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基于DCT级联ICF算法降低相干光正交频分复用系统峰均抑制比

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摘　要：为解决相干光正交频分复用中高峰均抑制比的问题,提出一种离散余弦变换(DCT)和迭代限幅滤波(ICF)级联的新算法。ICF算法是对限幅算法进行改善,添加了迭代过程,可以改善限幅运算对系统误码率的影响。基于DCT算法有较小的误码率和低计算复杂度的特点,所提算法对频域调制信号进行离散余弦变换,以降低高峰值信号的概率,再通过级联ICF算法来实现对峰均抑制比的降低。结果表明,与原始信号相比,当互补累积分布函数为10^{-4}时,所提算法的优化幅度为4.685 dB。在误码率为10^{-3}时,所提算法的光信噪比为20.96 dB,同时能做到长距离传输。除此之外,所提方案的总计算量为19 970。仿真数据表明,考虑峰均抑制比、误码率和计算复杂度等综合因素,所提方案性能最优。

关键词：正交频分复用;峰均抑制比;误码率;迭代限幅滤波;离散余弦变换
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0 Introduction

Optical Orthogonal Frequency Division Multiplexing (OOFDM) technology is formed by the multicarrier modulation in the optical communication[1]. The high-speed serial data parallel transmission in OOFDM technology is accomplished by frequency division multiplexing, and provides excellent resistance to multipath fading. Since OOFDM symbols are superimposed by modulated subcarrier signals, each of the subcarrier signals has the same or similar phase, the superimposed signals are modulated with the similar original signal in phase, which results in a greater instantaneous power peak. A high Peak-To-Average Power Ratio (PAPR) are produced[2]. It is commonly believed that the high PAPR is the major disadvantage to OOFDM because high PAPR causes linear distortion of the signal through the laser[3]. Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) is one of the OOFDM technology that introduced coherent light, and has a high PAPR. High PAPR can lead to degraded system performance and a number of problems such as spectral interference, signal non-linear distortion, and Bit Error Rate (BER) degradation. Signal distortion can also occur in the High-power Amplifier (HPA) area of nonlinearity[4].

So as to settle this problem, many ways were brought up, such as Selective Mapping (SLM)[5], Partial Transmit Sequence (PTS)[6], clipping and filtering[7], block coding. All of these are conventional methods,

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and they are roughly divided into three major categories: probability class technology[8], signals predistortion class technology and coding class technology[9]. On the basis of traditional PAPR reduction methods, many innovative algorithms have been brought up. In 2019, AGHDAMA M H et al, proposed a PTS method based on the adaptive particle swarm optimization. Experimental results showed that the proposed method significantly had reduced the PAPR and computational complexity[10]. In 2020, BHARATI S et al, integrated the clipping method in the SLM procedure. Simulation results indicated that the offered scheme acquires the performance of appropriate PAPR reduction with low computational complexity[11]. In 2021, SHIRATO Y et al, proposed the Time Domain Sequence Superposition-selected Mapping (TDSS-SLM) scheme for PAPR suppression. The simulation results indicated that the proposed algorithm could generate superior performance at relatively computational complexity and lower implementation cost in comparison to its original algorithm[12].

A high PAPR can generate nonlinear distortion easily in the CO-OFDM system. The nonlinear distortion can destroy the orthogonality between subcarriers, and decrease the BER. A new algorithm based on the combination of Discrete Cosine Transform (DCT) and Iterative Clipping and Filtering (ICF) is presented.

1 Principle of cascading algorithms

1.1 ICF algorithm principle

Among the methods to reduce the signal PAPR, the clipping and filtering algorithm is one of the signals predistortion class technology, which can simply and effectively achieve the goal of reducing the PAPR, the computational complexity and redundancy are relatively low, but the clipping and filtering is a nonlinear processing of the signal, it will cause the signal distortion and BER increase.

When the amplitude $|x_n|$ of the time domain signal $x_n=|x_n|e^{j\phi_n}$ after the IFFT is greater than the threshold value A, the amplitude can be set to the threshold value, the phase ϕ_n remains unchanged; and the amplitude $|x_n|$ is less than the threshold value, it is allowed to pass without any processing. The y_n for the amplitude limit is given as follows[13]

$$y_n=\begin{cases} A\cdot e^{j\phi_n} & |x_n|>A \\ x_n & |x_n|\leqslant A \end{cases} \qquad n=0,1,2,\cdots \tag{1}$$

In general, the limit level is expressed by the Clipping Ratio (CR)[14], CR = 20lg(A/σ)(dB), where, σ is the root average square of the signal power, A is a threshold value.

However, the clipping actually changes the amplitude characteristics of the signal in the time domain. This also means that noise is introduced into the system. This kind of noise will not only create in-band signal distortion, it will also cause out-of-band spectral dispersion, which has a great influence upon the system capability. This kind of phenomenon can be observed in Fig. 1, when the CR value is 3, 4, 5 respectively, with the CR value decreases, the signal distortion becomes more serious.

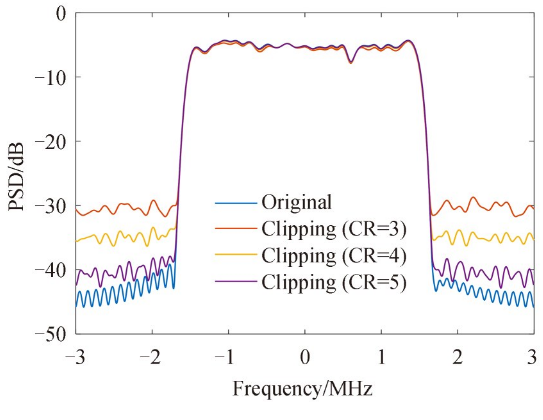


Fig. 1 PSD simulation curves

The ICF algorithm is a modified clipping and filtering algorithm, which is accomplished by repeating the process of the clipping and filtering algorithm several times. In addition, each clipping and filtering process requires an IFFT and FFT transform. At the same time, another IFFT transform is performed on the signal, IFFT will transform frequency domain signal to time domain signal.

1.2 Discrete cosine transform principle

DCT is an orthogonal transform with good sideband properties, likewise to the Hadamard transform method. To decrease the PAPR of CO-OFDM signals, the input signal is first used a DCT to reduce the probability of large peaks, before entering the IFFT module. The reduction of the signal PAPR can be achieved in CO-OFDM by using its feature of reducing the correlation of the input sequence. The one-dimensional DCT with sampling point of N is expressed as[15]

$$X_c(k)=a(k)\sum_{n=0}^{N-1}x(n)\cos\left[\frac{\pi(2n+1)k}{2N}\right]\qquad 0\leqslant k\leqslant N-1 \tag{2}$$

The one-dimensional IDCT with sampling point of N is given below

$$x(n)=\sum_{k=0}^{N-1}a(k)X_c(k)\cos\left[\frac{\pi(2n+1)k}{2N}\right]\qquad 0\leqslant n\leqslant N-1 \tag{3}$$

The value of $a(k)$ is expressed as

$$a(k)=\begin{cases}\dfrac{1}{\sqrt{N}} & k=0\\[2ex] \sqrt{\dfrac{2}{N}} & 1\leqslant k\leqslant N-1\end{cases}$$

The one-dimensional DCT of sampling point N shown in Eq. (2) can also be written in matrix form, where the row or column vectors of the DCT matrix are all orthogonal.

$$\begin{bmatrix}X(0)\\X(1)\\\vdots\\X(N-1)\end{bmatrix}=\frac{1}{\sqrt{N}}\begin{bmatrix}1 & 1 & \cdots & 1\\ \sqrt{2}\cos\left(\dfrac{\pi}{2N}\right) & \sqrt{2}\cos\left(\dfrac{3\pi}{2N}\right) & \cdots & \sqrt{2}\cos\left[\dfrac{(2N-1)\pi}{2N}\right]\\ \vdots & \vdots & \ddots & \vdots\\ \sqrt{2}\cos\left[\dfrac{(N-1)\pi}{2N}\right] & \sqrt{2}\cos\left[\dfrac{3(N-1)\pi}{2N}\right] & \cdots & \sqrt{2}\cos\left[\dfrac{(2N-1)(N-1)\pi}{2N}\right]\end{bmatrix}\cdot\begin{bmatrix}x(0)\\x(1)\\\vdots\\x(N-1)\end{bmatrix} \tag{4}$$

1.3 PAPR problem for CO-OFDM system

From the previous introduction we already know that high PAPR is an important issue in CO-OFDM systems, and in CO-OFDM system, the value of PAPR is defined as the specific value of the largest instantaneous power over the mean power within a CO-OFDM symbol, which can be presented in the following way

$$\mathrm{PAPR}=10\lg\frac{\max\limits_{0\leqslant k\leqslant NL-1}\left\{\left|x(n)\right|^2\right\}}{E\left[\left|x_k\right|^2\right]} \tag{5}$$

where, $E[\cdot]$ is the math expectations, the time domain output signal x_k[16] is obtained by IFFT and L-fold oversampling of continuous signal $x(t)$

$$x_k=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}X_n\cdot\mathrm{e}^{\mathrm{j}2\pi kn\Delta fT/L}\qquad k=0,\ 1,\ \cdots,NL-1 \tag{6}$$

where X_n denotes the data symbol over first subcarrier, N stands for the number of subcarriers, and the symbol period is T, $\Delta f=1/(NT)$ is the subcarrier frequency interval and L is the sampling multiplier.

In a multicarrier modulation system, the Complementary Cumulative Distribution Function (CCDF) indicates the probability of the average value of the peak over a certain threshold PAPR_0. Therefore, CCDF can measure the distribution of the signal PAPR when it is required to express a CO-OFDM signal PAPR value, which can be represented by the following[17]

$$\mathrm{CCDF} = P(\mathrm{PAPR} > \mathrm{PAPR}_0) = 1 - \left[1 - \exp(-\mathrm{PAPR}_0)\right]^N \tag{7}$$

1.4 Principle of DCT-ICF algorithm

The algorithm schematic of the presented scheme of DCT- ICF cascade in this paper is illustrated in Fig.2.

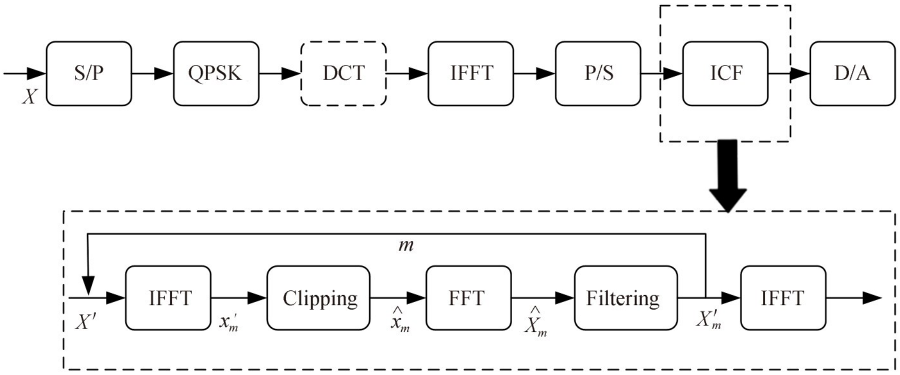


Fig.2 Principle schematic diagram of DCT-ICF algorithm

The algorithm is performed in the following steps:

1) The raw data X is input, the data sequence is transformed to several low-speed parallel data through serial-to-parallel (S/P) conversion. Moreover, the parallel data is QPSK modulated, which is $X_0, X_1, X_2, \cdots, X_{N-1}$.

2) DCT is performed on the generated signal, thus reducing the PAPR, which is the Eq .(2), after the IFFT.

3) The signal is subjected to IFFT operation to achieve the modulation process of the CO-OFDM complex equivalent of the baseband signal.

4) With the completed of IFFT, a parallel-serial (P/S) conversion is performed and the signal is the input signal X' for the ICF algorithm.

5) Signal enters the circulation of the ICF algorithm and passes through the IFFT, which converts the frequency domain signal X' into time domain signal x'_m. The signal is clipped and filtered, and the time domain $\hat{x}_m$ is converted into frequency domain $\hat{X}_m$ during the FFT transformation. $\hat{x}_m$ is filtered by several times of clipping to obtain.

2 Simulation and result analysis

The system of CO-OFDM with DCT-ICF scheme is shown in the functional block diagram of Fig.3. It consists of five major parts, namely the CO-OFDM transmitter module, the Radio Frequency (RF)-to-optical upconverter module, the optical channel module, the optical-to-RF downconverter, and the CO-OFDM receiver module. The system is built by Optisystem and MATLAB.

In this article, both the results of simulation and the algorithm capability are evaluated to demonstrate the effectiveness for the DCT-ICF scheme in CO-OFDM system. The major experimental parameters of the simulation are established as follows: the transmission rate of the system is 50 Gb/s; the amount of subcarriers is 256, signal is modulated by QPSK modulation; OFDM symbol is 200 in length; signal sequence number is 10 000; the frequency of the Continuous Wave (CW) laser at the transmitter is 193.1 THz, the linewidth of the CW laser is 0.01 MHz; the optical amplifier has a gain with 16 dB, noise figure is 3.2 dB.

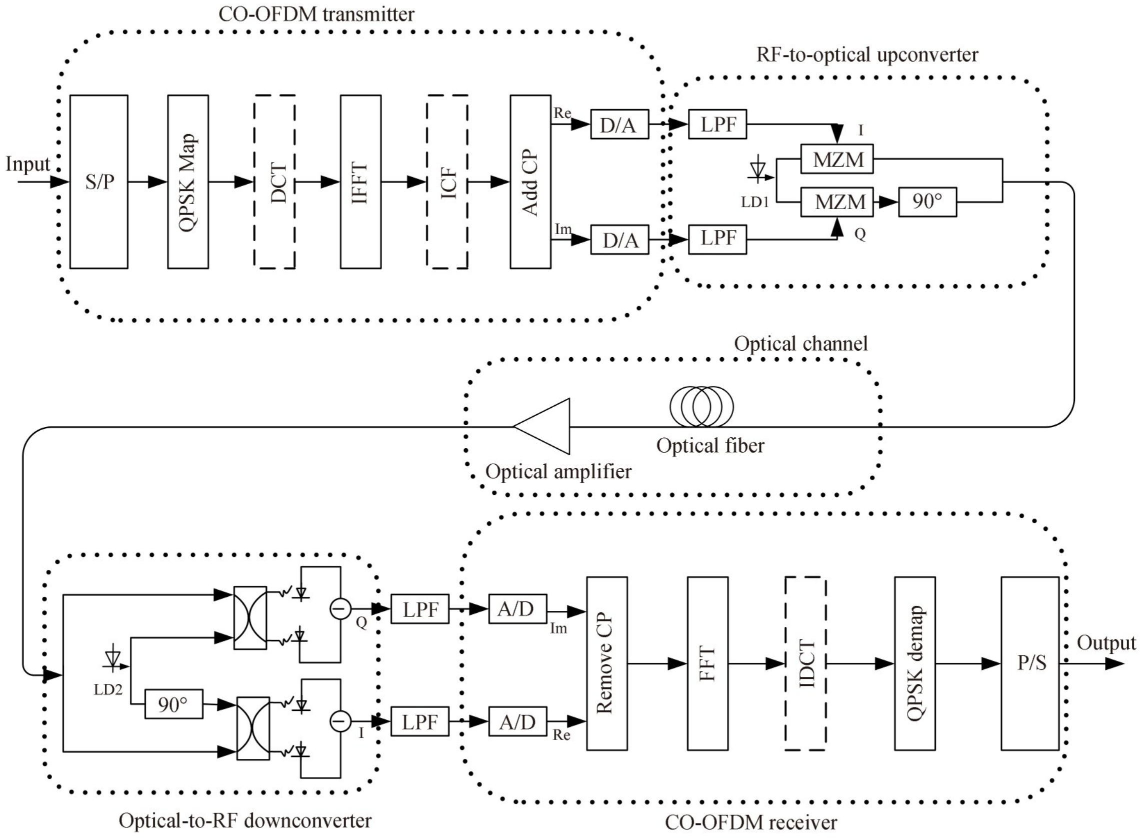
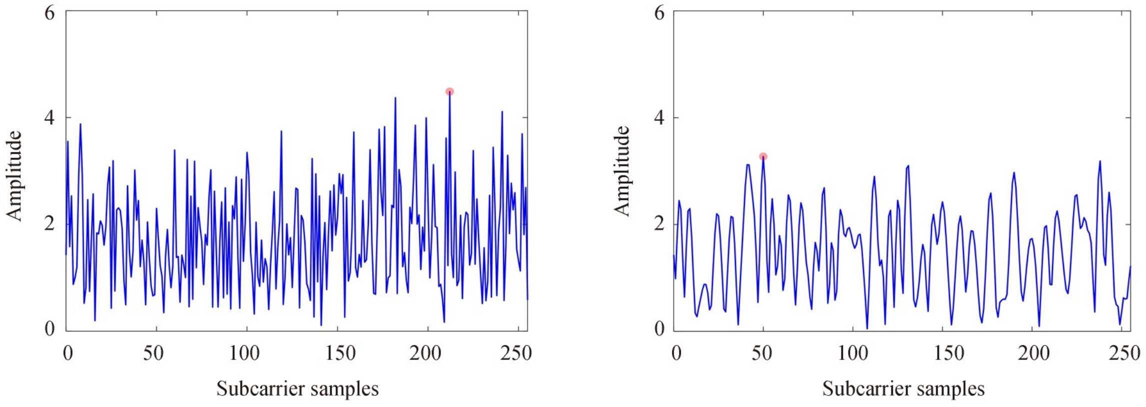


Fig.3 CO-OFDM system principle frame of proposed scheme

2.1 Time domain waveform

As displayed in Fig. 4, the time domain waveforms of the original signal and the processed signal with DCT-ICF algorithm are shown. Fig. 4(a) indicates the original signal time domain waveform, with a peak value of 4.485. As displayed in Fig.4(b), after the DCT-ICF algorithm, the peak value of the time domain waveform is 3.273, which is 1.212 less than the original signal. This result indicates that DCF-ICF algorithm has the ability to suppress PAPR.



(a) Time domain waveform of the original signal

(b) Time domain waveform of DCT-ICF algorithm

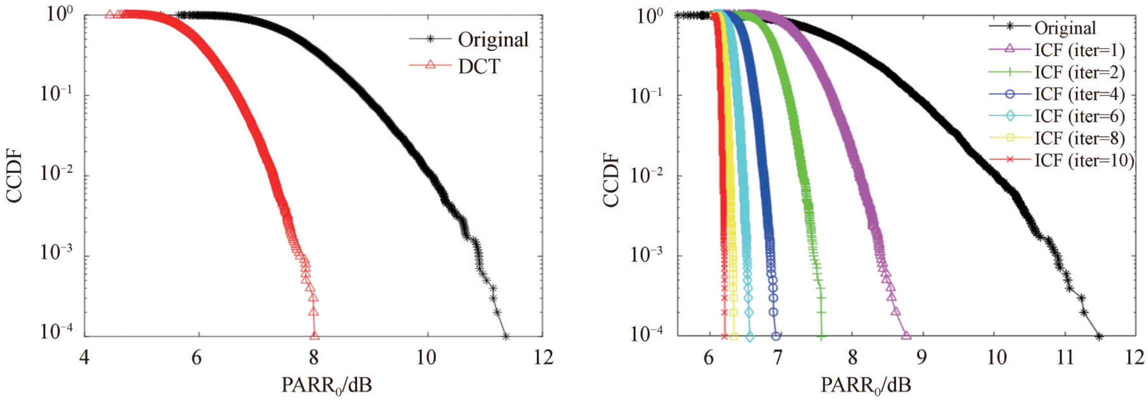
Fig.4 Time domain waveforms of OFDM signals

2.2 PAPR performance analysis

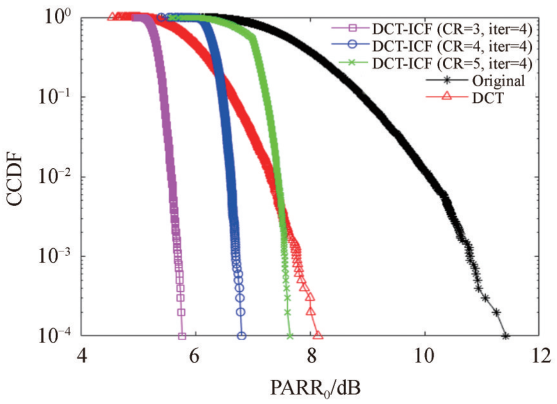
As shown in the Fig.5(a), when the CCDF is 10^{-4}, the CCDF curve of the DCT algorithm shows that the $PAPR_0$ value of the original signal is 11.48 dB. After DCT, the $PAPR_0$ value is 8.022 dB, and the $PAPR_0$ value of the signal after DCT is optimized by 3.458 dB. The results show that DCT can effectively cut down the signal PAPR.

Fig.5(b) demonstrates the CCDF curve of ICF algorithm for diverse iteration numbers and the vertical coordinate is the CCDF value. When CCDF is 10^{-4} and CR is 4, with the gradual increase in the iteration numbers, $PAPR_0$ value of the presented algorithm also decreases successively, which are 8.763 dB, 7.571 dB, 6.93 dB, 6.559 dB, 6.31 dB and 6.205 dB. The filtering operation will cut down the out-of-band interference in the spectrum of the signal. However, it can also cause severe regeneration of peaks. Thus, the presented algorithm requires several iterations to accomplish the suppression of PAPR.

As shown in Fig.5(c), this figure demonstrates the CCDF curves for the original signal, DCT algorithm and DCT-ICF algorithm at CR is 3, 4 and 5. And in the presence of CCDF is 10^{-4}, the value of $PAPR_0$ corresponding to the original signal, DCT, DCT-ICF (CR=3, iter=4), DCT-ICF (CR=4, iter=4) and DCT-ICF (CR=5, iter=4) algorithms are 11.48 dB, 8.112 dB, 5.759 dB, 6.795 dB and 7.615 dB separately. The results show that the joint algorithm of DCT-ICF has a stronger ability to suppress PAPR than the DCT algorithms.



(a) DCT algorithm (b) ICF algorithm with different number of iterations

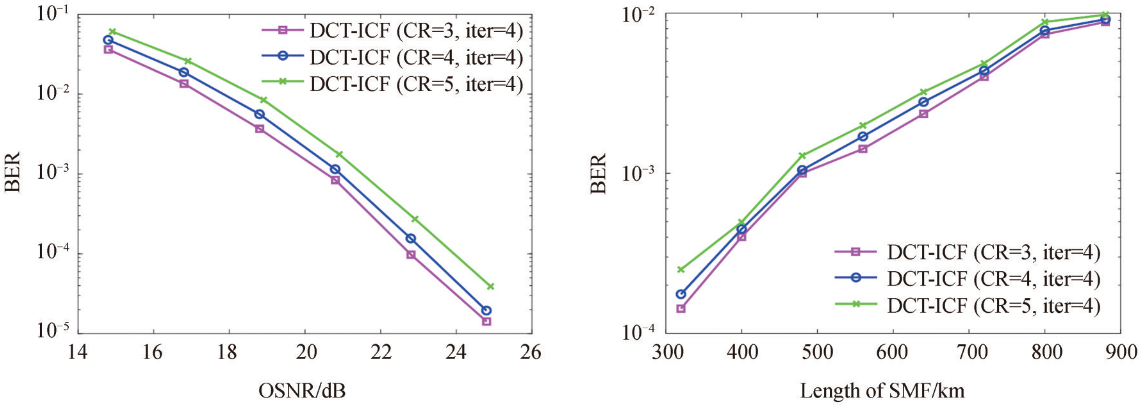


(c) Different algorithms

Fig.5 CCDF simulation curve of OFDM

2.3 Analysis of BER

Transformation curve of BER with Optical Signal to Noise Ratio (OSNR) variation for the joint DCT-ICF algorithm is displayed in Fig.6(a). The BER decreases with the increasing of OSNR. The higher the CR value, the higher the BER. It can be seen when the BER is 10^{-3}, the CR is 3, 4 and 5 respectively, the corresponding OSNR values are 20.76 dB, 20.96 dB and 21.47 dB separately. BER of the joint algorithm varies with the length of the SMF as display in Fig.6(b), and as the Single Mode Fiber (SMF) length increases from 320 km to 880 km, the BER keeps increasing, in the meanwhile, the BER increases with larger CR values.



(a)Transformation curve of BER with OSNR

(b) Transformation curve of BER with length of SMF

Fig.6 BER performance analysis

2.4 Computational complexity analysis

The calculation complexity for each algorithm is mainly expressed in terms of the multiplication calculation amount and addition calculation amount that are required for the FFT/IFFT. DCT algorithm requires two operations of DCT and IDCT. The computational complexity of the three algorithms is obtained in Table 1. Table 2 demonstrates the computational amount of different algorithms at $N=256$ and iter $=4$. The total computational cost of the proposed algorithm is 19 970.

Table 1 Computational complexity of different algorithms

Algorithm	Addition calculation amount	Multiplication calculation amount
DCT	$3N\log_2 N-2N+2$	$N\cdot\log_2 N$
ICF	$N\cdot\log_2 N\cdot\text{iter}$	$(N/2)\cdot\log_2 N\cdot\text{iter}$
DCT-ICF	$3N\log_2 N-2N+2+N\cdot\log_2 N\cdot\text{iter}$	$N\cdot\log_2 N+(N/2)\cdot\log_2 N\cdot\text{iter}$

Table 2 Computational amount of different algorithms at *N*=256 and iter=4

Algorithm	Addition calculation amount	Multiplication calculation amount	Total computational cost
DCT	5 634	2 048	7 682
ICF	8 192	4 096	12 288
DCT-ICF	13 826	6 144	19 970

3 Conclusion

In this paper, taking into account the PAPR and BER, a cascade algorithm of DCT and ICF is put forward to decrease the PAPR of CO-OFDM system. Simulation results demonstrate that the algorithm can accomplish effective PAPR suppression in CO-OFDM systems and maintain good BER compared to the DCT algorithm. The presented algorithm sacrifices a small amount of computational complexity compared to the conventional ICF algorithm, achieves the PAPR reduction and ensures the BER performance. In summary, the proposed algorithm has certain feasibility.

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Reducing Peak-to-average Power Ratio of Coherent Optical Orthogonal Frequency Division Multiplexing System by DCT Cascading ICF Algorithm

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Abstract: Optical Orthogonal Frequency Division Multiplexing (OOFDM) technology is a new optical transmission technology. It is the product of the combination of Orthogonal Frequency Division Multiplexing (OFDM) technology and optical fiber communication technology, and has all the advantages of these two technologies. In recent years, OOFDM has become one of the research hotspots in the field of optical communication due to its unique advantages, especially the Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) system. The CO-OFDM system has the advantages of high spectral efficiency, receiving sensitivity, and robustness, which make it become a research hotspot for realizing high-capacity, high-speed and long-distance optical fiber communication. The CO-OFDM signal is superimposed by modulated subcarrier signals. When the phases of the multiple subcarrier signals are the same, the superimposed signal power can be much greater than the average power, which can result in high Peak-to-average Power Ratio (PAPR). High PAPR not only causes nonlinear distortion when the system passes through optical amplifiers, DAC, ADC and other devices, but also leads to a decrease Bit Error

Rate (BER). To solve the PAPR problem of CO-OFDM in OOFDM, the characteristics of related algorithms are studied. The clipping algorithm is the nonlinear processing of the signal, it will cause degradation performance such as high BER, low transmission rate, short transmission distance. An improved ICF algorithm is studied, which can improve the impact of the clipping algorithm on the system BER because of the iterative process. DCT transform is an orthogonal transform, which has a good effect of decorrelation and concentration the energy of the signal. DCT can change the correlation of the input sequence and further reduce the PAPR of the signal. A new structure of the DCT cascade improved clipping algorithm is proposed. From the time domain waveform diagram, the peak value of the original signal is 4.485, and the peak value of the DCT-ICF algorithm is 3.273. Compared with the original signal, the proposed algorithm effectively reduces the peak value of the time domain waveform by 1.212. From the perspective of the Complementary Cumulative Distribution Function (CCDF), which measures the PAPR distribution of the signal. When the CCDF is 10^{-4}, the PAPR_0 value of the original signal is 11.48 dB, the DCT algorithm is 8.022 dB, the ICF (CR=4, iter=4) algorithm is 6.93 dB, and the DCT-ICF (CR=4, iter=4) scheme is 6.795 dB. Compared with the original algorithm, the optimized amplitude of the DCT algorithm is 3.458 dB, the ICF (CR=4, iter=4) algorithm is 4.55 dB, and the proposed algorithm is 4.685 dB. When the BER is 10^{-3}, the Optical Signal to Noise Ratio (OSNR) of the DCT-ICF (CR=3, iter=4) algorithm is 20.76 dB, DCT-ICF (CR=4, iter=4) algorithm is 20.96 dB, and DCT-ICF (CR=5, iter=4) algorithm is 21.47 dB, it can achieve long-distance transmission. And the BER can increase with the increase of the SMF transmission distance. The proposed algorithm has good BER performance. In addition to that, the total amount of computational amount of the proposed algorithm is 19 970. In this paper, the DCT algorithm and clipping algorithm are introduced in detail, and their principles are analyzed. According to their characteristics, the DCT-ICF algorithm is proposed. In terms of Power Spectral Density (PSD), the ICF algorithm improves the nonlinear distortion of the clipping algorithm in the system, and then improves the system performance. From the time domain waveform, the proposed algorithm reduces the signal peak significantly. According to the CCDF simulation curve, the proposed algorithm can effectively suppress the PAPR. From the transformation curve of BER with OSNR and the transformation curve of BER with SMF length, it can be seen that the proposed algorithm can maintain good performance during the transmission process. In consideration of the computational complexity, the proposed algorithm has a lower computational effort. In conclusion, the algorithm is feasible after considering various factors.

Key words: Orthogonal frequency division multiplexing; Peak-to-average power ratio; Bit error rate; Iterative clipping and filtering; Discrete cosine transform

OCIS Codes: 060.4510; 060.1660; 060.2330