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Signal Assisted Clipping Distortion Recovery for OFDM Systems Based on Compressed Sensing

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ABSTRACT The clipping distortion, which generated in the orthogonal frequency division multiplexing systems will have a serious impact on the bit error performance, can be mitigated by clipping distortion recovery techniques. In this paper, we propose a compressed sensing (CS) based signal assisted Clipping Distortion Recovery (saCDR). At the transmitter, we use the clipping position to generate an auxiliary signal to transmit sparse information. The proposed method solves the problem that it is difficult to obtain the sparsity K when the receiver uses orthogonal matching pursuit (OMP) for clipping distortion recovery. At the receiver, we propose the location-assisted OMP algorithm (laOMP), which greatly reduces the system complexity and can still ensure good recovery performance under severe clipping scenarios. Simulation results show that the proposed method can obtain good bit error rate performance under different channels.

INDEX TERMS Clipping distortion, orthogonal frequency division multiplexing systems (OFDM), clipping, compressed sensing (CS).

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) technology has been widely used in standards such as long-term evolution (LTE), fifth-generation (5G), wireless local area networks (WLANs) and (Digital Video Broadcasting) DVB, and will also play an important role in the future space and terrestrial integrated network [1]– [5]. OFDM technology has superior performance in combating multipath fading and increasing data transmission rate, but the problem of high peak-to-average power ratio (PAPR) in OFDM system still exists [6]– [9].

In order to reduce the PAPR of OFDM systems, many PAPR reduction methods have been proposed, and clipping is one of the simplest and most effective [10]– [14]. Clipping reduces the PAPR of the system by clipping the peak of the transmitted signal [15]. This method of directly changing the waveform will bring out-of-band radiation and clipping distortion [16]. Out-of-band radiation can be solved by filtering, but clipping distortion will seriously affect the bit error rate (BER) performance of the system, so it is necessary to recover the clipping distortion at the receiver [17]– [19].

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The early proposed clipping distortion recovery methods used the principle of peak regeneration of the clipping signal, and iteratively recovers the clipping distortion in the time domain or the frequency domain [20], [21]. Compressed sensing (CS) was proposed in 2006, and some scholars noticed that the clipping distortion is sparse in the time domain, so they applied the CS technology to the clipping distortion recovery [22], [23]. Early scholars proposed to use a pilot or empty sub-carriers to recover clipping distortion based on compressed sensing, but both methods waste the frequency domain resources [24], [25]. Therefore, some scholars have proposed peak-distortion recovery based on data subcarriers [25].

When studying compressed sensing for clipping distortion recovery, many scholars have used a simple and efficient OMP algorithm [26]. However, when using the OMP algorithm for clipping distortion recovery, it is hardly considered that the receiver in the actual system is difficult to obtain the sparsity K of the clipping distortion. Scholars proposed to use the sparsity adaptive matching pursuit (SAMP) for clipping distortion recovery [27]. SAMP algorithm can adaptively search for sparsity at the receiver. This solves the problem that it is difficult for the receiver to obtain sparsity, but there is still a problem of high complexity through adaptively searching for sparsity.

In this paper, we improve the OMP algorithm and propose a signal-assisted clipping distortion recovery algorithm. Our main work is as follows: (1) The method of superimposing auxiliary signals at the transmitter is proposed to transmit the sparsity information, which solves the problem that the receiver cannot obtain the sparsity using the OMP algorithm; (2) The proposed auxiliary signals can not only transmit the sparsity information, it can also transmit position information of the non-zero value of clipping distortion. Using the position information of non-zero values in the sparse signal, we have proposed a location-assisted OMP algorithm. Using the laOMP algorithm can greatly reduce the complexity of the system; (3) At the receiver, we also propose an iterative receiving method, which iteratively recovers more accurate auxiliary signals and clipping distortion, thereby improving the BER performance of the system. The simulation results show that the receiver only needs a very small number of iterations to obtain excellent reception performance, which can keep the complexity of the receiver small. The proposed method does not need to reserve empty subcarriers or pilots, and it can also have good BER performance when the clipping degree is large and the clipping distortion loses sparseness. However, the proposed method leads to a reduction in the PAPR reduction performance and is only applicable to the multiple phase shift keying(MPSK) constellation modulation method.

The rest of this paper is as follows. Section II is the system model, including the OFDM transmitter and the receiver based on CS. Section III proposes the recovery process of clipping distortion based on auxiliary signals. Section IV is the simulation results and analysis. Section V is the summary.

II. SYSTEM MODEL

A. OFDM SYSTEM TRANSMITTER WITH CLIPPING

In the OFDM system, the data at the transmitter is modulated and mapped to obtain an OFDM frequency domain signal X . Then, the signal X is subjected to the inverse fast fourier transform(IFFT) operation to obtain the time domain signal x , and the formula is expressed as follows:

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k \exp\left(j \frac{2\pi kn}{N}\right), \quad 0 \leq n \leq N-1. \quad (1)$$

And $X = [X_0 \ X_1 \ \dots \ X_{N-1}]$, $x = [x_0 \ x_1 \ \dots \ x_{N-1}]$, N represents the number of subcarriers.

After obtaining the time domain OFDM signal x , we can calculate the PAPR of the system. The PAPR is defined as follows:

$$\text{PAPR} = 10 \log_{10} \frac{\max [|x_n|^2]}{E [|x_n|^2]} \text{ (dB)}. \quad (2)$$

where $E[\cdot]$ means expectation. This formula calculates the PAPR of a single OFDM symbol. Usually in order to describe the statistical characteristics of the signal's PAPR more accurately, we will calculate its complementary cumulative distribution function(CCDF) [28]. It represents

the probability that the PAPR of the signal exceeds a specific PAPR value PAPR_0 :

$$\text{CCDF} = P_r (\text{PAPR} \geq \text{PAPR}_0). \quad (3)$$

In order to reduce the PAPR of the OFDM signal, the signal x will pass through the clipping operation module. Clipping is to reduce the excessively high part of the time domain signal to a specific amplitude A . The clipping process can be modeled as the following process:

$$\bar{x}_n = \begin{cases} x_n & |x_n| \leq A \\ A \cdot e^{j \cdot \arg[x_n]} & |x_n| > A. \end{cases} \quad (4)$$

where $\arg[\cdot]$ represents the angle of the complex-valued signal. And the relationship between clipping amplitude and clipping rate(CR) is:

$$\text{CR} = 20 \log \frac{A}{E [|x_n|]} \text{ dB}. \quad (5)$$

CR is a value greater than zero, and the smaller the clipping rate CR, the greater the degree of clipping of the signal.

The signal after clipping is \bar{x} , and can be represented by the unclipping signal x and the clipping distortion c :

$$\bar{x} = x + c. \quad (6)$$

Similarly, the frequency domain representation of the clipping signal can be written as:

$$\bar{X} = X + C. \quad (7)$$

where C is the frequency domain representation of clipping distortion. We know that when the clipping rate is larger, the degree of clipping of the signal will be smaller, then the number of non-zero values K of the clipping distortion will also be smaller. When $K \ll N$, the clipping distortion c is sparse, and its sparsity is K , then we can use the algorithm based on CS to recover the clipping distortion at the receiver.

After clipping, the OFDM time domain signal will add cyclic prefix(CP) and pass through the DA conversion module, and finally transmit through the antenna at the transmitter.

B. CS BASED OFDM SYSTEM RECEIVER

1) INITIAL ESTIMATION

The receiver receives the signal that has passed through the channel and obtains the OFDM frequency domain signal after AD conversion, CP removal operation, and fast fourier transform(FFT). The received signal can be expressed as:

$$Y = H \cdot \bar{X} + Z. \quad (8)$$

where H represents the frequency response of the channel, Z represents the frequency domain representation of additive white Gaussian noise. To simplify the consideration, we assume that the receiver can obtain perfect channel state information. After equalization, the signal can be expressed as:

$$H^{-1} \cdot Y = \bar{X} + H^{-1} \cdot Z. \quad (9)$$

Using the maximum likelihood estimation on the equalized signal, the initial estimated signal $\hat{X} = [\hat{X}_0 \hat{X}_1 \cdots \hat{X}_{N-1}]$ can be expressed as follows:

$$\hat{X}_k = \arg \min \left| H_k^{-1} \cdot Y_k - s \right|, \quad s \in \chi. \quad (10)$$

where χ represents points on the constellation.

2) RELIABLE SUBCARRIER SELECTION

After getting the initial estimated signal, we can calculate the approximate value of clipping distortion:

$$\begin{aligned} H^{-1} \cdot Y - \hat{X} &= C + X - \hat{X} + H^{-1} \cdot Z \\ &= C + \theta. \end{aligned} \quad (11)$$

where $\theta = (X - \hat{X}) + H^{-1} \cdot Z$ is the observation noise of clipping distortion. It can be seen that part of the observation noise is the estimation error introduced by the initial estimation, and the other part is the channel noise.

In order to reduce the influence of observation noise θ on clipping distortion, it is necessary to select a part of subcarriers as reliable observations. Kim estimated the observation noise in the paper and got $\hat{\theta}$ [26]. The reliable subcarrier selection criterion used was

$$K = \left\{ k: \left| \hat{\theta}_k \right|^2 < E \left\{ |C_k|^2 \right\} \right\}. \quad (12)$$

K is the index of the selected subcarrier. The above formula indicates that the subcarrier with the estimated value of the observed noise energy less than the average energy of the clipping distortion is selected as the reliable observation.

There are also scholars who have done research on the selection of reliable subcarriers [29], and we can unify these selection criteria into a simple way

$$\delta [I(k)] = \text{sort} \left\{ \left| H^{-1} \cdot Y - \hat{X} \right|^2 \right\}, \quad k = 1, 2, \dots, N. \quad (13)$$

where $\text{sort}\{\cdot\}$ indicates that the clipping distortion with observation noise are sorted from small to large, and $I(k)$ is the index when the clipping distortion is not sorted. Then truncating it to obtain a reliable subcarrier selection criterion

$$K = \{I(k), k = 1, 2, \dots, M\}. \quad (14)$$

where $M = \lfloor \beta N \rfloor$, $\lfloor \cdot \rfloor$ means downward rounding, β is between 0 and 1, and some scholars have studied that $\beta = 0.6 \sim 0.8$ has good performance [30]. This selection criterion means that the subcarriers with the M smallest clipping distortion with observation noise are selected as our reliable subcarriers. This can avoid the situation that the channel conditions are too bad and the number of selected reliable subcarriers is very few. We will use this reliable subcarrier selection method in our proposed method and the comparative OMP algorithm.

3) RECONSTRUCTION OF CLIPPING DISTORTION

After we have M reliable subcarrier indexes, we can get a selection matrix S of size $M \times N$. The row of the selection matrix is the row corresponding to the index of reliable subcarriers in the unit matrix. The reliable observation value \tilde{Y} can be selected through the selection matrix.

$$\begin{aligned} \tilde{Y} &= S (H^{-1} \cdot Y - \hat{X}) \\ &= S (C + \theta) \\ &= SFc + S\theta \\ &= \Phi c + \eta. \end{aligned} \quad (15)$$

where F is a Fourier transform matrix of size $N \times N$, and Φ is a sub-matrix of the Fourier transform matrix. When the sub-matrix of the Fourier transform matrix is used as the sensing matrix, it can well meet the restricted isometric property [31]. the clipping distortion c is sparse, and η can be regarded as the observation noise in compressed sensing. Therefore, the above formula satisfies the mathematical model of compressed sensing. The clipping distortion can be solved by solving the following equation.

$$\min \|c\|_1 \text{ subject to } \|\Phi c - \tilde{Y}\|_2 \leq \varepsilon. \quad (16)$$

The clipping distortion \hat{c} can be recovered by compressed sensing algorithm. The commonly used compressed sensing recovery algorithm is the OMP algorithm. This greedy-based algorithm is simple and has an excellent recovery performance.

4) REESTIMATION

After the clipping distortion \hat{c} is reconstructed, the frequency domain clipping distortion \hat{C} can be obtained by Fourier transform. We can remove the clipping distortion and reestimate the received data so that we can obtain more accurate estimation results. The maximum likelihood estimation is also used, the process is as follows:

$$\hat{X}_k = \arg \min \left| H_k^{-1} \cdot Y_k - \hat{C}_k - s \right|, \quad s \in \chi. \quad (17)$$

After reestimation, the reestimated signal can be subjected to subsequent signal processing such as demapping.

III. PROPOSED CS BASED SIGNAL ASSISTED CLIPPING DISTORTION RECOVERY

A. TRANSMITTER WITH AUXILIARY SIGNAL

When using the OMP algorithm as the sparse reconstruction algorithm, it is necessary to know the sparsity of the signal. But in the clipping distortion recovery, the sparseness is difficult to obtain. We propose a signal-assisted clipping distortion recovery(saCDR). The structure of the transmitter of the superimposed auxiliary signal is shown in figure1.

The frequency-domain OFDM signal $X = [X_0 X_1 \cdots X_{N-1}]$ is subjected to IFFT to obtain $x = [x_0 x_1 \cdots x_{N-1}]$, and after the signal is clipped using (4), the clipped signal \bar{x} is obtained. In the clipping process, we can know the clipping position information, expressed as $p = [p_1, p_2, \dots, p_K]$ with

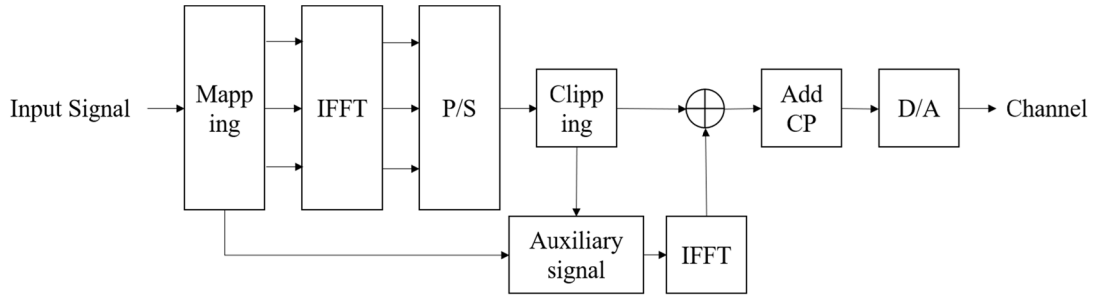


FIGURE 1. Transmitter of saCDR.

the index. K is the number of clipping positions, which is also the sparsity of the clipping distortion \mathbf{c} , and also the sparsity of the auxiliary signal \mathbf{A} that we want to generate. The index in \mathbf{p} indicates the non-zero value position in \mathbf{c} , which is also the non-zero value position in the auxiliary signal \mathbf{A} . The auxiliary signal generation method is as follows:

$$\mathbf{A} = E [\dots, X_{p_1}, \dots, 0, \dots, X_{p_2}, \dots, 0, \dots, X_{p_K}, \dots]_N \quad (18)$$

where E is an energy coefficient greater than 0. After the system sets the value of E , it will be stored at both the transmitter and the receiver of the system. The value of E will affect the PAPR and BER of the system, which will be analyzed in detail in the simulation of Chapter IV. The vector after E indicates that the complex-valued symbol with index p in the frequency-domain OFDM signal \mathbf{X} is reserved, and the other positions are set to zero. Through this method, the frequency-domain representation of the auxiliary signal can be obtained, and then the N -point IFFT can be used to obtain the time-domain representation of the auxiliary signal. Then the clipped signal and the auxiliary signal are superimposed together and the subsequent signal processing process is performed. The signal sent by the transmitter is expressed as

$$\dot{\mathbf{x}} = \bar{\mathbf{x}} + \mathbf{a} = \mathbf{x} + \mathbf{c} + \mathbf{a}. \quad (19)$$

The above process is the transmitter of the superimposed auxiliary signal that we put forward. The final transmitted signal not only contains the clipping distortion, but also contains the auxiliary signal we generated. We transmit the sparsity information of the clipping distortion through the generated auxiliary signal. Since the auxiliary signal is directly superimposed on the clipping signal, it does not require additional bandwidth.

B. CS BASED RECEIVER OF saCDR

We will elaborate on how the signal-assisted receiver based on compressed sensing works. We take MPSK as an example. The block diagram of the receiver is shown in figure 2.

The signal received by the receiver is

$$\mathbf{y} = \mathbf{h} * \dot{\mathbf{x}} + \mathbf{n}. \quad (20)$$

where \mathbf{h} is the impulse response of the channel, the influence of the signal through the channel can be expressed by the convolution operation $*$, and \mathbf{n} is the additive white Gaussian noise. The received signal \mathbf{Y} can be obtained by N -point FFT

$$\mathbf{Y} = \mathbf{H}\dot{\mathbf{X}} + \mathbf{N}. \quad (21)$$

For convenience, we assume that the receiver knows perfect channel state information, and the received frequency domain signal can be obtained by equalization.

$$\mathbf{H}^{-1}\mathbf{Y} = \dot{\mathbf{X}} + \mathbf{H}^{-1}\mathbf{N}. \quad (22)$$

Then use the maximum likelihood estimation to make an initial estimation on the frequency domain signal. The signal obtained by the decision is $\hat{\mathbf{X}} = [\hat{X}_0, \hat{X}_1, \dots, \hat{X}_{N-1}]$.

After the initial estimation, we can get

$$\begin{aligned} \mathbf{H}^{-1}\mathbf{Y} - \hat{\mathbf{X}} &= \dot{\mathbf{X}} - \hat{\mathbf{X}} + \mathbf{H}^{-1}\mathbf{N} \\ &= \mathbf{A} + \mathbf{X} - \hat{\mathbf{X}} + \mathbf{C} + \mathbf{H}^{-1}\mathbf{N}. \end{aligned} \quad (23)$$

We treat $\mathbf{X} - \hat{\mathbf{X}} + \mathbf{C} + \mathbf{H}^{-1}\mathbf{N}$ as noise, and assume that the recovered auxiliary signal is $\hat{\mathbf{A}}$. First we recover the non-zero position information in the auxiliary signal:

$$\hat{\mathbf{p}} = \left\{ \hat{p}_k : \left| H_k^{-1} Y_k - \hat{X}_k \right| > \frac{E}{2} \gamma \right\}. \quad (24)$$

γ represents the normalized constellation energy, which is 1 in the MPSK modulation. The non-zero position of the auxiliary signal obtained after the decision is $\hat{\mathbf{p}} = [\hat{p}_1, \hat{p}_2, \dots, \hat{p}_{\hat{K}}]$, where \hat{K} is the sparsity of the auxiliary signal. The auxiliary signal of the initial estimation can be expressed by the decision signal as

$$\hat{\mathbf{A}} = E \cdot [\dots, \hat{X}_{\hat{p}_1}, \dots, 0, \dots, \hat{X}_{\hat{p}_2}, \dots, 0, \dots, \hat{X}_{\hat{p}_{\hat{K}}}, \dots]. \quad (25)$$

Similar to the generation of the auxiliary signal, the complex value symbol corresponding to the position information $\hat{\mathbf{p}}$ in the initial decision signal $\hat{\mathbf{X}}$ is retained, the other values are set to zero, and the energy coefficient E is all multiplied.

After obtaining the auxiliary signal, we reconstruct the clipping distortion. We use the method in (13) and (14) to obtain the position of the reliable subcarrier, and obtain

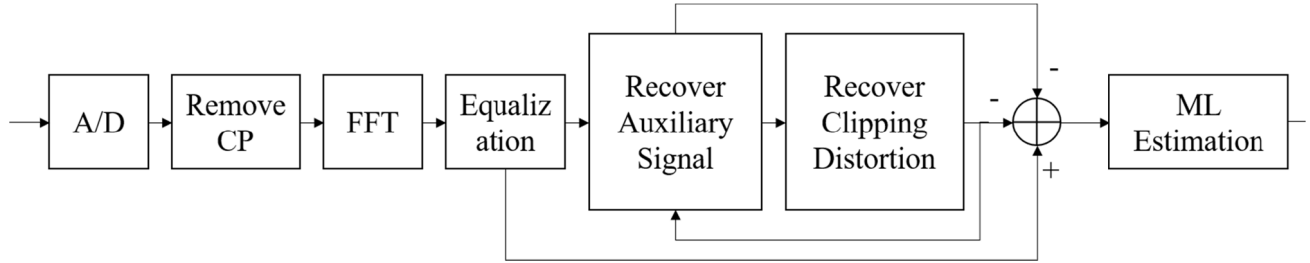


FIGURE 2. Receiver of saCDR.

TABLE 1. Iterative clipping distortion recovery.

Input: (1) Received signal \mathbf{Y} ; (2) Energy coefficient E ; (3) Channel information \mathbf{H} ; (4) Iterative number N_{iter} .
Output: Frequency domain signal $\hat{\mathbf{X}}$.
(1) Initialization: Clipping distortion $\hat{\mathbf{C}}_0 = \phi$; $t = 0$. (2) Estimate $(\mathbf{H}^{-1}\mathbf{Y} - \hat{\mathbf{C}}_t)$ to get $\hat{\mathbf{X}}_t$. (3) The position information $\hat{\mathbf{p}}_t$ of the auxiliary signal is recovered according to Equation (24), and the selection matrix \mathbf{S}_t is obtained. (4) Recover the auxiliary signal $\hat{\mathbf{A}}_t$ according to Equation (25). (5) The laOMP algorithm is used to recover the clipping distortion $\hat{\mathbf{c}}_{t+1}$ for the reliable observation value $\mathbf{S}_t(\mathbf{H}^{-1}\mathbf{Y} - \hat{\mathbf{X}}_t - \hat{\mathbf{A}}_t)$, and the clipping distortion is obtained by FFT to obtain the frequency domain representation $\hat{\mathbf{C}}_{t+1}$. (6) $t = t + 1$, when $t < N_{iter}$, return to (2), otherwise go to the next step. (7) Make a final ML estimate of $(\mathbf{H}^{-1}\mathbf{Y} - \hat{\mathbf{C}}_t - \hat{\mathbf{A}}_{t-1})$ to get the output $\hat{\mathbf{X}}$.

the selection matrix \mathbf{S} . The process of obtaining reliable observations by selecting the matrix is as follows:

$$\begin{aligned}
 \mathbf{S}(\mathbf{H}^{-1}\mathbf{Y} - \hat{\mathbf{X}} - \hat{\mathbf{A}}) &= \mathbf{S}(\hat{\mathbf{X}} - \hat{\mathbf{X}} - \hat{\mathbf{A}} + \mathbf{H}^{-1}\mathbf{N}) \\
 &= \mathbf{S}(\mathbf{C} + \mathbf{X} - \hat{\mathbf{X}} + \mathbf{A} - \hat{\mathbf{A}} + \mathbf{H}^{-1}\mathbf{N}) \\
 &= \mathbf{S}(\mathbf{C} + \boldsymbol{\theta}) \\
 &= \mathbf{S}\mathbf{F}\mathbf{c} + \mathbf{S}\boldsymbol{\theta} \\
 &= \boldsymbol{\Phi}\mathbf{c} + \boldsymbol{\eta}.
 \end{aligned} \tag{26}$$

Next, we can reconstruct the clipping distortion through the sparse recovery algorithm. We propose a location-assisted OMP algorithm—laOMP, the specific process of the algorithm will be described later. In addition, we also propose an iterative receiver. After obtaining the clipping distortion $\hat{\mathbf{C}}$, the clipping distortion can be used in the estimation of frequency-domain signal and recovery of auxiliary signal again, thereby obtaining a more accurate frequency domain signal $\hat{\mathbf{X}}$ and auxiliary signal $\hat{\mathbf{A}}$. The entire iteration process at the receiver is as follows:

C. PROPOSED laOMP ALGORITHM

In the OMP algorithm, you need to know the sparsity \mathbf{K} , and then iterate to find the non-zero position of the recovered signal. In our proposed method, the non-zero value position of the peak clipping distortion can be obtained through the auxiliary signal, so it can be used to omit the process of

TABLE 2. laomp algorithm.

Input: (1) $M \times N$ dimension sensing matrix \mathbf{B} ; (2) M -dimensional observation vector \mathbf{s} ; (3) Sparse index set \mathbf{p}_K .
Output: Estimation of sparse signals $\hat{\mathbf{c}}$
(1) Compute the sensing matrix subset $\mathbf{B}_K = \{\mathbf{b}_{\delta_1}, \mathbf{b}_{\delta_2}, \dots, \mathbf{b}_{\delta_K}\}$, where $\mathbf{p}_K = \{\delta_1, \delta_2, \dots, \delta_K\}$. (2) Calculate the sparse value $\hat{\mathbf{c}}_K = \arg \min_{\mathbf{c}} \ \mathbf{s} - \mathbf{B}_K \mathbf{c}_K\ = (\mathbf{B}_K^T \mathbf{B}_K)^{-1} \mathbf{B}_K^T \mathbf{s}$. (3) The sparse signal estimate $\hat{\mathbf{c}}$ has a value of $\hat{\mathbf{c}}_K$ on the sparse index set \mathbf{p}_K and a value of 0 on the remaining positions.

iteratively finding the non-zero value position in the OMP algorithm. The proposed location-assisted OMP algorithm can greatly reduce the complexity. The algorithm is as follows:

D. COMPLEXITY ANALYSIS

The complexity of the traditional OMP algorithm is mainly composed of two parts: (1) The calculation of the correlation coefficient is an inner product of an $N \times M$ dimensional matrix and an $M \times 1$ dimensional vector, and the total complexity here is $(2M - 1)N$. (2) The least square method is used to estimate the non-zero value of the signal and update the residual error. The algorithm complexity to iterate to the k -th step is $6kM$. Combining the above two main calculation processes, we can calculate the OMP algorithm complexity as $O(KMN)$.

The laOMP algorithm we proposed eliminates the iterative process and only requires a least squares calculation process. The computational complexity of the least square method is $4KM$, so the computational complexity of the laOMP algorithm is $O(KM)$. Since $K \leq M \ll N$, the overall complexity of clipping distortion recovery is greatly reduced. Although we adopted an iterative receiving process at the receiver, it can be seen from the subsequent simulation results that only 3 iterations are needed to obtain excellent results, so the overall complexity is still $O(KM)$.

IV. SIMULATION RESULTS

We have done many simulations to prove the performance advantages and disadvantages of the proposed signal-assisted clipping distortion recovery method. In the simulation, OFDM uses 256 subcarriers, and in order to make the simulation results clearer, the constellation modulation method uses

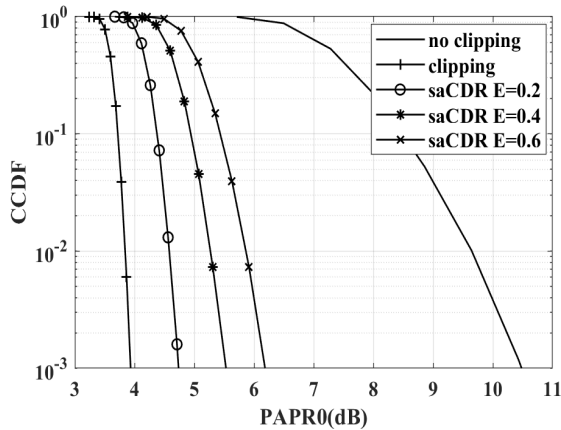


FIGURE 3. PAPR reduction performance of saCDR.

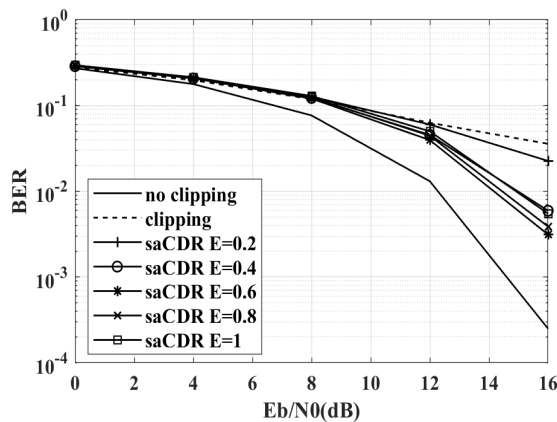


FIGURE 4. The effect of changing energy factor E on the BER.

16PSK. The simulation content is mainly the PAPR reduction performance and the BER performance under various channel conditions. In the comparison of BER performance, we add a control group that uses the OMP algorithm for clipping distortion recovery, and assume that the receiver can obtain a perfect signal sparsity K .

Figure 3 shows the effect of the proposed method on the signal PAPR. In the simulation, the clipping rate CR is set to 3dB. We compared the effect of different spreading factors E on the PAPR of the transmitted signal. In the figure, the PAPR in the case of unclipping and clipping without recovery is added for comparison. Using the clipping method can effectively reduce the PAPR of the system, while compared with the non-superimposed auxiliary signal, the saCDR method with the superimposed auxiliary signal will increase the PAPR of the system. When the CCDF value is 10^{-3} , the PAPR of the system will increase by about 0.6dB to 0.8dB as E increases by 0.2. And as E increases, the PAPR increases slowly. It can be seen from Figure 3 that superimposing the auxiliary signal will cause the PAPR reduction performance to be slightly weakened, which is a bad influence brought by the proposed method.

Figures 4 and 5 respectively show the effect of the energy factor E and the number of iterations N_{iter} on the system BER under the AWGN channel. The clipping rate CR at the

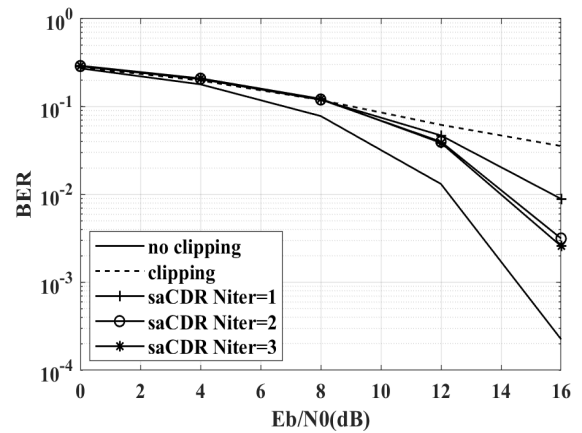


FIGURE 5. The effect of changing the number of iterations on the BER.

transmitter is set to 3dB in both simulations. In Figure 4, we use 2 iterations. As E increases, the bit error rate will decrease. Because with the increase of E , the correct rate of the receiver when recovering the auxiliary signal will be higher, and accordingly, the correct rate of clipping distortion recovery will be higher. However, as E increases more, it will cause an increase in the BER. This is because the increase of E will lead to an increase in the error limit of the modulation method. We have analyzed in another paper that the superimposed signal will affect the theoretical BER of the constellation [32]. That is to say, although the correct rate of reception is increased, the BER that can be achieved is also increased, which will also cause a decline in overall performance. But we can see that when the energy factor is set to 0.6, a good balance can be obtained. In Figure 5, we set the energy factor to 0.6. It can be seen that as the number of iterations increases, the bit error rate performance is significantly improved. And when the number of iterations is 2 to 3, the system's BER performance has been greatly improved. And we have analyzed in the complexity analysis that the complexity of the proposed laOMP algorithm is greatly reduced compared to the OMP algorithm, and the iterative receiving process of the receiver only requires 2 to 3 iterations. So, the receiving complexity of the entire receiver is very low, which is a major advantage of saCDR.

Figure 6 compares the BER of different algorithms under the AWGN channel. In the simulation, the clipping rate CR is 3dB, the energy factor E is set to 0.6, and the saCDR iteration number is set to 3. It can be seen that under this simulation parameter setting, the proposed method has better BER performance than using the OMP algorithm as the recovery algorithm. And in the simulation of the OMP algorithm, we assume that the receiver knows the sparsity K , but this is difficult to achieve in actual situations. It can be seen from the simulation results of BER that our proposed method can solve the problem that the receiver cannot obtain the sparsity.

In order to verify the applicability of the proposed algorithm under different channels, we also simulated the

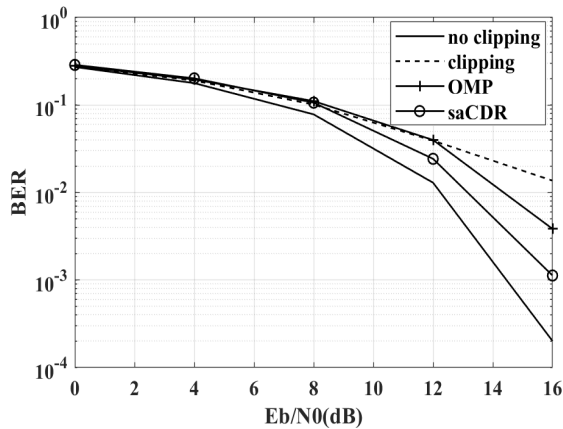


FIGURE 6. Comparison of BER performance under AWGN channel.

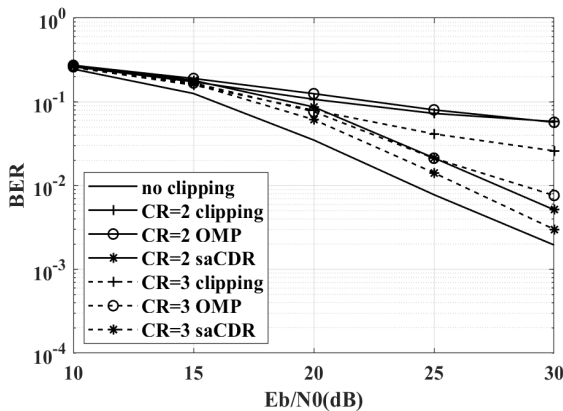


FIGURE 7. Comparison of BER performance under Rayleigh channel.

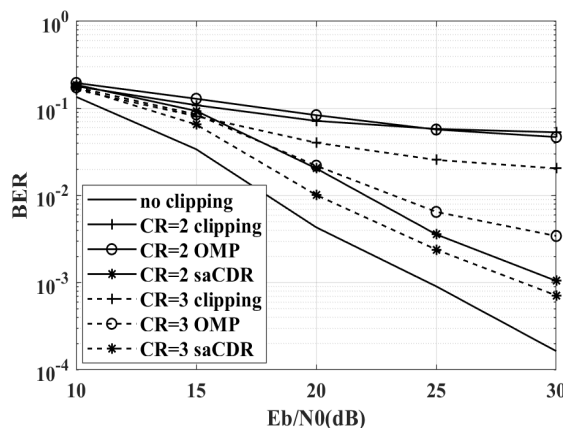


FIGURE 8. Comparison of BER performance under Rician channel.

BER of Rayleigh and Rician channels. In Figures 7 and 8, the energy factor is set to 0.6, and the number of iterations is set to 3. It can be seen that under the Rician channel, the BER performance of the system is better than that under the Rayleigh channel. And regardless of whether the clipping rate CR is set to 2 or 3, the proposed saCDR has better BER performance than the OMP algorithm. It can be seen in

both channels that the OMP algorithm almost does not work when CR is equal to 2. This is because when the clipping rate is low, many peaks of the transmitted signal are clipped, and the clipping distortion loses sparseness, which leads to a serious deterioration of the performance of the OMP algorithm. However, the proposed laOMP does not need to rely on the sparseness of the signal during recovery, and the recovery of the non-zero position information of the clipping distortion is transferred to the recovery of the auxiliary signal. Therefore, when the clipping rate is low, the proposed saCDR method can also have good BER performance. Combining Fig. 7 and Fig. 8, we can see that the proposed saCDR method has good adaptability under different channel environments, and can maintain good BER performance when the system has a low clipping rate.

V. CONCLUSION

This paper proposes a signal-assisted clipping distortion recovery method based on compressed sensing. The proposed method does not need to reserve empty subcarriers or pilots for clipping distortion recovery. By superimposing the auxiliary signal, we solved the problem that the receiver cannot obtain the sparsity K using the OMP algorithm. Simulations show that the complexity of the proposed improved algorithm combined with auxiliary signals is very low. Moreover, when the clipping degree of the signal is large and the clipping distortion loses sparseness, a good BER performance can also be obtained. However, the proposed method still has problems that affect the PAPR reduction effect and is only applicable to the MPSK modulation method. In the future, these two shortcomings need to be improved.

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