. Let $N/2=MP$.

Before precoding, the MP data symbols are firstly divided into M groups of size P with the mth group denoted as a vector

$$\boldsymbol{s}_m=\left[x(mP),\quad x(mP+1)\quad\cdots\quad x(mP+P-1)\right]^{\mathrm{T}},\quad m=0,\ 1\ \cdots\ M-1\,. \tag{4}$$

The grouped DCT precoding process is to apply a $P\times P$ DCT matrix to each vector of $\boldsymbol{x}_m$.

The DCT is a real transform which consists of multiplying the data by a cosine function. The $P\times P$ DCT transform matrix $\boldsymbol{C}$ is given as:

$$C_{ij}=\begin{cases}\dfrac{1}{\sqrt{P}} \\ \sqrt{(2/P)}\cos\left[\dfrac{(2j+1)\pi}{2P}\right], & \text{if}\quad i>0\end{cases}, \tag{5}$$

where i represents row entry and j represents the column entry. For a $1\times P$ vector of $\boldsymbol{s}_m$, $\boldsymbol{S}_m$ is its DCT transform, so we have $\boldsymbol{S}_m=\boldsymbol{C}\boldsymbol{s}_m$, where $\boldsymbol{C}$ is called as the DCT matrix. After precoding, the new data is expressed as a vector $\boldsymbol{X}=[S_1\ S_2\ \cdots\ S_M]^{\mathrm{T}}$. Assume $\bar{\boldsymbol{X}}$ is the HS vector of $\boldsymbol{X}$, so the input of IFFT is $\left[\boldsymbol{X}\quad \bar{\boldsymbol{X}}\right]^{\mathrm{T}}$.

POFs provide a new, flexible alternative for local area network (LAN) connections. Mode dispersion is a distortion mechanism occurring in multimode fibers and other waveguides, in which the signal is spread in time because the propagation velocities of the optical signal for all modes are not the same. Modal dispersion in POF is also considered as a type of intersymbol interference (ISI). So without loss of generality, we don't consider effect of the nonlinearity of distributed feedback (DFB) laser diode (LD) and optic-electro (O/E) detection component. At the receiver, the signal is

$$r(t)=x(t)h(t)+n(t)\,. \tag{6}$$

The channel is not monic, and is obtained from the used

POF in our system, which can be expressed as[9]:

$$h(t)=\frac{A}{\sqrt{2\pi}\sigma}\cdot e-\frac{(t-\tau\cdot L_{\mathrm{pof}})^2}{2\cdot\sigma^2}, \tag{7}$$

where the parameters are defined as $\sigma=0.132/B_{3\,\mathrm{dB}}$, $\tau=4.97\times10^{-9}$ s/m, L_{pof} (m) is the POF length, and $B_{3\,\mathrm{dB}}$ is the 3 dB bandwidth of POF. In this paper, we adopt the standard step-index (SI)-POF with bandwidth of 40 MHz× 100 m and numerical aperture (NA) of 0.5. In the below simulations, the number of precoding groups M is set as 2.

Fig.2 shows the CCDF comparison of optical IM/DD OFDM systems with the two DCT precoding schemes for PAPR reduction with N=256 subcarriers and QPSK modulation. We can see that at $CCDF$=10^{-3}, the grouped DCT precoding may reduce PAPR by about 0.8 dB compared with the original OFDM signal. We also notice that the conventional DCT precoding may reduce PAPR by about 1.4 dB. According to the performance of PAPR, the conventional DCT precoding scheme outperforms the grouped DCT precoding.

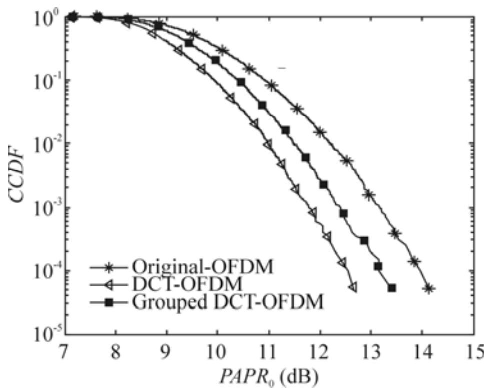

Fig.2 CCDF comparison of precoding for original-OFDM, DCT-OFDM and grouped DCT-OFDM

The BER of optical system depends on Eq.(6). In the IM/DD optical OFDM system, the channel is POF with 50 m, and the QPSK modulation is adopted. In the simulation, the bit rate is 256 Mbit/s, and the impulse of fiber channel is shown in Eq.(7). Fig.3 shows the performance comparison of IM/DD optical OFDM systems for plastic optical fiber channel with two DCT precoding schemes. The number of subcarriers is 256. We can see that the BER of system is not degraded compared with that of the original optical OFDM system without precoding. At BER=10^{-3}, the system with grouped precoding scheme may reduce 1.7 dB signal-to-noise ratio (SNR). With the increase of the SNR, the performance of precoded system is better than that of the system without precoding. We can see the conventional DCT precoding has the best BER performance.

In order to reduce the computational complexity of DCT precoding, we propose a grouped DCT precoding scheme for optical OFDM system. In this paper, M precoding matrices are adopted. In Ref.[10], a fast P point DCT algorithm was proposed and the algorithm requires $\frac{P}{2}\log_2 P$ multiplications and $\frac{3P}{2}\log_2 P-P+1$ additions for P-length sequence. Because the inverse DCT (IDCT) is used at transmitter end, and DCT is used at receiver end, the $P\log_2 P$ multiplications and $2(\frac{3P}{2}\log_2 P-P+1)$ additions are added in every DCT precoding matrix. The increased overall computational complexity is $MP\log_2 P$ multiplications and $2M(\frac{3P}{2}\log_2 P-P+1)$ additions because the M DCT precoding matrices are used for optical OFDM system.

If the conventional DCT precoding matrix is used, the increased overall computational complexity is $MP\log_2 MP$ multiplications and $2(\frac{3MP}{2}\log_2 MP-MP+1)$ additions.

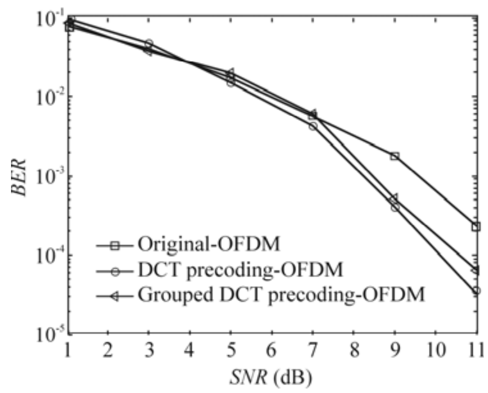

Fig.3 BER performance comparison of the optical OFDM systems with different pecoding schemes

When M=2 and P=64, the complexity ratio of the additions between the proposed grouped DCT precoding scheme and the conventional DCT precoding scheme is about 0.87, and the complexity ratio of the multiplication is 0.86. So the total complexity of the proposed algorithm is reduced by about 15%. However, if the complexity is a primary concern, the number of groups M may be bigger.

This paper investigates the grouped DCT precoding scheme for PAPR reduction in optical OFDM IM/DD system. The proposed scheme reduces the computational complexity compared with the conventional DCT precoding matrix. When the number of groups is 2, the overall reduction computational complexity is about 15%. The PAPR reduction is evaluated for simulation, and the performance of optical system is researched for POF channel. Simulation results show that the grouped DCT precoding not only reduces the PAPR, but also does not degrade the BER of system. At high SNR, the grouped DCT precoding may enhance the performance of BER, so the grouped DCT precoding scheme is very effective for optical OFDM system.

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