Joint Channel Estimation and Nonlinear Distortion Recovery Based on Compressed Sensing for OFDM Systems

Li-Jun Ge, Yi-Tai Cheng, and Bing-Rui Xiao
School of Electronics and Information Engineering, Tianjin Polytechnic University, Tianjin (300387), China
Email: {gelj_001, yitaicheng}@hotmail.com; xiaoxiaoxiao0219@gmail.com

***Abstract*—**In order to solve the problems of high PAPR and channel estimation in OFDM systems, a new algorithm of joint channel estimation and Nonlinear Distortion (NLD) recovery based on compressed sensing is proposed for nonlinearly distorted OFDM systems, using the dual-sparsity of channel and NLD. In quasi-static channel, the channel is estimated by adopting Golay complementary sequences to against NLD, and the NLD is estimated by using compressed sensing based on pectinate pilots. In time-varying channel, a scheme of pilot grouping and cascaded clipping is proposed. The pilots are divided into two groups. The first group, which is protected from NLD influence, is adopted to estimate the channel by compressed sensing, and the second group is used to estimate the NLD by compressed sensing as well, based on the estimated channel information. Simulation results show a good performance of the proposed algorithm without any priori information. And also advantages are brought for the system without any PAPR reduction algorithms or iterative operations.

***Index Terms*—**OFDM, compressed sensing, channel estimation, nonlinear distortion

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is the core technology in the field of high-speed wireless communication. It has many advantages such as efficient bandwidth utilization, strong ability to against Inter-Symbol Interference (ISI) and frequency selective fading. Channel estimation and Peak-to-Average Power Ratio (PAPR) reduction are the two key technologies of OFDM systems. Channel estimation accuracy directly affects the system performance under fading channels, and high PAPR causes Nonlinear Distortion (NLD) when OFDM signals pass through a power amplifier.

There are substantial articles about OFDM channel estimation, among which the methods based on auxiliary information are most widely studied. Typical estimation methods are Least Squares (LS) [1], Minimum Mean Square Error (MMSE) [2], Linear Minimum Mean Square Error (LMMSE) [3], etc. In recent years, with the proposal of compressed sensing, a large number of scholars began to explore its application in the field of wireless communication, and study the theory of pilot aided channel estimation in OFDM systems [4], [5]. Studies show that sparse channel estimation based on Compressed Sensing (CS), using the same number of pilots, could achieve better performance than traditional methods.

However, most of the existing channel estimation methods do not take the nonlinearity of OFDM signals into consideration. It is thought that no nonlinear distortion is existed or good solutions have been implemented for PAPR reduction. Classic algorithms of PAPR reduction include pre-distortion [6], Partial Transmit Sequence (PTS) [7], Selective Mapping (SLM) [8], etc. They are implemented in the transmitter and most of them have high complexity.

There are also some researches engaged in nonlinear distortion recovery. In early days, an iterative method based on signal reconstruction in the receiver was proposed to eliminate the nonlinear distortion [9]. Then, compressed sensing was applied to OFDM systems for impulse noise removal by using the pilots [10]. The nonlinear distortion of OFDM signals can be regarded as a sparse additive noise, and compressed sensing can be used to estimate the noise in the receiver [11]. However, although the methods stated above could avoid implementing complex PAPR reduction algorithms in the transmitter, they do not take the effect of fading channel on NLD estimation into account.

In a nonlinear OFDM system, the nonlinear distortion of auxiliary information has an impact on channel estimation, and meanwhile the fading channel seriously affects the performance of NLD estimation. So the channel estimation and the NLD estimation influencing and restricting each other becomes the difficulty of joint estimation. In recent years, only a few scholars did research on joint estimation of the channel and the NLD in a nonlinear OFDM system [12]-[14]. Reference [12] and [13] present an iteration-based joint algorithm that the channel estimation is based on LS and DFT interpolation, and the NLD elimination is based on decision feedback and signal reconstruction. In this method, the estimation accuracy is affected by the number of the pilots and the probability of wrong decision, and the priori information of clipping in the transmitter needs to be known for reconstruction. In [14], compressed sensing was firstly applied in the joint estimation that LMMSE combined with compressed sensing algorithm was adopted, and the priori information of the channel needs to be known in the receiver. In a word, the methods stated above require iterative computation which results in a low efficiency of

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Corresponding author email: yitaicheng@hotmail.com
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the algorithm. And, the priori information of channel or clipping is needed which limits its application scope.

In this paper, we presents a new algorithm of channel estimation and NLD cancellation based on compressed sensing for nonlinearly distorted OFDM systems, using the dual-sparsity of the channel and NLD. In quasi-static channel, the channel is estimated by adopting Golay complementary sequences to against NLD, and the NLD is estimated by using compressed sensing based on pectinate pilots. In time-varying channel, a method that group pilots and cascaded clipping scheme is proposed. The pilots are divided to two groups. The first one is adopted to estimate the channel by compressed sensing based on eliminating the NLD influence. The other one is used to estimate the NLD by compressed sensing as well based on eliminating the channel influence. The study has taken the effects of nonlinearity on the system into account, and joint estimation in the receiver avoids implementing complex PAPR reduction algorithms in the transmitter. Besides, the priori information is out of need, and the iterative computation is avoided.

II. System Model and Compressed Sensing Principle

A. OFDM System Model

In OFDM systems, the frequency-domain OFDM signal $\boldsymbol{X}=[X_0, X_1, \ldots, X_{N-1}]^{\mathrm{T}}$ is transmitted by N mutually orthogonal subcarriers. The symbol X_k sent over the k-th subcarrier is selected from a PSK or QAM constellation. The time-domain signal through IDFT modulation could be expressed as

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j2\pi kn/N}, \quad n = 0,1,\ldots,N-1 \tag{1}$$

Define vector $\boldsymbol{x}=[x_0, x_1, \ldots, x_{N-1}]^{\mathrm{T}}$, (1) could be represented in a matrix form as

$$\boldsymbol{x} = \boldsymbol{Q}\boldsymbol{X} \tag{2}$$

where $\boldsymbol{Q}$ represents a $N\times N$ dimensional IDFT matrix with elements $Q_{m,n} = \frac{1}{N}e^{j2\pi(m-1)(n-1)/N}, 1\le m\le N, 1\le n\le N$. A cyclic prefix with length N_g is appended to form a complete OFDM symbol and then the symbol is output by DAC.

NLD is generated when the signal passes through the amplifier due to the limitation of the linearity. The signal with NLD can be expressed as [15]

$$x_n^{'} = \beta x_n + d_n \tag{3}$$

where β is chosen so that the signal sequence x_n and the distortion sequence d_n are uncorrelated. Vector $\boldsymbol{d}=[d_0, d_1, \ldots, d_{N-1}]$ is introduced to represents the NLD which is regarded as sparse additive noise. For convenient analysis, β is defined as 1. So the signal with NLD can be re-expressed as

$$\boldsymbol{x}' = \boldsymbol{x} + \boldsymbol{d} = \boldsymbol{Q}\boldsymbol{X} + \boldsymbol{d} \tag{4}$$

In order to make the amplifier work in the linear scope, the signal is clipped in the transmitter, and the time-domain signal after clipping can be expressed as

$$x_n{}' = \begin{cases} x_n, & |x_n| \le \mathrm{A} \\ \mathrm{A}\, x_n / |x_n|, & |x_n| > \mathrm{A} \end{cases} \tag{5}$$

where A is the normalized threshold. In order to characterize the clipping impact on the signal, the PAPR after clipping is defined as $10\lg\left[\mathrm{A}^2/\mathrm{E}(|x_n|^2)\right]$. So the bigger the threshold value is, the higher the PAPR is, and that the NLD noise is sparser, and the NLD impact on the system is lighter.

Affected by multipath channel, the received OFDM signal in vector form can be written as

$$\boldsymbol{y} = \boldsymbol{h}\otimes\boldsymbol{x}' + \boldsymbol{z} = \boldsymbol{h}\otimes(\boldsymbol{x}+\boldsymbol{d}) + \boldsymbol{z} \tag{6}$$

where $\otimes$ represents cyclic convolution, vector $\boldsymbol{z}=[z_0, z_1, \ldots, z_{N-1}]^T$ is the additive white Gaussian noise, and $\boldsymbol{h} = [h_0, h_1, \ldots, h_{L-1}, \boldsymbol{0}_{1\times(N-L+1)}]^{\mathrm{T}}$, where h_l, l=0, 1,…, L-1 is the channel impulse response (CIR).

The received frequency-domain signal after DFT is given by

$$Y_k = \sum_{n=0}^{N-1} y_n e^{-j2\pi nk/N}, \quad k = 0,1,\ldots,N-1 \tag{7}$$

Define vector $\boldsymbol{Y}=[Y_0, Y_1, \ldots, Y_{N-1}]^{\mathrm{T}}$, then (7) can be written in matrix form

$$\boldsymbol{Y} = \boldsymbol{Q}^{\mathbf{H}}\boldsymbol{y} = \boldsymbol{H}\boldsymbol{X} + \boldsymbol{H}\boldsymbol{Q}^{\mathbf{H}}\boldsymbol{d} + \boldsymbol{Z} \tag{8}$$

where $\boldsymbol{Q}^{\mathbf{H}}$ is a $N\times N$ dimensional Fourier transform matrix, $\boldsymbol{H}$=diag(H_0, H_1, …, H_{N-1}) is a diagonal matrix derived from the channel frequency response vector $\boldsymbol{Q}^{\mathbf{H}}\boldsymbol{h}$, $\boldsymbol{Z} = \boldsymbol{Q}^{\mathbf{H}}\boldsymbol{z}$ is the white Gaussian noise in frequency-domain form. (8) is the OFDM demodulation signal model influenced by multipath channel and NLD.

B. Compressed Sensing Principle

Compressed sensing is a kind of signal compression theory for sparse signals. Define a $N\times 1$ dimensional signal $\boldsymbol{x} = [x_1, x_2, \ldots, x_N]^{\mathrm{T}}$, $x_i \in \boldsymbol{R}^N$. It can be mapped by a set of orthogonal basis named $\boldsymbol{\Psi}$ that

$$\boldsymbol{x} = \boldsymbol{\Psi}\boldsymbol{a} \tag{9}$$

where $\boldsymbol{a}$ is the description of $\boldsymbol{x}$ in $\boldsymbol{\Psi}$ domain. If there are only K nonzero values in vector $\boldsymbol{a}$, and K is much smaller than N, then $\boldsymbol{x}$ is said to be compressible in $\boldsymbol{\Psi}$ domain. Observe the signal $\boldsymbol{x}$ that

$$\boldsymbol{y} = \boldsymbol{\Phi}\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{\Psi}\boldsymbol{a} \tag{10}$$

where $\boldsymbol{y} = [y_1, y_2, \ldots, y_M]^{\mathrm{T}}$ is the $M\times 1$ dimensional observation vector, $\boldsymbol{\Phi}$ is the $M\times N$ dimensional measurement matrix. Compressed sensing theory has been proved that if the measurement matrix $\boldsymbol{\Phi}$ meets the restricted isometric property (RIP) [16], the original signal $\boldsymbol{x}$ with sparsity K can be reconstructed from the M observations with a high probability. And,

$$M \geq cK \log_2 (N/K) << N \tag{11}$$

where c is a small constant [10].

Vector $\boldsymbol{x}$ can be reconstructed by calculating the optimal solution. Classic signal reconstruction algorithms recover $\boldsymbol{x}$ from a small number of observations as follow

$$\hat{\boldsymbol{x}} = \arg\min \| \boldsymbol{x} \|_1 \ \text{s.t.} \ \| \boldsymbol{\Phi x} - \boldsymbol{y} \| \leq \varepsilon \tag{12}$$

where ε is a very small noise value. To get the solution of formula (12), there are two kinds of methods: one is the method based on convex optimization, such as basis pursuit (BP) algorithm. This kind of methods is of high reconstruction accuracy, but not easy to implement because of the high computational complexity; the other kind of method is based on greedy iterative, such as matching pursuit (MP) algorithm, orthogonal matching pursuit (OMP) algorithm [10]. The reconstruction via greedy algorithms is not as accurate as that of convex optimization ones. But the operation is simple, and easy to access.

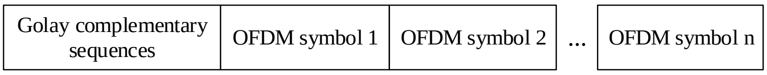

Fig. 1. Signal structure in quasi-static channel

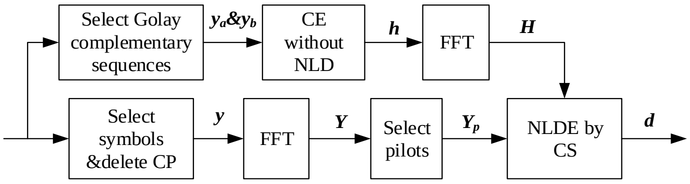

Fig. 2. Joint algorithm in quasi-static channel

III. The Joint Algorithm Proposed in This Paper

A. Quasi-Static Channel

In wireless communication, when the communication terminal does not move or moves slowly, the channel does not change or change very slowly relative to the symbol period. This kind of channel is called quasi-static channel. In this paper, we first propose a joint estimation scheme for the quasi-static channel that the channel is estimated by Golay complementary sequences and the NLD is estimated by compressed sensing based on the pilots. Fig. 1 shows the signal structure in quasi-static channel. Fig. 2 shows the operation principle of the proposed joint algorithm. Golay complementary sequences are not sensitive to NLD because they are composed of binary sequences. They can be received correctly through hard decision in the receiver even if there exists NLD. Therefore, in this paper, Golay complementary sequences as the block training sequences in a frame are used to estimate the CIR in a frame period. Then, the known channel information can be used to estimate the NLD of each symbol based on the pilots.

Golay complementary sequences are composed of binary sequences $\boldsymbol{a}$ and its complementary sequences $\boldsymbol{b}$. The sum of the self-correlation of $\boldsymbol{a}$ plus the self-correlation of $\boldsymbol{b}$ has only one peak, other values are all zero. According to this property, the channel can be accurately estimated by using Golay complementary sequences [17]. The main idea is that: after transmission through channel, the Golay complementary sequences $\boldsymbol{a}$ and $\boldsymbol{b}$ are convolved with the CIR respectively, getting $\boldsymbol{y_a}$ and $\boldsymbol{y_b}$; then, the correlation of $\boldsymbol{y_a}$ and the local $\boldsymbol{a}$, and that of $\boldsymbol{y_b}$ and the local $\boldsymbol{b}$, are calculated respectively; due to the Golay complementary property of $\boldsymbol{a}$ and $\boldsymbol{b}$, the CIR $\hat{\boldsymbol{h}}$ can be directly obtained from the sum of the two correlations.

Perform Fourier transform of $\hat{\boldsymbol{h}}$, then the frequency-domain channel response $\hat{\boldsymbol{H}}$ can be obtained. Substitute $\hat{\boldsymbol{H}}$ to the signal model (8), then

$$\boldsymbol{Y} = \hat{\boldsymbol{H}}\boldsymbol{X} + \hat{\boldsymbol{H}}\boldsymbol{Q}^{\mathrm{H}}\boldsymbol{d} + \boldsymbol{Z} \tag{13}$$

After transformation, there is

$$\boldsymbol{V} = \boldsymbol{Y} - \hat{\boldsymbol{H}}\boldsymbol{X} = \hat{\boldsymbol{H}}\boldsymbol{Q}^{\mathrm{H}}\boldsymbol{d} + \boldsymbol{Z} \tag{14}$$

Select the lines corresponding to the positions of the pilots, then the formula is written as

$$\boldsymbol{V_p} = \boldsymbol{Y_p} - \hat{\boldsymbol{H}}_{\boldsymbol{p}}\boldsymbol{X_p} = \hat{\boldsymbol{H}}_{\boldsymbol{p}}\boldsymbol{Q}_{\boldsymbol{p}}^{\mathrm{H}}\boldsymbol{d} + \boldsymbol{Z_P} \tag{15}$$

where $\boldsymbol{X_p}$, $\boldsymbol{Y_p}$, $\boldsymbol{Z_p}$, $\boldsymbol{V_p}$ are $P \times 1$ dimensional column vectors, $\hat{\boldsymbol{H}}_{\boldsymbol{p}}$ is a $P \times P$ dimensional diagonal matrix, $\hat{\boldsymbol{H}}_{\boldsymbol{p}} = \mathrm{diag}(H_0, H_1, \ldots, H_{P-1})$, P is the quantity of the pilots. Corresponding to (10), use compressed sensing to estimate the NLD, then

$$\hat{\boldsymbol{d}} = \arg\min \| \boldsymbol{d} \|_1 \ \text{s.t.} \ \| \hat{\boldsymbol{H}}_{\boldsymbol{p}}\boldsymbol{Q}_{\boldsymbol{p}}^{\mathrm{H}}\boldsymbol{d} - \boldsymbol{V_p} \|_2 \leq \varepsilon \tag{16}$$

In this paper, we use the OMP algorithm to obtain $\hat{\boldsymbol{d}}$. According to the compressed sensing theory, the estimated channel information is regarded as the measurement matrix, so the accuracy of channel estimation will affect the performance of NLD estimation directly. This paper presents the corresponding simulation analysis on this issue in Section IV.

B. Time-Varying Channel

In time-varying channel, the changes of channel characteristics between adjacent symbols cannot be ignored. Most of the existing methods use the comb-type pilots of each symbol to estimate channel in real time. In nonlinear OFDM systems, however, the pilots are affected by the NLD that if the pilots with NLD are used to estimate channel directly, the system performance will decline seriously. To solve this problem, this paper proposes a scheme which divides the pilots into two groups and introduces cascade clipping in the transmitter to protect the pilots from being affected by NLD. By making use of the dual-sparsity of the channel and the NLD, joint estimation of the channel and the NLD in the receiver by compressed sensing is proposed. The structure of the grouped pilots is shown in Fig. 3. Fig. 4 shows the principle of the joint algorithm in time-varying channel.

To estimate the channel and the NLD by compressed sensing, we design two groups of comb-pilots: the first group is used for channel estimation, defined as vector $\boldsymbol{X_{pCE}}=[X_{pCE,1}, X_{pCE,2}, \ldots, X_{pCE,Q}]$, where Q is the number of channel estimation pilots; the second group is used to estimate the NLD, defined as vector $\boldsymbol{X_{pNLDE}}=[X_{pNLDE,1}, X_{pNLDE,2}, \ldots, X_{pNLDE,R}]$, where R is the number of NLD estimation pilots. To eliminate the influence of NLD on the group of pilots for channel estimation and improve the channel estimation accuracy, this paper proposes the cascaded clipping scheme, on the basis of the traditional clipping method, to reduce the NLD of the pilots caused by clipping.

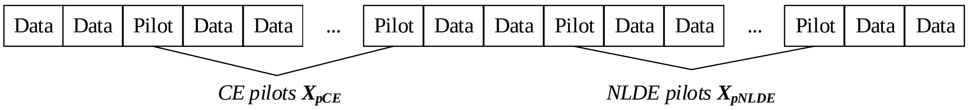

Fig. 3. Signal structure in time-varying channel

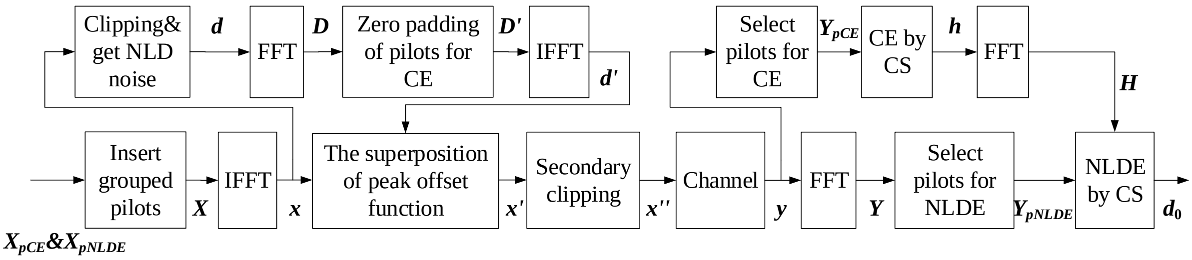

Fig. 4. Joint algorithm in time-varying channel

The specific steps are as follows:

$\boldsymbol{d_n}$ is the clipping distortion noise of the time-domain OFDM signal $\boldsymbol{x_n}$, then

$$d_n = \begin{cases} 0, & |x_n| \le \mathrm{A} \\ \mathrm{A}\, x_n / |x_n| - x_n, & |x_n| > \mathrm{A} \end{cases} \tag{17}$$

where A is the threshold of clipping. Do Fourier transform of vector $\boldsymbol{d}=[d_0, d_1, \ldots, d_{N-1}]^{\mathrm{T}}$, then

$$\boldsymbol{D} = \boldsymbol{Q}^{\mathrm{H}}\boldsymbol{d} \tag{18}$$

where $\boldsymbol{Q}^{\mathrm{H}}$ is the Fourier matrix. The elements in $\boldsymbol{D}$ whose positions are corresponding to the group of channel estimation pilots $\boldsymbol{X_{pCE}}$ are set to 0 to eliminate the NLD and the obtained vector is denoted as $\boldsymbol{D'}$. Then transform $\boldsymbol{D'}$ back to the time domain, that

$$\boldsymbol{d}' = \boldsymbol{Q}\boldsymbol{D}' \tag{19}$$

where $\boldsymbol{Q}$ is the inverse Fourier matrix. And then, add the above clipping distortion vector to the OFDM signal $\boldsymbol{x}=[x_0, x_1, \ldots, x_{N-1}]^{\mathrm{T}}$, that

$$\boldsymbol{x}' = \boldsymbol{x} + \boldsymbol{d}' \tag{20}$$

Now the clipping operation for the first time is completed.

After the first clipping, the peaks of the signal will rise in a certain degree because of the zero padding operation in the frequency domain. So the peaks need to be clipped for the second time to make the amplitude of the signal below the threshold.

$$x_n'' = \begin{cases} 0, & |x_n'| \le \mathrm{A} \\ \mathrm{A}\, x_n' / |x_n'|, & |x_n'| > \mathrm{A} \end{cases} \tag{21}$$

Assuming that the NLD vector is $\boldsymbol{d''}$ after the second clipping, then the signal after clipping can be expressed as

$$\boldsymbol{x''} = \boldsymbol{x'} + \boldsymbol{d''} = \boldsymbol{x} + \boldsymbol{d'} + \boldsymbol{d''} \tag{22}$$

The second clipping will introduce the NLD to the first group of pilots again, but at that moment, the influence of the NLD is slight. Furthermore, multi-level cascaded clipping, which repeatedly executes the above process (17-20), can be adopted to get higher performance for NLD removal. The simulation in the fourth part of this paper shows that two-level cascaded clipping can get an obvious effect in eliminating the NLD. So by weighing the performance and the complexity, the cascade level in an actual system can be decided.

After carrying out the above operations, the channel can be estimated based on the pilots $\boldsymbol{X_{pCE}}$ in the receiver. And then, take the channel information as known priori information and use the other group of pilots $\boldsymbol{X_{pNLDE}}$ to estimate the NLD of the signal. Substitute (22) into (6) and do Fourier transform. Then we can get

$$\boldsymbol{Y} = \boldsymbol{H}\boldsymbol{X} + \boldsymbol{H}\boldsymbol{Q}^{\mathrm{H}}\boldsymbol{d}' + \boldsymbol{H}\boldsymbol{Q}^{\mathrm{H}}\boldsymbol{d}'' + \boldsymbol{Z} \tag{23}$$

Select the lines corresponding to the positions of the channel estimation pilots, then

$$Y_{pCE} = H_{pCE}X_{pCE} + H_{pCE}Q_{pCE}^{H}d' + H_{pCE}Q_{pCE}^{H}d'' + Z_{pCE} \quad (24)$$

Since $Q_{pCE}^{H}d' = 0$, after the first time clipping, (24) can be simplified to

$$Y_{pCE} = H_{pCE}X_{pCE} + H_{pCE}Q_{pCE}^{H}d'' + Z_{pCE} \quad (25)$$

After the second time clipping, the NLD is little which can be regarded as a noise that (25) is simplified to

$$Y_{pCE} = H_{pCE}X_{pCE} + Z_{pCE}' \quad (26)$$

To meet the basic form of compressed sensing principle, rewrite (26) to

$$Y_{pCE} = X_{pCE}'H_{pCE}' + Z' = X_{pCE}'Q_{pCE}^{H}h + Z_{pCE}' \quad (27)$$

where

$$X_{pCE}' = \mathrm{diag}\left(X_{pCE,1}, X_{pCE,2}, \ \ldots, X_{pCE,Q}\right)$$
$$H_{pCE}' = \left[H_{pCE,1}, H_{pCE,2}, \ \ldots, H_{pCE,Q}\right],$$

and h is the CIR.

Based on (27), we use compressed sensing to estimate h, then

$$\hat{h} = \arg\min \| h \|_1 \ \text{ s.t. } \ \| X_{pCE}'Q_{pCE}^{H}\hat{h} - Y_{pCE} \|_2 \le \varepsilon \quad (28)$$

And we also use the OMP algorithm with low complexity to obtain h.

Perform Fourier transform of $\hat{h}$ that obtain the frequency-domain channel response $\hat{H}$. Then substitute it to (13) and select the lines corresponding to positions of the NLD pilots, then

$$\begin{aligned} Y_{pNLDE} = \ & \hat{H}_{pNLDE}X_{pNLDE} + \\ & \hat{H}_{pNLDE}Q_{pNLDE}^{H}(d' + d'') + Z_{pNLDE} \end{aligned} \quad (29)$$

Rewrite the equation to

$$\begin{aligned} V_{pNLDE} &= Y_{pNLDE} - \hat{H}_{pNLDE}X_{pNLDE} \\ &= \hat{H}_{pNLDE}Q_{pNLDE}^{H}d_0 + Z_{pNLDE} \end{aligned} \quad (30)$$

where d_0 is the sum of the NLD in each clipping.

Here we also use compressed sensing to obtain d_0 that

$$\begin{aligned} & \hat{d}_0 = \arg\min \| d_0 \|_1 \\ \text{s.t.} \quad & \| \hat{H}_{pNLDE}Q_{pNLDE}^{H}\hat{d}_0 - V_{pNLDE} \|_2 \le \varepsilon \end{aligned} \quad (31)$$

And we still adopt the OMP algorithm to calculate (31).

According to the compressed sensing theory, we can know that to estimate the multipath channel and the NLD with a sparsity, the quantity of the pilots for each group is a key to the joint estimation performance. In the fourth part of this paper, we give detailed simulation analysis of the grouping mode.

IV. Simulation Analysis

To investigate the performance of the proposed algorithms, we build a simulation environment based on the IEEE 802.15.3c standard of the 60GHZ OFDM system, with 512 subcarriers, 64 QAM modulation, 5/8 LDPC coding, the channel estimation sequences in the preamble composed of Golay complementary sequences with a_{128} and b_{128}, the uneven distributed comb pilots in each frequency-domain block, etc. Besides, the IEEE 802.15.3c working group recommends eight kinds of 60GHz channel models CM1 ~ CM8, in which CM1 has the smallest mean square delay spread, and the channel is the sparsest.

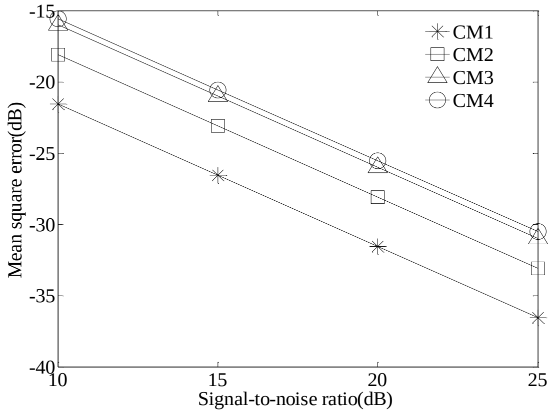

Fig. 5. Performance of channel estimation by Golay complementary sequences in different channels

To investigate the performance of the first joint algorithm in quasi-static channel, the simulations of the following Fig. 5-Fig. 6 are based on the constructed channels, whose impulse responses are selected from the channel models specified in the above standard, but changing once per frame. Fig. 5 shows the mean square error (MSE) performance of channel estimation, under quasi-static CM1 ~ CM4, based on the Golay complementary sequences. From the figure we can see that the channel estimation accuracy is improved with the increase of signal-to-noise ratio (SNR). The estimation performance in CM1 achieves the best, and that in CM4 gets the worst. When the SNR is 25dB, the MSE of estimated channel response is -36.16dB in CM1.

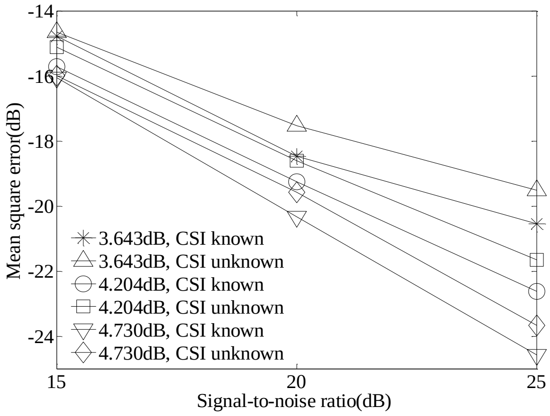

Fig. 6. Performance of NLD estimation by CS

Fig. 6 shows the MSE of the NLD estimation by compressed sensing, under quasi-static CM1 and different clipping thresholds, and the pilots number is 64. It can be seen that the higher of the threshold is, the higher the estimation accuracy is, which is according with the principle of compressed sensing. In order to observe the impact of channel estimation accuracy on NLD estimation, we compare the NLD estimation performance under two conditions that the channel information are known and unknown. The result shows that the MSE of the NLD estimation with unknown channel information is slightly higher than that with the known channel information in the same threshold case, but the MSEs of these two situations are very close. When the SNR is 25dB and the clipping threshold is 4.204dB, the MSE difference between them is 0.960 dB.

In the second joint algorithm, pilot grouping and cascaded clipping are needed. Table I shows the variance of NLD on the first group of pilots under different thresholds and different times of cascaded clipping when the SNR is 25dB. It shows that the higher the threshold is, the smaller the variance is. With the increase of clipping times, the variance becomes smaller. And it can be found that the variance of double clipping decreases obviously compared with the traditional clipping, but has little difference to triple clipping. So considering the system operational efficiency, two times of clipping may be better.

TABLE I: VARIANCE OF NLD ON PILOTS AFTER CLIPPING

Clipping threshold	Traditional clipping	Double clipping	Triple clipping
3.044dB	0.01879	0.00022	0.00020
3.643dB	0.01212	0.00009	0.00008
4.204dB	0.00791	0.00004	0.00004

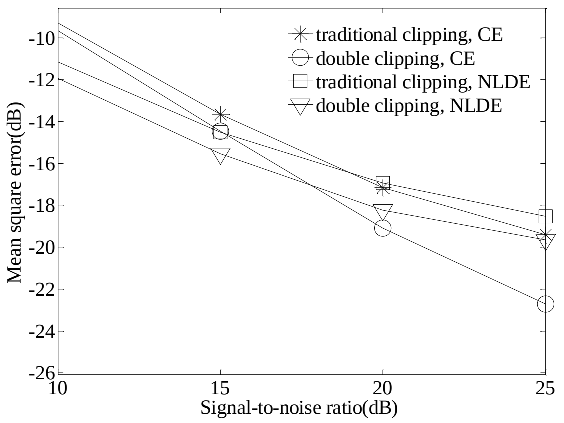

Fig. 7. Performance of the proposed joint algorithm by CS in different clipping times

To investigate the performance of the second joint algorithm in time-varying channel, the simulations of the following Fig. 7-Fig. 12 are all based on time-varying CM1 changes once per symbol. Fig. 7 shows the MSE performance of compressed sensing based joint estimation with traditional clipping and double clipping. The number of pilots for NLD estimation is 64, and that for channel estimation is 22. The figure shows that with the increase of SNR, the precision of the NLD and the channel estimation becomes higher. And the performance of the proposed cascaded clipping is better than that of the traditional one, because the first clipping operation in the cascade structure protects the pilots from NLD interference for channel estimation. Therefore, the obtained channel information is accurate, which brings benefit to the NLD estimation in the subsequent processing based on the other group of pilots. When the SNR is 25dB and the clipping threshold is 3.643dB, the MSE of channel estimation is -22.837dB and that of NLD estimation is -19.075dB in the double clipping case.

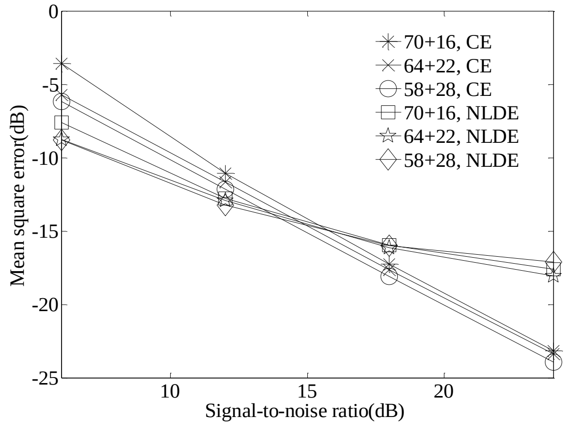

Fig. 8. Performance of the proposed joint algorithm of different pilot grouping modes under the threshold of 3.643dB

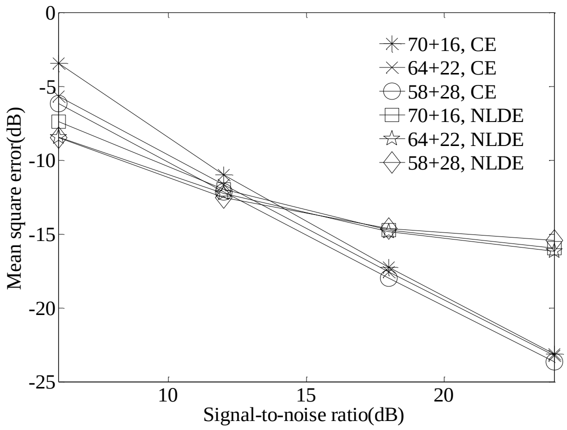

Fig. 9. Performance of the proposed joint algorithm of different pilot grouping modes under the threshold of 3.044dB

Fig. 8 and Fig. 9 show the performance of the proposed joint estimation with different modes of pilot grouping in the double clipping case, when the thresholds are 3.643dB and 3.044dB respectively. The total number of pilots is 86. We can see that the channel estimation accuracy of the system with 58 and 28 pilots for NLD estimation and channel estimation, is higher than that of the system with 64 and 22 corresponding pilots. And the performance of 70 and 16 pilots is the worst. While the NLD estimation accuracy of 64 and 22 pilots, is higher than that of 70 and 16 ones. And the performance of 58 and 28 pilots is the worst. Simulation shows that the more the pilots are used on one factor, the better the estimation accuracy will be. Therefore, it is necessary to trade off the modes of pilot grouping in practice. From Fig. 9, the same conclusion can be got. Since the NLD in Fig. 9 is more serious, the joint estimation performance is a little poorer than that in Fig. 8, in the same mode of pilot grouping.

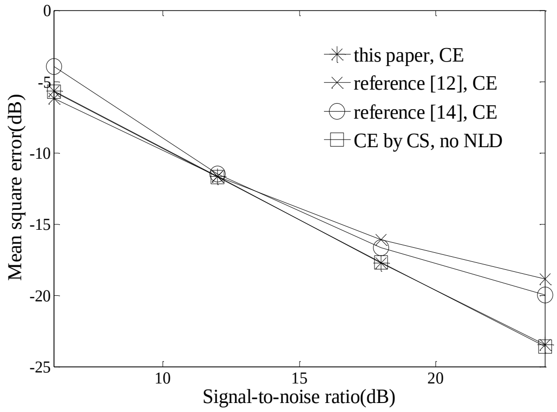

Fig. 10. Performance of channel estimation of different joint algorithms

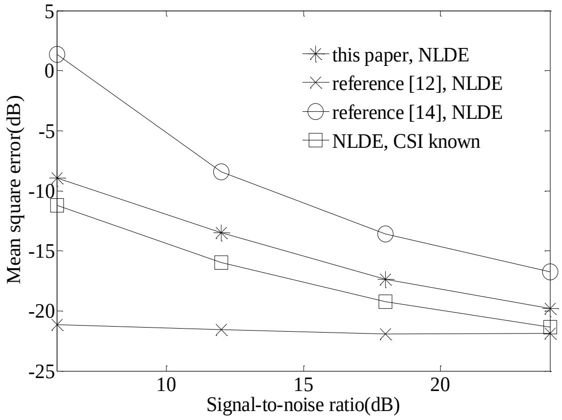

Fig. 11. Performance of NLD estimation of different joint algorithms

Fig. 10 and Fig. 11 compare the MSE of the proposed joint estimation algorithm and the conventional ones given in [12] and [14], and Fig. 12 shows the Bit Error Rate (BER) performance of the system. The algorithm of NLD estimation in reference [14] is changed from SOCP to OMP in order to compare the performance fairly. In this three figures, the threshold are 4.204dB as the same, the total pilot number are all equal to 86, and the joint algorithm given in [12] and [14] both do iterative operation for three times. Then, it can be seen from figure 10 that for the proposed algorithm weakens the effect of NLD on channel estimation pilots, the performance of channel estimation by OMP algorithm is better than that by LMMSE combined with OMP iterative method given in [14], and it is also better than that by LS and DFT combined with signal reconstruction by decision-feedback equalizer method proposed in [12].

In terms of NLD estimation shown in Fig. 11, signal reconstruction method performs the best because of the known priori information of clipping threshold. The performance of the proposed method in this paper is obviously better than that in [14], for the excellent performance of channel estimation. In addition, when the SNR is high, the performances of these three joint estimation algorithms are very close to each other. Generally speaking, the method in this paper is superior to that in [12] and [14], and needs no priori information of channel or NLD. From Fig. 12, it can be seen that the system BER of the proposed joint algorithm is close to that of the other two methods in low SNR case, but obviously superior to them in high SNR case.

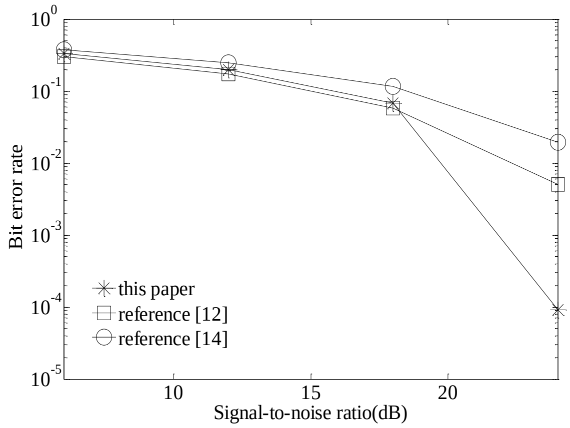

Fig. 12. BER performance of the system with different joint algorithms.

V. Conclusion

In this paper, we propose a new algorithm of joint channel estimation and nonlinear distortion recovery based on compressed sensing for nonlinearly distorted OFDM systems. As Golay complementary sequences are not sensitive to NLD, the channel estimation is accurate in quasi-static channel, and the performance of NLD estimation via compressed sensing is good. In time-varying channel, the grouped pilots for channel estimation are protected from NLD influence by cascaded clipping, so the channel estimation is accurate especially in high SNR case. The NLD is estimated by compressed sensing as well based on the corresponding grouped pilots, with the estimated channel information. And the NLD estimation performance is close to that of the signal reconstruction method in high SNR case. As to the performance of the system, with the higher accuracy of channel estimation, the proposed joint algorithm performs better than the other two schemes in high SNR case.

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Li-Jun Ge is an associate professor in Communication Engineering Department of Electronics and Information Engineering School of Tianjin Polytechnic University. During the past three years, he was in charge of several projects supported by the nation or the city and published many academic papers. His research interests include OFDM and OFDM-UWB wireless communication technologies.

Yi-Tai Cheng is engaging in a wireless communication research for the master's degree in the major of communication and information systems in Tianjin Polytechnic University.

Bing-Rui Xiao is engaging in a wireless communication research for the master's degree in the major of communication and information systems in Tianjin Polytechnic University.