OFDM PAPR Reduction with Digital Amplitude Predistortion

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Abstract

The major drawback of orthogonal frequency division multiplexing (OFDM) systems is the high peak to average power ratio (PAPR), which results in signal distortion when the transmitter has nonlinear components. Even though the predistortion is used to compensate for the high power amplifiers (HPA), some amount of input back-off (IBO) is required to remove nonlinear distortion completely since the PAPR is very high. In this paper, we propose the PAPR reduction methods of clipping and ACE (active constellation extension) to compensate for the nonlinear distortion. Then, the amount of required IBO is lowered so that power efficiency is improved than the only predistortion case. Based on the memoryless solid state power amplifier (SSPA) of Rapp model, computer simulations and analysis in this paper demonstrates that, especially when the HPA is working near or in the saturation region, a predistorter will cease to be in effect. In such cases, PAPR reduction techniques may be resorted to help to improve the HPA efficiency.

1. Introduction

The OFDM is an attractive technique for wireless multimedia communication by virtue of its excellent properties in frequency-selective fading environments. However, OFDM system exhibits large PAPR, which cause a loss in energy efficiency due to the need of power back-off at the HPA. Therefore, it is important to reduce PAPR of OFDM signal and to compensate for nonlinear distortion of the power amplifier.

Existing PAPR reduction methods use clipping, coding or multiple signal representation [1-3]. Among of them, the clipping scheme is the simplest method to reduce the PAPR. However, the quality of its output signal is degraded by out-of band radiation and in-band distortion [4]. The out-of band spectral regrowth can be alleviated by time-domain filtering. Then, the ACE technique, allows the in-band fading to extend the signal constellation only into desired directions without sacrifice the subcarrier tones.

In this work, we adderss a clipping and ACE PAPR reduction method based on amplitude predistortion of HPA. Predistortion is applied to countermeasure the nonlinearity of HPA and to improve the power efficiency of HPA. However, Predistortion may cease to be in effect when the HPA is working near or in the saturation region. We can resort to clipping and ACE PAPR reduction technique to solve such problems. Consequently, the predistortion with low PAPR signal is an important problem to decrease the HPA nonlinearity and to improve the power efficiency of HPA.

The OFDM signals and PAPR are described in Section II. In Section III , joint PAPR reduction and HPA preditortion methods are simply presented. The analysis and computer simulations of PAPR reduction effects on HPA linearization are given in Section IV with some conclusions drawn in SectionV.

2. PAPR for OFDM Systems

Let $\boldsymbol{c} \in \mathbb{C}^N$ be the frequency-domain OFDM symbol and $\{\boldsymbol{c}(i), i = 1, \ldots, N\}$ be the symbol value carried by the *i*-th sub-carrier. Then, the time-domain complex baseband transmitted signal, $\boldsymbol{x} \in \mathbb{C}^{\ell N}$, corresponding to $\boldsymbol{c}$ with ℓ times over-sampling is expressed as

$$x(k) = \frac{1}{\sqrt{\ell N}} \sum_{i=1}^{N} \boldsymbol{c}(i) e^{j\frac{2\pi}{\ell N}ki}, k = 1, \ldots, \ell N \tag{1}$$

which can also be written in matrix form $\boldsymbol{x} = [x_0, \ldots, x_{\ell N-1}]^{\mathrm{T}} = \boldsymbol{Q}\boldsymbol{c}$, where $\boldsymbol{Q}$ is the IDFT matrix with the (*k*,*i*)th entry $q_{n,k} = (1/\sqrt{N}) e^{j2\pi ik/N}$.

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Let $\mathrm{E}[\cdot]$ denote the mathematical expectation and the amplitude, $\|\boldsymbol{x}\|_2$ denote the second norm of a vector. The PAPR (in decibel) of $\boldsymbol{x}$ is defined as

$$PAPR(\boldsymbol{x}) = 10\lg \frac{\max\limits_{0\le k\le N-1} |\boldsymbol{x}(k)|^2}{\mathrm{E}[\|\boldsymbol{x}\|_2^2]} \tag{2}$$

The continuous time PAPR can be approximated using the discrete time PAPR, which is obtained by over-sampling the OFDM signal. In a system with QPSK modulation, ℓ=4 time over-sampling signal is considered enough to estimate PAPR [5].

3. Effects of PAPR Reduction on HPA Preditortion

3.1 Clipping and ACE Based PAPR Reduction

The objective of PAPR reduction is to reduce the probability of large-amplitude signals. In this section, we discuss the amplitude clipping and ACE technique for PAPR reduction.

Amplitude clipping leads to in-band distortion and out of band radiation. To suppress the out-of-band radiation, filtering after clipping is used. The filtering is done with the FIR (finite impulse response) filter of Hamming windowing. In order to satisfy the spectral constraint, active constellation extension (ACE) technique is required to eliminate the in-band distortion. Active constellation extension (ACE) is a very attractive scheme due to its good performance of PAPR reduction for constellation without any BER loss in reception.

Let $\boldsymbol{\Gamma}$ be the index set of all data tones: $\boldsymbol{\Gamma} = \{\forall k, s.t., 0 \le k \le N-1\} = \{\boldsymbol{\Gamma}_a \cup \boldsymbol{\Gamma}_c\}$, where $\boldsymbol{\Gamma}_a$ is the index set of active sub-channels for reducing PAPR. The basic principle of ACE is that it extends the outer constellation set away such that the minimum distance between the constellation points is not reduced. The PAPR reduced in ACE can be formulated as

$$\min_{\boldsymbol{C}} \|\boldsymbol{x} + \boldsymbol{Q}^*\boldsymbol{C}\|_\infty^2 \tag{3}$$

Subject to: X_k+C_k be feasible for $k \in \boldsymbol{\Gamma}_a$, C_k=0, for $k \notin \boldsymbol{\Gamma}_a$

where $\boldsymbol{C}$ is the extension vector whose components C_k are nonzero only if $k \in \boldsymbol{\Gamma}_a$ [6].

3.2 Polynomial Predistortion as Linearization Method

The HPA non-linearity introduces out-of-band and in-band distortion [7]. Although PAPR reduction methods can reduce the peak power, it is not enough to suppress the distortion. Predistortion should be used to limit the spectral regrowth.

Rapp model is taken into consideration in this paper, which is widely used in most literatures for HPA performance analysis. The AM/AM transfer function of the HPA and the associated polynomial predistoter can be modeled as follows:

HPA AM/AM transfer characteristic:

$$f_A(x) = \frac{x}{\left[1 + (\frac{x}{A_{sat}})^{2p}\right]^{\frac{1}{2p}}}, x \in [0, +\infty] \tag{4}$$

where x represents the complex envelope of the input signal, A_{sat} denotes the amplifier input saturation voltage and p is the smoothness factor. The curves in Fig.2 show the effect of smoothness factors p.

Predistortion function:

$$f_A^{-1}(x) = \frac{x}{\left[1 - (\frac{x}{A_{sat}})^{2p}\right]^{\frac{1}{2p}}}, x \in [0, A_{sat}] \tag{5}$$

Polynomial predistortion obtained by Taylor series expansion of $f_A^{-1}(x)$ with A_{sat} = 1 in the case p=1 and p=2:

$$h(x)_{p=1} = x + \frac{1}{2}x^3 + \frac{3}{8}x^5 + \frac{5}{16}x^7 + \frac{35}{128}x^9 + \frac{63}{256}x^{11} + \frac{231}{1024}x^{13} + \frac{429}{2048}x^{15} + \ldots \quad (6)$$

$$h(x)_{p=2} = x + \frac{1}{4}x^5 + \frac{5}{32}x^9 + \frac{15}{128}x^{13} + \frac{195}{2048}x^{17} + \frac{663}{8192}x^{21} + \ldots \quad (7)$$

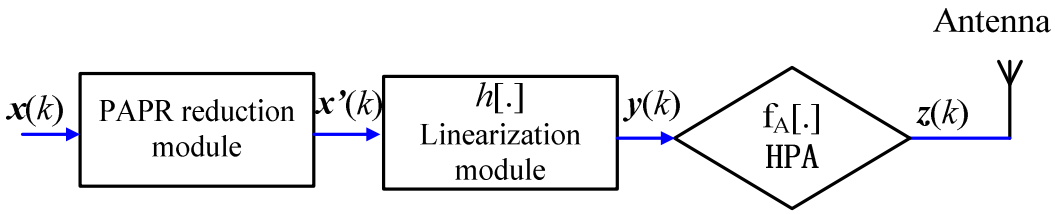

Fig. 1. Simplified diagram of PAPR reduction and HPA linearization.

The predistortion is a linearization method in which the input signals are conversely predistorted before the HPA. HPA linearization system can be described as the cascade of the two function modules, the PAPR reduction module and predistortion module, as shown in Fig. 1.

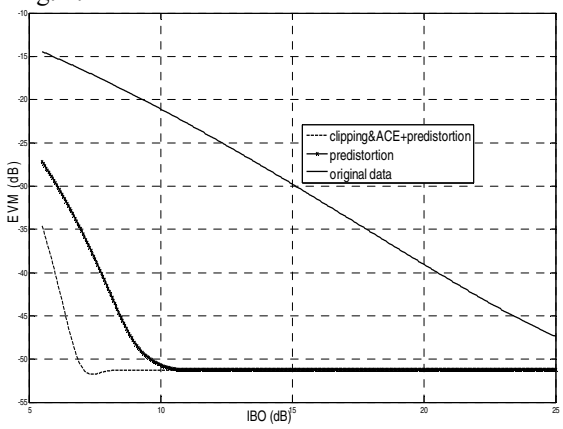

Fig.2. Predistorter method with and without PAPR reduction, and original data in Rapp model when p=1.

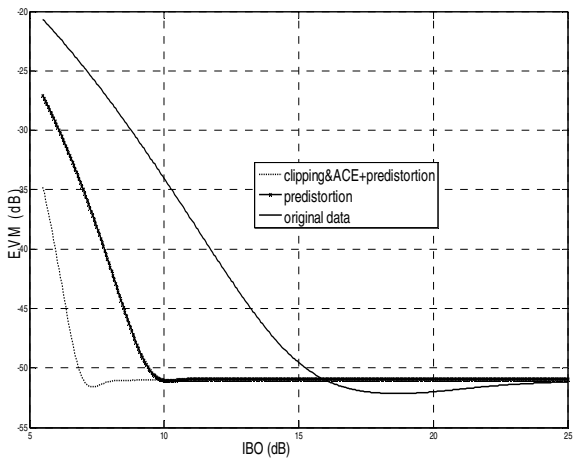

Fig.3. Predistorter method with and without PAPR reduction, and original in Rapp model when p=2.

4. Simulation results

In the simulation, the parameters are set as below:

The number of used sub-carriers in OFDM systems: N=4096.

Modulation format: QPSK.

Amplifier: SSPA with Rapp's coefficient, p=1 and p=2

Effects of PAPR reduction on HPA linearization will be evaluated in terms of IBO and Error Vector Magnitude (EVM) performances in this section.

The EVM is defined as:

$$EVM \triangleq \sqrt{\frac{\sum_{i=0}^{N-1}\left|\hat{\boldsymbol{c}}(i)-\boldsymbol{c}(i)\right|^2}{N\cdot E\left\{\left|\boldsymbol{c}\right|^2\right\}}} \tag{8}$$

Subject to: $\hat{\boldsymbol{c}}(i)$ and $\boldsymbol{c}(i)$ be feasible for $i\in\boldsymbol{\Gamma}_c$, $\hat{\boldsymbol{c}}(i)=\boldsymbol{c}(i)=0$ C_k, for $i\notin\boldsymbol{\Gamma}_a$, where $\hat{\boldsymbol{c}}$ denotes the frequency-domain OFDM symbol after HPA.

IBO v.s. EVM performance shown in Fig.2 is about the predistortion system with and without PAPR reduction where the smoothness factor *p* of the Rapp model is set to1. In Fig.2, the more IBO, the better EVM performance and the poorer HPA power efficiency. When a peak reduction method is applied, IBO of the amplifier (EVM=40 dB) with predistorter is suppressed by 1.7**5** dB as compared with the case without peak reduction. The PAPR reduction and predistortion method suppresses the IBO better by about 14.55 dB than the original system. As seen in the Fig.3, when the smoothness factor *p*=2, the predistorter method plus PAPR reduction can achieve 1.85 dB and 5.75 dB IBO gain than predistorter method without PAPR reduction and original system, respectively. Consequently, it is clear that a good predistortion may be acquired but with low power efficiency. However, if the process PAPR reduction is utilized, we can improve the HPA power efficiency to a great extent with permitted average power increase.

5. Conclusion

In this work, we have introduced the joint combination of ACE based PAPR reduction and predistortion. Predistortion can be utilized to compensate for the HPA's nonlinearity. Nevertheless, when the input signals' amplitude exceeds the compensation level, predistortion will cease to be feeble. In this case, PAPR reduction technique plays an important role in reducing the probability of signals falling into saturated area. Also, power efficiency of HPA can be increased. Overall, the tests of the proposed method show a good performance of linearity improvement at the cost of a slight increse in average power.

6. References

1. Xiaodong Zhu, Wensheng Pan, Hong Li, and Youxi Tang, "Simplified Approach to Optimized Iterative Clipping and Filtering for PAPR Reduction of OFDM Signals," *IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 61, NO. 5*, MAY 2013, pp:1891-1901.

2. Shih-Kai Lee, Yen-Ching Liu, Hsin-Liang Chiu, and Yung-Chih Tsai, "Fountain Codes With PAPR Constraint for Multicast Communications," *IEEE TRANSACTIONS ON BROADCASTING, VOL. 57, NO. 2*, JUNE 2011, pp:319-325.

3. Seung-Sik Eom, Haewoon Nam, and Young-Chai Ko, "Low-Complexity PAPR Reduction Scheme Without Side Information for OFDM Systems," *IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 60, NO. 7*, JULY 2012, pp.3657-3669.

4. Y.-C. Wang, and Z.-Q. Luo, "Optimized Iterative Clipping and Filtering for PAPR Reduction of OFDM Signals," *IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 59, NO. 1*, JANUARY 2011, pp. 33-37.

5. Qingwen Han, Xiaoping Zeng, Lingqiu Zeng, Tao Wang, "Joint PAPR Reduction Method Base On ACE POCS and Peak Clipping," *2010 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery*, pp.371-375.

6. Kitaek Bae, Jeffrey G. Andrews, and Edward J. Powers, "Adaptive Active Constellation Extension Algorithm for Peak-to-Average Ratio Reduction in OFDM," *IEEE COMMUNICATIONS LETTERS, VOL. 14, NO. 1, JANUARY 2010*, pp.39-41.

7. Li Bo, Yang Zhi-xing, Pan Chang-yong, Zhang Tao-tao, Ge Jian-hua, "Effects of PAPR Reduction on HPA Predistortion," *IEEE Transactions on consumer Electronics,Vol. 51 ,No. 4, Nov. 2005*, pp.1143-1147.