PAPR Reduction with Amplitude Clipping and Subband Filter in Filtered-OFDM System

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Abstract. To reduce the PAPR (Peak-to-Average Power Ratio) in the Filtered-OFDM (F-OFDM) system, we propose an amplitude clipping method working together with the subband filter in the F-OFDM system. Firstly, a power level is preset to clip the real and imaginary parts of F-OFDM signals for reducing the peak energy of transmitted signals. Then the spectrum leakage and distortion caused by amplitude clipping are mitigated by the designed subband filter of F-OFDM system. The simulation results demonstrate that such a combined method can suppress PAPR effectively and maintains good BER (Bit Error Rate) performance compared with the traditional OFDM system.

Keywords: F-OFDM · PAPR · Subband filter · Amplitude clipping

1 Introduction

OFDM (Orthogonal Frequency Division Multiplexing) [1, 2] is the main multi-carrier modulation technology that is widely used in 4G system. OFDM offers a considerable high spectral efficiency, power efficiency, and immunity to the frequency selective fading channels. There are more challenges for 5G mobile communication technologies to support stricter transmitting requirements. F-OFDM (Filtered-OFDM) [3–5], OFDM with subband filter, is proposed by Huawei as an approach to reduce high frequency spectrum leakage and large out-of-band interference for 5G system [6–8].

One challenging issue in OFDM system is high Peak-to-Average Power Ratio (PAPR) of transmitted signals. F-OFDM signals also consist of many independent and orthogonal sub-carriers, and have the problem of high PAPR [9–11]. Meanwhile, the subband filter in the F-OFDM system can also increase the PAPR. Hence, efficient PAPR reduction is needed for F-OFDM system. The PAPR reduction schemes can mainly be categorized into signal scrambling techniques (e.g., block codes and PTS) and signal distortion techniques such as amplitude clipping. Amplitude clipping [12, 13] is the simplest technique for PAPR reduction. It is a predistortion technology that basically clips the parts of the signals when they are above a preset clipping level. However, clipping method introduces both in-band distortion and out-of-band radiation into OFDM signals, which degrades the system performance such as BER and spectral efficiency. To counter the drawbacks of amplitude clipping, one filter can be added after clipping to reduce the in-band distortion and out-of-band radiation.

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This paper proposes to reduce PAPR of F-OFDM system [14, 15] by amplitude clipping and subband filtering. With our proposed method, the PAPR of the F-OFDM system can be reduced, and the out-of-band radiation caused by amplitude clipping can be reduced by the inherent subband filter in F-OFDM system. Hence, it is not necessary to design a special filter after clipping in our approach. The simulation results demonstrated that our proposed method can suppress PAPR effectively and still maintains a good BER performance in F-OFDM system.

This paper is organized as follows. In Sect. 2, we describe the PAPR reduction method for F-OFDM system by using amplitude clipping and subband filter. Section 3 presents and discusses the simulation results of our proposed method. Section 4 concludes this paper.

2 F-OFDM with Amplitude Clipping and Subband Filter

F-OFDM is an improvement on the basis of OFDM. F-OFDM has lower out-of-band leakage by dividing the whole band into multiple subbands and add subband filter in the sender and receiver of OFDM system. This helps F-OFDM system to have higher spectral efficiency compared with OFDM. Moreover, F-OFDM system enables flexible waveforms in the 5G networks. Each subband of F-OFDM system can be processed independently by configuring different parameters, such as sub-carrier spacing, IFFT points and CP (Cyclic Prefix) length, to make the waveform meet the requirements for different 5G scenarios. The system model of F-OFDM system is shown in Fig. 1. Compared with traditional OFDM system, the F-OFDM system adds two new modules, subcarrier mapping and subband filter.

To reduce the high PAPR in F-OFDM system, our proposal utilizes amplitude clipping technology and the subband filter in F-OFDM system. The added clipping module (in red color) is shown in Fig. 1. The power level is preset to control the peak values of F-OFDM signals, and the spectrum leakage can be suppressed by the designed subband filter.

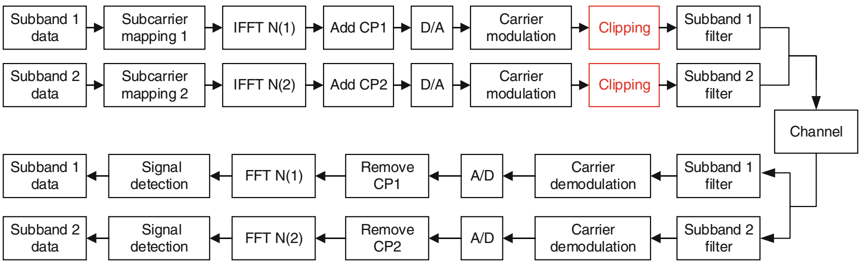

Fig. 1. F-OFDM system model with PAPR reduction (Color figure online)

2.1 Subcarrier Mapping

The F-OFDM algorithm need to give index numbers of all subcarriers and map different subband data to different sub-carriers separated in frequency domain. The subcarrier mapping function ensures that different subbands are configured with different parameters for simultaneous transmission and the signals can be decoupled in the receiver.

Figure 2 shows an example by taking two subbands. It is assumed that the number of subcarriers of the first subband is M_1, the number of subcarriers of the second subband is M_2, and the size of IFFT points is 2048. The serial number of 2048 subcarriers is [K_{min} K_{max}]. K_{min} and K_{max} is the integers within the scope of [−1023, 1024]. We suppose the number of subcarriers of guard band for the first subband is N_1, and the number of subcarriers of guard band for the second subband is N_2.

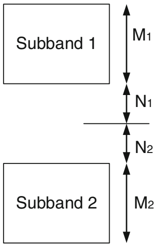

Fig. 2. Subcarrier mapping between subbands

The serial number of the sub-carriers of the second subband can be calculated by

$$[\frac{K_{\max}+N_1}{2}+N_2+1, \frac{K_{\max}+N_1}{2}+N_2+M_2] \tag{1}$$

There $K_{\max}+N_1$ must be an even number.

For example, there are two subbands with band width 720 kHz, and suppose that the sub-carrier spacing of the first subband is 15 kHz, the second subband sub-carrier spacing is 30 kHz, that means M_1 = 48, M_2 = 24. Then the serial number of the first subband can be set as [−24,−1] [1,24], the sub-carrier with number 0 can be considered to be the direct current component without data mapping in it. We assume N_1 = 0, N_2 = 1, then the sub-carrier number of the second subband will be [14,37]. To determine the values of N_1 and N_2, we need to consider the power spectrum, the interference between subbands and the parameters of all the subbands. To simplify the analysis, our work in this paper only analyzes the performance of PSD and PAPR in one subband.

2.2 The PAPR Reduction with Amplitude Clipping

PAPR is defined as the ratio of maximum peak power and mean power, which is represented as

$$PAPR_{dB} = 10\lg\left\{\frac{\max\limits_{0\leq n<N}\left(|x_n|^2\right)}{\frac{1}{N}\sum_{n=0}^{N-1}|x_n|^2}\right\} \tag{2}$$

Complementary cumulative distribution function (CCDF) can be used to evaluate the performance of PAPR. CCDF shows the possibility of PAPR that exceeds a given threshold. Amplitude clipping technology reduces the peak energy of signal by setting a power level. However, traditional amplitude clipping method can lead to signal distortion and out-of-band leakage after clipping process, and it needs to add a filter to mitigate this issue. Our proposal combines the subband filter in F-OFDM system and amplitude clipping technology. Thus, the subband filter plays another role in our approach to mitigate the drawbacks of amplitude clipping. The subband filter in F-OFDM system can reduce frequency spectrum leakage and out-of-band interference effectively. Hence, it is not necessary to design a special filter after clipping in our proposed approach. Meanwhile, F-OFDM system divides the whole band into multiple subbands, and we can perform clipping and filtering in each subband.

Denote the send signals as x_n, the clipping process on the real part and imaginary part of the transmitted signals can be represented as

$$\mathrm{Re}(X_n) = \begin{cases} \mathrm{Re}(x_n) & |x_n| \leq A \\ p \times \mathrm{Re}(x_n) & |x_n| > A \end{cases} \tag{3}$$

$$\mathrm{Im}(X_n) = \begin{cases} \mathrm{Im}(x_n) & |x_n| \leq A \\ p \times \mathrm{Im}(x_n) & |x_n| > A \end{cases} \tag{4}$$

where X_n is the F-OFDM signal after clipping, A is the given power threshold, p is the limiting factor with scope of [0,1]. The peak energy of F-OFDM signal can be suppressed directly by clipping process. Then X_n will be filtered by the subband filter, which can reduce the out-of-band leakage effectively and improve the performance of transmitted signals. In Sect. 3, the simulation results will demonstrate that our proposed method can suppress PAPR effectively and still maintains good BER performance in F-OFDM system.

2.3 Design of Subband Filter

It can be noted in the F-OFDM system block diagram that the F-OFDM signal is transformed to the time domain after IFFT before the subband filter. It is discrete time domain signal on each sub-carrier. We need to design D/A transfer filter $g(t)$ to transfer the discrete signal to continuous wave signal (e.g., rectangular wave, square-root raised cosine wave). To reduce high PAPR of the signal, the signal is clipped after carrier modulation by setting a power level to reduce peak energy and the clipped signal is further filtered by the subband filter. The subband filter can reduce the out-of-band leakage and the signal distortion caused by clipping process. The design of subband filter uses the traditional window function method, that is to add different window functions to the Sinc function in time domain. It can be expressed by

$$W_{\sin c} \times W_{win} = W_{filter} \tag{5}$$

The design of subband filter in this paper is based on Hanning window which is known as cosine square or ascending cosine window. The time domain form of Hanning window can be expressed as

$$W(n) = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi n}{N-1}\right)\right] R_N(n) \tag{6}$$

The spectral function of Hanning window can be represented as

$$W\left(e^{j\omega}\right) = \left\{0.5W_R(\omega) + 0.25\left[W_R\left(\omega - \frac{2\pi}{N-1}\right) + W_R\left(\omega + \frac{2\pi}{N-1}\right)\right]\right\}e^{-j\left(\frac{N-1}{2}\right)\omega} \tag{7}$$

$$= W(\omega)e^{-j\left(\frac{N-1}{2}\right)\omega} \tag{8}$$

where $W_R(e^{j\omega}) = W_R(\omega)e^{-j\left(\frac{N-1}{2}\right)\omega}$.

When N is very greater than 1, it can be approximated as

$$W(\omega) \approx 0.5W_R(\omega) + 0.25\left[W_R\left(\omega - \frac{2\pi}{N}\right)\right] + W_R\left(\omega + \frac{2\pi}{N}\right) \tag{9}$$

The sum of the three parts makes the sidelobe largely canceled out, and energy is more concentrated in the main lobe.

When designing the subband filter, the filter length N need to be chosen to be an appropriate value because larger N helps to reduce the spectrum leakage but may lead to larger PAPR and degrade the BER performance.

3 Simulation and Discussion

3.1 Simulation Parameters of F-OFDM System

In the simulated F-OFDM system, the size of IFFT is 2048, the number of effective sub-carriers is 336, and the other sub-carriers are set to zero. The sub-carrier spacing is set to 15 kHz according to 3GPP standard, then the subband band width is 5.04 MHz. In addition, the CP length is 128. Table 1 shows the parameters of F-OFDM system for simulation. We choose 4QAM as the modulation method on the subcarriers. The sending signal before the subband filter is rectangular wave signal. The order of the subband filter ($N - 1$) is chosen to be 128 to balance the tradeoff between the spectrum leakage reduction and the BER performance.

Table 1. Parameters of simulation

Parameter	Sub-band
Modulation system	4QAM
Sub-carrier spacing	15 kHz
FFT points	2048
Used sub-carriers	336
CP length	128
Bandwidth	5.04 MHz
Symbol period	1/15 K = 66.67us
Carrier frequency	76.8 MHz

3.2 Simulation Results and Discussion

Figure 3 shows the respective PSD (Power Spectrum Density) of clipping OFDM signal and clipping F-OFDM signal. We can see that the subband filter results in smaller out-of-band leakage in the clipping F-OFDM signal than that in the clipping OFDM signal, and the clipping F-OFDM signal has better PSD performance compares with clipping OFDM signal. Note that

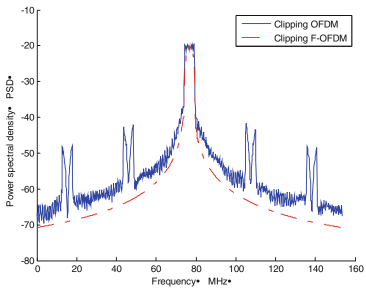

Fig. 3. PSD of clipping OFDM signal and clipping F-OFDM signal

Figure 4 shows the CCDF of OFDM signal, F-OFDM signal, clipping OFDM signal and clipping F-OFDM signal. The simulation results show that the subband filter deteriorates the PAPR performance such that the PAPR of F-OFDM signal is higher than that of OFDM signal. We can see clearly that the PAPR of clipping F-OFDM signal is much lower than that of the F-OFDM signal, which means our proposed method can reduce PAPR effectively.

Figure 5 shows the BER performance of OFDM and F-OFDM system. It can be seen that clipping F-OFDM system has a better BER performance than the clipping OFDM system. The BER of clipping F-OFDM system is a little bit higher than that of F-OFDM due to the fact that the clipping process causes out-of-band interference. Then we can know that our proposed method not only has good PAPR performance but also maintains good BER performance.

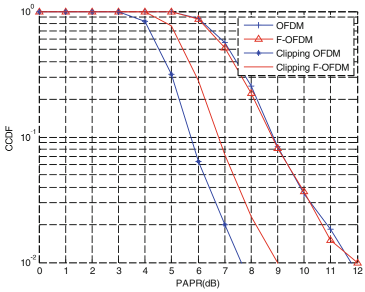

Fig. 4. PAPR of OFDM and F-OFDM

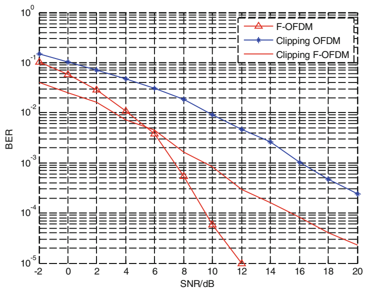

Fig. 5. BERs of OFDM and F-OFDM

4 Conclusion

Filter-OFDM signals for 5G wireless system also have the problem of high PAPR like OFDM system. This paper proposes to reduce the PAPR of F-OFDM system by amplitude clipping and subband filtering. Our proposed approach can suppress the PAPR of the F-OFDM system and reduce the in-band distortion and out-of-band radiation by the inherent subband filter in F-OFDM system. Thus, the subband filter plays another role in our approach to mitigate the drawbacks of amplitude clipping. Hence, it is not necessary to design a special filter after clipping as is required when using amplitude clipping in the traditional OFDM system. We investigated our proposal by simulation according to the 3GPP transmission parameters and we demonstrated that our proposed method can suppress PAPR effectively and maintains a good BER performance in F-OFDM system.

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