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Effect of Peak-to-Average Power Ratio Reduction on the Multicarrier Communication System Performance Parameters

Dr. K. Amit Bindaj, Mr. D. Veeranna, Mr. Gandham Srinivasa Rao, Mrs. J. Rajyalaxmi, N. Srinivas Rao

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karpurapu.gavasj@gmail.com, dev.veer57@gmail.com, gandham.ece@gmail.com, rajyalakshmivarshini@gmail.com
nomula09@gmail.com

Abstract— Orthogonal Frequency Division Multiplexing (OFDM) and other multicarrier transmission systems hold great promise for achieving large bit rates in wireless communication systems. High-speed data transmission across multipath fading channels is possible with OFDM because it is a spectrally efficient modulation approach that does not require extensive equalisation procedures. However, this improved spectrum efficiency and reduced need for equalisation comes at the expense of power efficiency. Since OFDM transmissions have a very high Peak-to-Average Power Ratio (PAPR), the RF component of the transmitter is particularly inefficient in using power. The impact of PAPR suppression on multicarrier communication system performance is studied here. Power Amplifier (PA) and DAC power consumption, power amplifier (PA) efficiency, DAC signal-to-noise ratio (SNR), and bit error rate (BER) performance are all taken into account. Our research shows that decreasing PAPR improves power amplifier efficiency and decreases PA and DAC power consumption regardless of the PAPR reduction approach used. It has also been demonstrated that, for a given BER performance, the need for Input-Backoff (IBO) decreases as PAPR is decreased.

Keywords— Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), Crest Factor (CF), DAC, Input-Backoff (IBO), OFDM, Peak-to-Average Power Ratio (PAPR), and Power Amplifier Efficiency

I. INTRODUCTION

Wireless digital communication is rapidly expanding, resulting in a demand for portable wireless systems that are reliable and have high spectral efficiency. Multicarrier transmission,also known as Orthogonal Frequency Division Multiplexing(OFDM) has been considered as a promising candidate to achieve high rate data transmission in a mobile environment [1], [2]. Due to its robustness against the frequency-selective fading, which produces inter symbol interference (ISI) and degrades the performance [3], OFDM technique has been adopted in some wireless standards such as Digital Audio Broadcasting (DAB), Terrestrial Digital Video Broadcasting(DVB-T), the ETSI HIPER LAN/2 standard, IEEE 802.11a/g/n standard for WLAN and the IEEE 802.16 standard for WiMax [4].

One of the major drawback of OFDM is that its signal has high Peak-to-Average Power Ratio (PAPR) compared to a single carrier signal because an OFDM signal is the sum of many narrowband signals in the time domain [5]. If the peak transmit power is limited either by regulatory or application constraints, the effect is to reduce the average power allowed under multicarrier transmission relative to that under constant power modulation techniques [6]. This in turn reduces the range of multicarrier transmission. Moreover, to avoid the performance degradation of OFDM signal due to high PAPR, the power amplifier (PA) must be operated in linear region(with large Input-Backoff (IBO)), where the power conversion is inefficient. This may have deleterious effect on battery life time in portable mobile devices, where the drawback of high PAPR may outweigh all the potential benefits of OFDM.

A number of techniques have been proposed to deal withhigh PAPR problem. These techniques can be broadly classified into four categories :

1) Clipping [7]- [9]2) Coding [10]- [13]
3) Constellation extension [5], [14]
4) Multiple signal representation such as SLM [15] andPTS [16]

There are many work available in the literature such as[17]- [21] which addresses the impact of non-linearities on the performance of a communication system or the OFDM system.Chris et al has discussed the impact of non-linear distortion onthe OFDM bit error rate and symbol error rate in [22] and [23]respectively. However, to the best of our knowledge, we couldnot find such contributions that address the impact of PAPRreduction on the performance of a multicarrier communicationsystem. This is the basic motivation of our work whichanalytically investigates the impact of PAPR reduction on different aspects of wireless multicarrier transmission system.The major component of multicarrier communication system which is affected by PAPR is Power Amplifier (PA) andthe Digital-to-Analog Converter (DAC) [24]. Therefore, in thispaper we have considered the following parameters to study

Sanjay Singh is with the Department of Information and Communication Technology, Manipal Institute of Technology, Manipal, India, 576104, (e-mail: sanjay.singh@ieee.org)

M.Sathish Kumar and H.S Mruthyunjaya is with the Department of Electronics and Communication Engineering, Manipal Institute of Technology, Manipal, India, 576104

the effect of PAPR reduction:

- Power consumption of PA
- Power amplifier efficiency
- Power consumption of DAC
- Relation between BER and IBO

This paper analytically investigates the effect of PAPR reduction on the performance of a multicarrier communication system irrespective of the PAPR reduction technique applied. Ittries to answer the following question due to PAPR reduction:

1) what is the saving in power consumption by poweramplifier?
2) what is the improvement in PA efficiency?
3) what is the power saving by DAC?
4) what is the effect on IBO to maintain same BER?

The rest of the paper is organized as follows. Section 2

III. EFFECT OF PAPR REDUCTION ON POWER AMPLIFIEREFFICIENCY

Efficiency is a critical factor in PA design. Power amplifier's power consumption is evaluated by drain efficiency, which is defined as [28] the ratio of RF output provides the background material for the OFDM signal, PAPR, and distribution of PAR. Section 3 analyzes the impact of

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PAPR reduction on power amplifier efficiency. Section 4 discusses the power consumption and SNR of DAC when a PAPR reduction technique is employed. Section 5 discusses types of nonlinearities, models and their effect on BER performance. Finally section 6 concludes the paper.

II. PAPR IN OFDM SYSTEM

For the purpose of analyzing the effect of PAPR reduction of OFDM signal, a simplified version of practical OFDM system model has been considered here. Specifically, we ignore the guard interval because it does not contribute to the PAPR [25]. Assuming that any pulse shaping in the transmitter is flat over all of the subcarriers, and deals only with the PAPR of the baseband signal. For one OFDM symbol with N subcarriers,

Assuming that a PAPR reduction method has been employed.

The average DC-input power, P_{inPAPR}, is required to give identical output power, in comparison to the average DC-input power when no PAPR reduction method is used, P_{in} is givenby

$$P_{inPAPR} = \xi P_{in} \qquad (6)$$

where ξ is a scaling factor, whose value should be less than unity in order to have low value of input DC power for PA afterthe application of PAPR reduction technique. Considering ζ' as the reduced PAPR value with a PAPR reduction techniqueapplied and ζ as the PAPR value, when no PAPR reduction method is applied. Since $\zeta' < \zeta$, so the value of ξ is given by

On substituting for ξ in (6) gives

P_{in}. (8)

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0} c_k e^{\frac{j2\pi kt}{T}} \qquad 0 \le t \le T \qquad (1)$$

ζ is the frequency domain

The decrease in power consumption (ΔP_c) due to PAPR

information symbol mapped

reduction is obtained as:

to the k_{th} subcarrier of the OFDM symbol and T is the OFDMsymbol duration. The PAPR of the given frequency domain samples, $c = \{c_0, c_1, c_2, \cdots, c_{N-1}\}$ is defined as [32] follows:

2

$$\Delta P_c = P_{in} - P_{inPAPR}. \qquad (9)$$

On substituting for P_{inPAPR} from (8) to (9) yields

$PAPR$ max

TABLE I

SAVING IN POWER CONSUMPTION BY POWER AMPLIFIER DUE TO PAPR REDUCTION

PAPR Reduction Algorithm	ζ (dB)	ζ^x (dB)	$\Delta Pc = (\frac{\zeta - \zeta}{\zeta}) Pin \times 100$
A1	12	11	8.3%
A2	12	10	16.7%
A3	12	09	25%
A4	12	08	33.3%

The dynamic power consumption is due to switching between symbols and therefore has not been considered here. The static power

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consumption P_s of DAC is given [27] by

$$P_s = V_{dd} I_0 E[\sum_{i=0}^{n-1} 2^{i} b_i]$$

1

TABLE II

POWER AMPLIFIER EFFICIENCY PERFORMANCE DUE TO PAPR REDUCTION ALGORITHMS

PAPR Reduction Algorithm	ζ(dB)	ζ'(dB)	$\eta_{PAPR} = \frac{\zeta}{\zeta^x}\eta$
A1	12	11	1.09η
A2	12	10	1.2η
A3	12	09	1.33η
A4	12	08	1.5η

From Table 2, it can be observed that the efficiency of poweramplifier improves by more than 9% with every 1 dB decrease in PAPR of OFDM signal.

- V_{dd} is the power supply
- I_0 is the unit current source corresponding to LSB (b_0)
- $E[.]$ is the expectation operator
- n is the resolution of DAC
- b_i is the digital input bit stream

The value of I_0 is constant and depends upon the given hard-ware technology. From (17) it is observed that the static power consumption of DAC, P_s is a function of DAC resolution only, that is

$$f : P_s \rightarrow (2^n - 1). \qquad (18)$$

Having a PAPR reduction technique applied; for a given value of SNR, the new value of DAC resolution, n' is obtained from

IV. EFFECT OF PAPR REDUCTION ON DIGITAL-TO-ANALOG CONVERTER

The digital-to-analog converter (DAC) converts the digital signal obtained at the output of the digital modulation blockto analog signal. It is the first block in the analog signal chain of the transmitter. For an ideal $n-bit$ converter, the signal-

(23)

while providing the required resolution. A current-steering DAC has a very high power efficiency and it is suitable for high-speed and high-resolution applications. The current- steering DAC, uses a number of binary scaled current source elements to generate the output voltage across a load resistor. The power consumption of a DAC is divided into two parts:

1) the static power consumption P_s and
2) the dynamic power consumption P_d

POWER SAVING BY DAC DUE TO PAPR REDUCTION

PAPR reduction algorithm	ζ(dB)	ζ^x(dB)	PAR^x_{dB}	n^x	$\Delta P_s = \frac{2^n - 2^{n^x}}{2^n - 1} P_s \times 100$
A1	12	11	5.5	2.61	6.42%
A2	12	10	5	2.53	12.47%
A3	12	9	4.5	2.45	18.17%
A4	12	8	4	2.36	24.22%

From Table 3, it is inferred that there is 6% saving in powerby DAC for every 1 dB reduction in PAPR.

V. TYPES OF NONLINEARITIES, MODELS AND THEIR EFFECT ON BER PERFORMANCE

There are many blocks in a communication system whose intended behavior is linear but the physical devices that are used to implement these functions may produce nonlinear effects over a certain range of operations. One of the example of such a device is a high-power amplifier, which exhibits limiting and saturation when the input amplitude or power is very large. Nonlinearities in communication systems are classified as

1) baseband and
2) bandpass

For example, a limiter is an example of a baseband nonlinear- ity whereas a radio frequency (RF) amplifier is a bandpass nonlinearity. The input to a bandpass nonlinearity will be centered at some frequency f_c and the spectral components of the output will lie in the neighborhood of f_c.

A. Baseband Nonlinearities

The input to a baseband nonlinearity is a real-valued signal,

B. Bandpass Nonlinearities

Memoryless bandpass models are used to characterize a variety of narrowband nonlinear bandpass devices encountered in communication systems. The word memoryless implies not only an instantaneous relationship between input and output, but also implies that the device does not exhibit frequency- selective behavior over the bandwidth of operation. The band- width of the nonlinear device and the bandwidth of the signal are both assumed to be much less than f_c, where f_c is the carrier frequency. Consider a cubic memoryless nonlinearityof the form

$$y(t) = x(t) - \alpha x^3(t) \qquad \alpha < 1 \tag{26}$$

where α is the scaling factor for the cubic component. As-suming that the input is a random signal in the form of

$$x(t) = A(t)\cos[2\pi f_c t + \varphi(t)] \tag{27}$$

where the amplitude $A(t)$ and the phase $\varphi(t)$ are lowpass random processes having bandwidth B f_c. From (26) and (27), output of the nonlinearity is given by

3α

$y(t) \quad = \quad [A(t) - \quad A(t)]\cos[2\pi f_c t + \varphi(t)] -$ —

$x(t)$ and its output is also a real-valued signal, $y(t)$. The 4 α 3 —

nonlinearity is modeled as $y(t) = F(x(t))$. The most commonly used models of baseband nonlinearities are the power series model and the limiter model. The power series modelis defined as [29] follows:

$$y(t) = \sum_{k=0}^{N} a_k x^k(t) \tag{24}$$

$$- \ _4 A \ (t)\cos[6\pi f_c t + 3\varphi(t)]. \tag{28}$$

In (28), the first term is at the center frequency f_c and the second term is at the third harmonic of the carrier frequency $3f_c$. The bandwidth of the third harmonic will be of the order of $3B$. Since the assumption is that f_c B, the second term is outside the bandwidth of interest. Thus the approximated output of the nonlinearity is given by

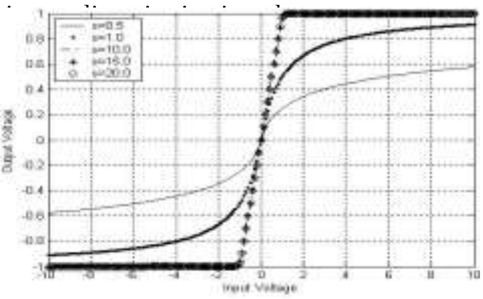
and the general limiter model has the form

$Msgn(x(t$

where M is the limiting value of the output, m is the limiting value of input and s is the shape parameter. Fig.1 shows the normalized input-output relationship for a limiter as defined by (25) for different values of s. It is noted that in Fig.1, s $=$ corresponds to a soft limiter and $m = 0$ corresponds to a hard limiter. Moreover, it is noted that with $m = 0$, the value of s has no effect on the characteristic of the nonlinearity as described by (25).

$$\approx\infty\ f(A(t))\cos[2\pi f_c t + \varphi(t)] \tag{29}$$

where $f(A(t)) = [A(t) \ \frac{3\alpha}{4} A(t)]$. For the power series model, the bandpass output $y(t)$ has the same form as that of the inputwith the output amplitude related to the input amplitude via $f(A(t))$ and the output phase is the same as the input phase. The function $f(A(t))$ is referred to as the input amplitude to output amplitude, or the AM-to-AM transfer characteristic of the nonlinearity. A limiter or power series model affects only the amplitude of the input signal. The phase is unaffected by the model. In terms of the complex envelopes of the input $x(t)$ and the output $z(t)$, the lowpass equivalent model for the power se



(30)

$$\tilde{z}(t) = f[A(t)]exp[j\varphi(t)]. \tag{31}$$

Fig. 1. Limiter Characteristic

C. AM-to-AM and AM-to-PM Models

Devices such as bandpass amplifiers, having spectra cen-tered on the carrier frequency, produce outputs that are band- pass in nature. The spectral components of these bandpass outputs are centered on the carrier frequency but have larger bandwidths than the input signal. Such devices can be modeled

using the complex envelope representations of the input and output signals. Suppose the input to a memoryless bandpass nonlinearity is of the form

$$x(t) = A(t)\cos[2\pi f_c t + \varphi(t)] = A\cos(\vartheta) \qquad (32)$$

where $\vartheta = 2\pi f_c t + \varphi(t)$. The output of the memoryless nonlinearity $y(t) = F(x(t))$ can be expressed as

$$y(t) = F(A\cos(\vartheta)). \qquad (33)$$

As $A\cos(\vartheta)$ is periodic in ϑ, $y(t)$ is also periodic in ϑ andtherefore can be expanded using Fourier series [33] as

$$y(t) = a_0 + \sum_{k=0}^{\infty} (a_k\cos(k\vartheta) + b_k\sin(k\vartheta)) \qquad (34)$$

where a_k and b_k are the Fourier coefficients and are given by

$$\frac{1}{\pi}\int^{2\pi}$$

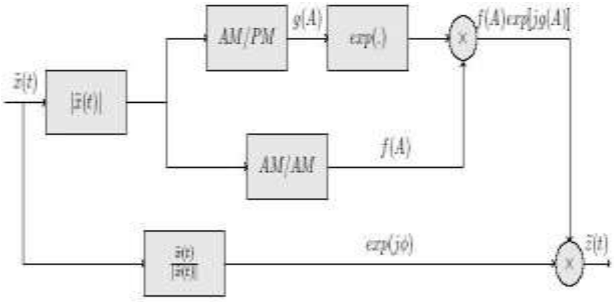


Fig. 2. Model of TWT

A PA operates efficiently when the power of the input signalis constant and almost equal to the saturation point of the amplifier. In such a case the power amplifier operates in the linear region and achieves the maximum amplification of the input signal. But in case of multicarrier transmission system, the power of the input signal is not constant as a result of

$\pi \quad 0$

which amplifier consumes more power, making the power amplifier very inefficient. The operating point of an amplifieris given by the back-off. High back-offs move the operating point of the amplifier to the linear region, which reduces the effects of nonlinearities. The input back-off (IBO) of a power amplifier is defined [34] as

The function $f(A)$ and $g(A)$ are the amplitude-to-amplitude (AM-to-AM) and amplitude-to-phase (AM-to-PM) transfer characteristics. The model given by (40) accounts for both theamplitude distortion and phase distortion introduced by the nonlinearity, and it can be expressed in terms of the complex lowpass equivalents of the input and output a

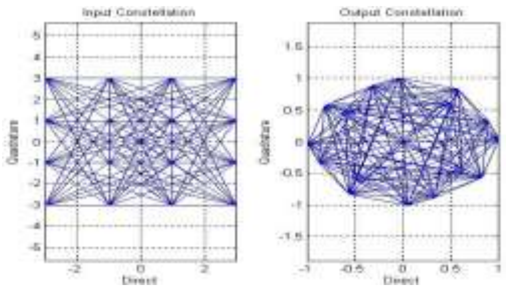
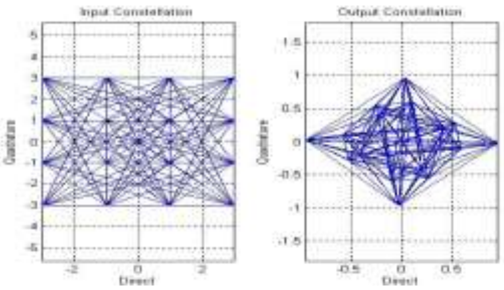


Fig. 6. Input and Output Constellation for 15dB backoff



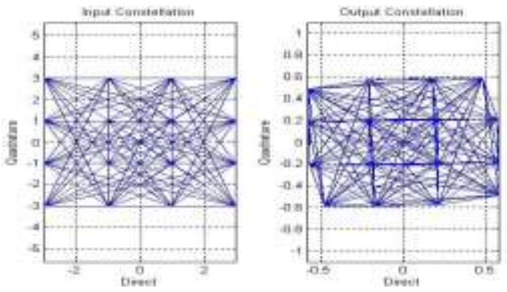


Fig. 3. Input and Output Constellation for 1dB backoff

Fig. 4. Input and Output Constellation for 5dB backoff

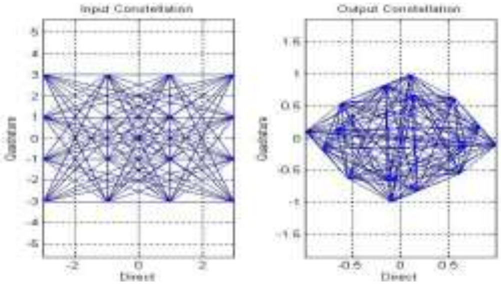


Fig. 7. Input and Output Constellation for 20dB backoff

It has been shown that the degree to which amplitude deterioration occurs when PA is used with IBO lessens as IBO increases. However, it is not energy efficient to run PA with a high IBO value. As a result, BER performance in the system suffers.

The use of PAPR reduction techniques results in power savings without sacrificing BER performance since the need for IBO decreases for a given BER level.

The consequence of non-linearity of PA is to bring a large number of signal constellation points closer together, as seen in Figs.3–7. Pairwise error probability is known to be a monotonic function of the Euclidean distance between any two locations in the signal space for an AWGN channel. The likelihood of an error rising as signal points become closer together in space. The BER performance of the communication system is therefore degraded due to the nonlinear- ity of the power amplifier. Furthermore, it VI. from Figs.4-7.

CONCLUSION

The use of OFDM in high-speed wireless communication networks is an exciting development. The typical OFDM system's high peak-to-average power ratio is a significant negative. In this study, we examine how different PAPR reduction techniques affect different characteristics of multicarrier communication systems. Power amplifier efficiency, SNR performance, DAC BER performance, and PA power consumption are all taken into account.

This study concludes that a reduction in PA power usage of 1 dB results in an 8% reduction in total PA power consumption.

PAPR. For every 1 dB drop in PAPR, the PA's efficiency increases by more than 9%.For DAC, every 1 dB reduction in PAPR results in a power savings of over 6%.

With a lower PAPR, the same DAC resolution can produce better SNR results. In addition, it has been demonstrated that nonlinearity of PA causes a shift in the location of a signal's constellation's points. Therefore, the system's BER performance declines. When the PA is run at higher IBO, the performance deterioration caused by BER is milder. When PAPR is reduced, the system can save power without sacrificing BER performance since fewer IBOs are needed to provide the same level of BER.

The real impact that PAPR reduction has on certain performance indicators is method-specific.

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