Improved ACE and ICF low complexity joint algorithm to reduce *PAPR* of CO-OFDM system*

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Active constellation expansion (ACE) and iterative clipping and filtering (ICF) are simple and effective techniques for reducing the peak-to-average ratio (*PAPR*) in coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems, but effective *PAPR* suppression requires a lot of iterations. To overcome this shortcoming, a joint algorithm based on improved active constellation expansion (IACE) and ICF (IACE-ICF) is proposed. The simulation results show that at the complementary cumulative distribution function (*CCDF*) of 10^{-4}, the *PAPR* of IACE-ICF (*G*=4, *iter*=4) algorithm is optimized by 1.507 dB, 1.13 dB and 0.204 dB compared with that of the IACE, ICF (*iter*=4) and ICF-IACE (*G*=4, *iter*=4) algorithms, respectively. Meanwhile, when the bit error rate (*BER*) is 10^{-3}, the optical signal to noise ratio (*OSNR*) of the proposed scheme is optimized by 2.04 dB, 1.75 dB and 1.4 dB compared with that of clipping, ICF (*iter*=4) and ICF-IACE (*G*=4, *iter*=4) algorithms, respectively. On the other hand, the proposed scheme can reduce the number of complex multiplications by 14.29% and complex additions by 28.57% compared with the ICF (*iter*=14) scheme.

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Coherent optical orthogonal frequency division multiplexing (CO-OFDM) technology combining the characteristics of OFDM technology and coherent optical communication, has the advantages of high spectral efficiency, strong anti-dispersion ability, high sensitivity and anti-symbol interference[1,2]. However, the OFDM symbol is formed by the superposition of multiple independent subcarriers. If the phases of the multiple subcarrier signals are the same, the superimposed signal power will be much greater than the average power of the signal, resulting in a relatively high peak-to-average power (*PAPR*)[3,4]. High *PAPR* will not only exceed the linear range of the amplifier, digital analog converter (D/A) and analog digital converter (A/D), but also make the system more sensitive to phase noise and non-linear effects[5], resulting in the reduction of system performance. High *PAPR* has always been regarded as the important disadvantage of CO-OFDM technology. Reducing the *PAPR* of the signal to improve the performance of the communication system has become a research hotspot of OFDM system. In recent years, in order to balance the relationship between *PAPR* performance and other influencing factors in CO-OFDM systems, numerous methods and techniques have been proposed, such as clipping, filtering[6,7], coding[8,9], selected mapping (SLM)[10,11] partial transmit sequence (PTS)[12,13], tone reservation (TR)[14], intelligence algorithm[15,16] and active constellation extension (ACE) algorithm[17,18], and so on. Among them, the clipping and filtering algorithms need to suppress the *PAPR* of the signal through multiple iterations, and the ACE algorithm needs multiple iterations between two overlapping convex sets to find the appropriate solution, which will increase the complexity of the system.

In this work, we propose a joint algorithm based on improved active constellation expansion (IACE) and ICF (IACE-ICF). OFDM signal first is processed by the IACE module. The IACE algorithm is multiplied by the spreading factor which expands the moving range of the constellation points and reduces the probability of the subcarriers phase coincide. In this scheme, the signal processed behind IACE module is used as the input signal of ICF module, which further reduces the *PAPR* of OFDM signal and achieves the ideal *PAPR* suppression performance without multiple iterations. And it has lower computational complexity and improves the bit error rate (*BER*) performance of the system.

N is the number of subcarriers, X_k is the complex vector in the frequency domain, and x_n is the time-domain signal obtained by IFFT:

$$x_n=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}X_k\mathrm{e}^{\mathrm{j}2\pi nk/N}\quad,\quad n=0,1,2\ldots,N-1. \tag{1}$$

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The *PAPR* of an OFDM signal is defined as the ratio between the maximum value and the average value of the instantaneous power of the OFDM signal in one symbol period[19]:

$$PAPR(\text{dB}) = 10\lg \frac{\max\{|x_n|^2\}}{E\{|x_n|^2\}} , \qquad (2)$$

where $E[\cdot]$ denotes the expectation operation.

In research, complementary cumulative distribution function (*CCDF*) is generally used to represent the distribution of *PAPR* in OFDM system. The probability that the *PAPR* of the OFDM signal exceeds the threshold $PAPR_0$, that is, its complementary cumulative distribution function is:

$$CCDF = P\{PAPR > PAPR_0\} = 1-(1-\mathrm{e}^{PAPR_0})^N, \qquad (3)$$

where $PAPR_0$ is the threshold value, and the *CCDF* value indicates the probability value when the input signal *PAPR* value is greater than the threshold value $PAPR_0$.

The block diagram of the IACE-ICF algorithm proposed in this paper is shown in Fig.1.

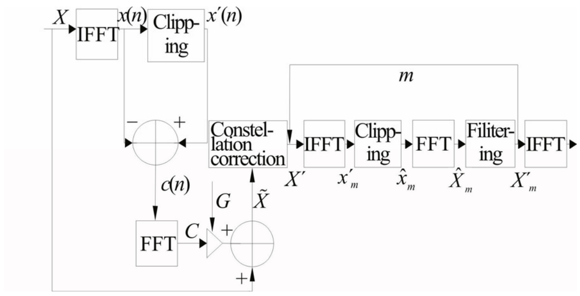


Fig.1 Block diagram of the proposed IACE-ICF scheme

The IACE algorithm expansion operation in the frequency domain, and the implementation process of frequency domain constellation expansion is as follows:

(1) The mapping data X is used as the input signal of proposed IACE scheme, which is transformed into the time domain signal x by IFFT. The threshold A is set according to the expected *PAPR*, the clipped signal is $x'(n)$.

(2) $c(n)$ is the signal after limiting amplitude minus the original signal. The signal undergoes FFT to obtain the frequency domain clipping noise signal C, because $c(n)$ has only a small number of non-zero elements, FFT operation on $c(n)$ will improve the efficiency of the system.

(3) The extended frequency domain signal $\tilde{X}$ is obtained by multiplying the expansion factor G, where $\tilde{X} = X + G\cdot C$.

(4) According to the set expandable area, the extended frequency domain signal $\tilde{X}$ is corrected, and the constellation corrected signal X' is used as the input signal of the ICF module.

(5) x'_m is the time domain signal after constellation correction, the signal $\hat{x}_m$ is obtained after m times of clipping and filtering,

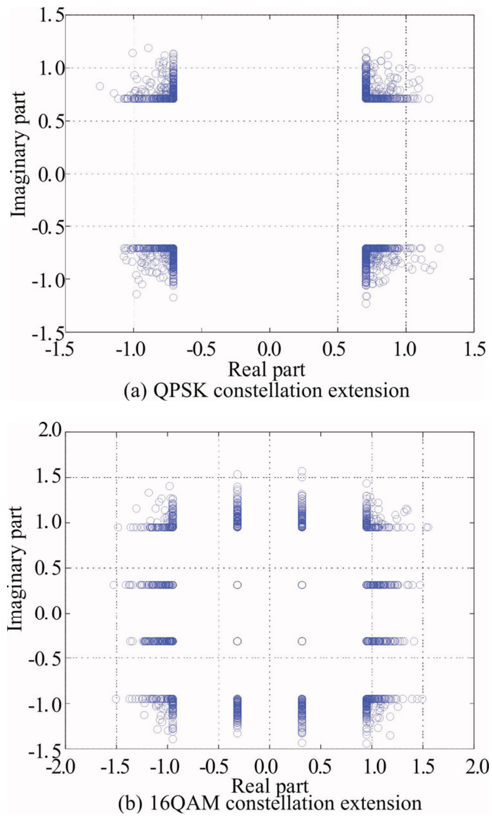
$$\hat{x}_m(n) = \begin{cases} T\mathrm{e}^{\mathrm{j}\varphi(n)} & |x'_m(n)| > T \\ x'_m(n) & |x'_m(n)| \le T \end{cases}, \; n = 0,1\ldots,N-1 , \qquad (4)$$

where $\varphi(n)$ represents the phase of $x'_m(n)$, T is the clipping level, and the clipping indicator is expressed by the clipping ratio (*CR*)

$$CR = 20\lg \frac{T}{\sigma} , \qquad (5)$$

where σ is signal rms power.

Fig.2 is a constellation expansion diagram of the proposed IACE algorithm with different modulation methods. Fig.2(a)—(d) are the quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (QAM), 64QAM and 256QAM, respectively. All the mapped constellation points are divided into three according to the distribution position: vertex constellation points, boundary constellation points and internal constellation points. The vertex constellation points can be extended in two directions, the boundary constellation points are only allowed to expand in one direction, the internal constellation points keep the original position unchanged. When QPSK modulation is adopted for OFDM signal with N subcarriers, the four mapping points are all extensible points. When 16QAM, 64QAM and 256QAM are adopted for OFDM signal with N subcarriers, the internal constellation points of $N/4$, $9N/16$ and $49N/64$ are not expandable, respectively. It can be seen from Fig.2 that with the increase of QAM modulation order, the proportion of constellation points participating in constellation expansion decreases, and *PAPR* suppression effect is limited.



(a) QPSK constellation extension

(b) 16QAM constellation extension

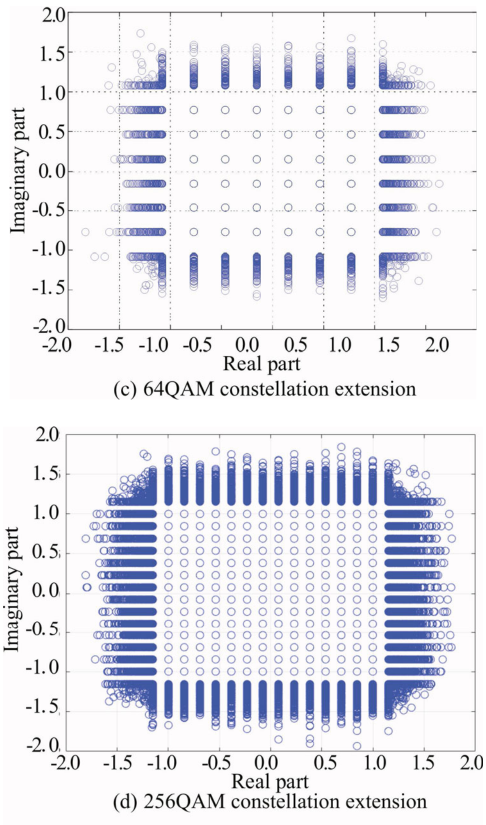


Fig.2 Expanded constellation diagrams under different modulation methods

Fig.3 shows the *CCDF* curves of the proposed IACE algorithm using different modulation methods. It can be seen from the figure that when $CCDF=10^{-4}$, the $PAPR_0$ of the IACE algorithm using QPSK, 16QAM, 64QAM and 256QAM are 7.389 dB, 9.287 dB, 10.48 dB and 11.28 dB, respectively. The *PAPR* suppression effect with the QPSK is the best, and it is shown that the algorithm is not suitable for higher order modulation.

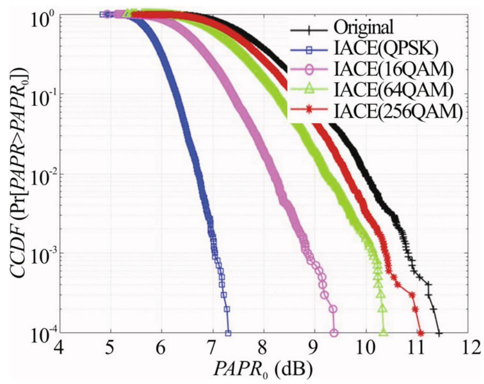


Fig.3 *CCDF* curves of IACE algorithm under different modulation methods

Because the proposed IACE algorithm cannot reduce the *PAPR* value of the OFDM signal to an ideal value, the ICF algorithm is cascaded to reduce the *PAPR* of the signal.

Fig.4 shows the *CCDF* curves of ICF algorithm under different iteration times. When $CCDF=10^{-4}$ and *CR* is 4, iterations are 1, 2, 4, 6, 8, 10, 12 and 14, respectively. The $PAPR_0$ values of the ICF scheme are 8.764 dB, 7.573 dB, 6.928 dB, 6.562 dB, 6.34 dB, 6.209 dB, 6.136 dB and 6.091 dB, respectively. Filtering can reduce out-of-band spectral interference, but it can also cause peak regeneration. Therefore, the ICF scheme needs many times of iterations to achieve the ideal *PAPR* suppression effect, which will greatly increase the calculation amount of the system. Therefore, the ICF scheme needs many times of iterations to achieve the ideal *PAPR* suppression effect, which will greatly increase the calculation amount of the system.

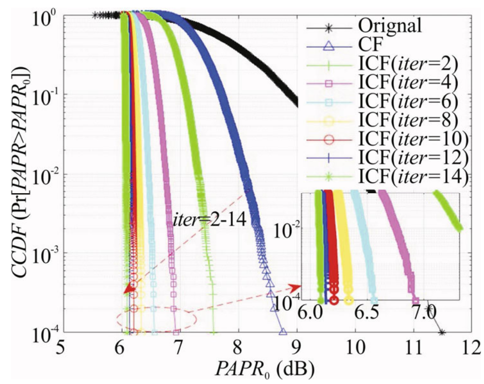


Fig.4 *CCDF* curves of ICF algorithm under different iteration times

As the *CCDF* curves shown in Fig.5, when $CCDF=10^{-4}$, the $PAPR_0$ values of the proposed IACE (G=4) algorithm and ICF (*iter*=4) algorithm are 7.305 dB and 6.928 dB. Compared with the original signal, the *PAPR* values are optimized by 4.265 dB and 4.642 dB, respectively.

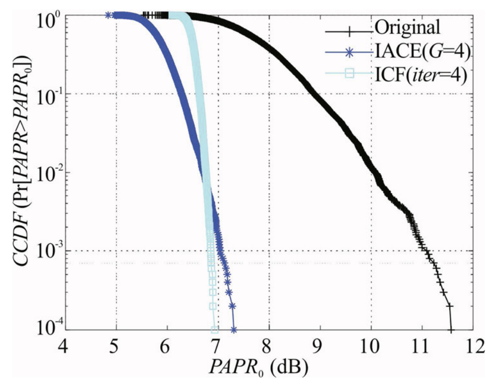


Fig.5 *CCDF* curves of the IACE (*G*=4) algorithm and ICF (*iter*=4) algorithm

Fig.6 shows the *CCDF* curves for suppressing *PAPR* of OFDM signal using different technologies. It can be seen that the proposed IACE-ICF (G=4, *iter*=4) algorithm has a better effect in reducing the *PAPR* of the signal. When *CCDF* is 10^{-4}, the $PAPR_0$ of ICF (*iter*=4), clipping, ICF-IACE (G=4, $iter$=4) and IACE-ICF (G=4, $iter$=4) are 6.928 dB, 6.31 dB, 6.002 dB and 5.798 dB, respectively. The $PAPR$ of IACE-ICF (G=4, $iter$=4) are optimized by 1.507 dB, 1.13 dB, 0.204 dB and 0.512 dB compared with those of IACE (G=4), ICF ($iter$=4), ICF-IACE (G=4, $iter$=4) and clipping algorithm, respectively.

In order to verify the feasibility of the proposed IACE-ICF algorithm, the CO-OFDM system is built. Fig.7 shows the CO-OFDM system with the IACE-ICF algorithm. The up-conversion structure in the system converts the electrical signals I and Q generated by 2-channel Matlab into optical signals and transmits them in the optical channel of the CO-OFDM system constructed by Optisystem software. The signal at the receiving end is processed in reverse. In our simulation, the bit rate is fixed at 20 Gbit/s, the number of subcarriers is 256, the modulation is QPSK, the length of CP is 32, a continuous wave (CW) laser is used as the light source with carrier frequency of 193.1 THz and line width of 100 kHz. The gain of the erbium-doped fiber amplifier (EDFA) is set to16 dB and the noise figure to 3.2 dB.

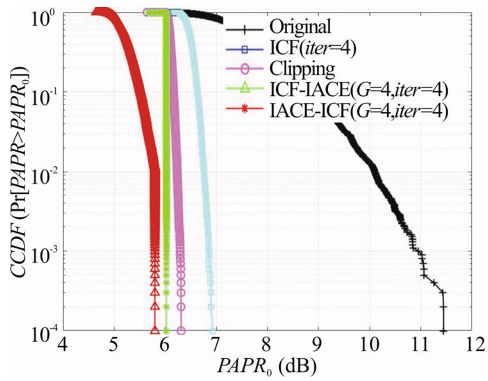
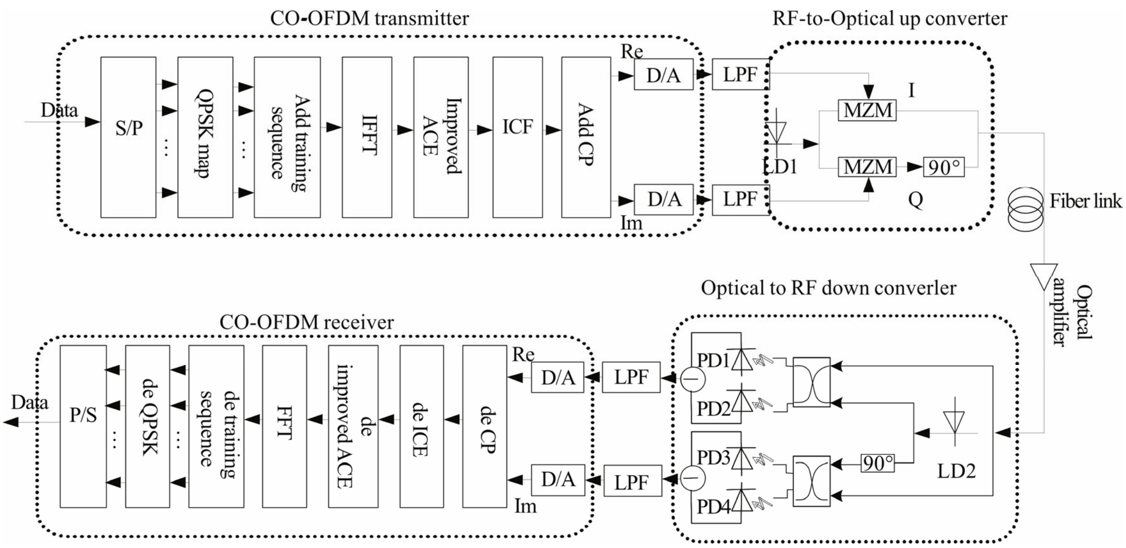


Fig.6 *CCDF* curves of OFDM signal under different algorithms



LPF: low-pass filter; MZM: Mach-Zehnder modulator; PD: photodetector; LD: laser

Fig.7 Structure diagram of CO-OFDM system with the IACE-ICF algorithm

The BER performances of CO-OFDM systems with different optical signal to noise ratio ($OSNR$) are shown in Fig.8. It can be seen when BER=10^{-3}, the $OSNR$ of clipping, ICF ($iter$=4), IACE (G=4), IACE-ICF (G=4, $iter$=4) and ICF-IACE (G=4, $iter$=4) algorithm are 22.14 dB, 21.85 dB, 19.7 dB, 20.1 dB and 21.5 dB, respectively. The $OSNR$ of IACE-ICF (G=4, $iter$=4) are optimized by 2.04 dB, 1.75 dB and 1.4 dB compared with those of clipping, ICF ($iter$=4) and ICF-IACE (G=4, $iter$=4) scheme. Besides we can also see that with the increase of $OSNR$, the IACE-ICF scheme has better BER performance compared with ICF and ICF-IACE schemes.

The BER performances of CO-OFDM systems with different transmission distances are shown in Fig.9. With the SMF transmission distance increased from 80 km to 560 km, the BER of the system is getting higher and higher, but the BER performance of the proposed IACE-ICF algorithm is still superior to those of the ICF and ICF-IACE schemes.

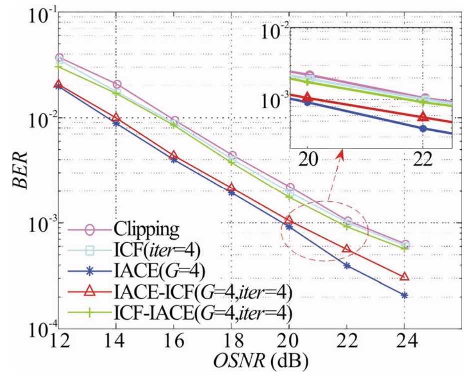


Fig.8 *BER* performance of CO-OFDM system with different *OSNR*

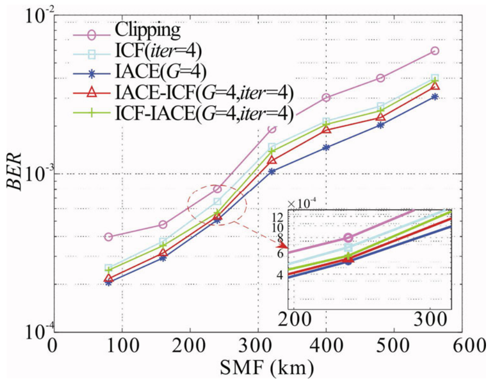


Fig.9 *BER* performance of CO-OFDM system with different transmission distances

The calculation complexity of different schemes is shown in Tab.1. The computational complexity is mainly reflected in the complex multiplication and complex addition required by FFT/IFFT. Tab.2 gives the calculation amounts of the four algorithms obtained by the formula shown in Tab.1. We can see that the computational complexity of IACE-ICF (G=4, *iter*=4) scheme is the cumulative sum of IACE (G=4) and ICF (*iter*=4) schemes. In order to obtain better *PAPR* suppression performance, the proposed scheme sacrifices the computational complexity.

Tab.1 Calculation formulas of several different algorithms

Algorithm	Complex multiplications	Complex additions
Clipping	$\frac{N}{2}\cdot\log_2 N$	$N\cdot\log_2 N$
ICF	$\frac{N}{2}\cdot\log_2 N\cdot N_{iter}$	$N\cdot\log_2 N\cdot N_{iter}$
IACE	$4N\cdot\log_2 N$	$6N\cdot\log_2 N$
IACE-ICF	$\frac{N}{2}\cdot\log_2 N\cdot N_{iter}$ $+4N\cdot\log_2 N$	$N\cdot\log_2 N\cdot N_{iter}$ $+6N\cdot\log_2 N$

Tab.2 The calculation of several different algorithms when *N*=256

Algorithm	Complex multiplications	Complex additions
Clipping	1 024	2 048
ICF (*iter*=14)	14 336	28 672
IACE (G=4)	8 192	12 288
IACE-ICF (G=4,*iter*=4)	12 288	20 480

The proposed calculation complexity reduction rate (*CCRR*) is defined as follows:

$$CCRR=(1-\frac{\text{complexity of new algorithm}}{\text{complexity of ICF algorithm}})\times 100\% \quad .(6)$$

It can be seen from Tab.3 that the proposed IACE-ICF (G=4, *iter*=4) algorithm reduces the complexity of the system, the number of multiplier calculations of this algorithm is reduced by 14.29%, and the number of addend calculations is reduced by 28.57%. Compared with the traditional ICF (*iter*=14) algorithm, the algorithm proposed in this paper has better *PAPR* suppression performance and can reduce the complexity of the system to a certain extent.

Tab.3 Comparison of *CCRR* between the proposed algorithm and ICF (*iter*=14) when *N*=256

Algorithm	Complex multiplications	Complex additions
ICF (*iter*=14)	-	-
IACE (G=4)	42.56%	57.14%
IACE-ICF (G=4,*iter*=4)	14.29%	28.57%

In order to effectively reduce the *PAPR* of the CO-OFDM system, a new joint algorithm of IACE-ICF is proposed. The simulation results show that the algorithm can greatly reduce the *PAPR* of the signal under the condition that the system *BER* is good, and is consistent with the traditional compared with the ICF algorithm, it can reduce the complexity of the system and improve the *BER* of the system.

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