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Increasing the power efficiency of an IEEE802.11a Power Amplifier

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Abstract—**OFDM modulation is extensively used in many applications. However, it also exhibits high peak-to-average power ratios (PAPR) requiring the associated transmit amplifier to have a very large linear region. This linear amplifier does therefore have poor power efficiency. To reduce the PAPR, clipping and filtering was carried out at baseband. This paper investigates the impact that clipping has on the resultant power efficiency and BER. The simulations show that when the input back-off (IBO) dynamically controls the input average power in every OFDM symbol, for a 64-subcarrier QPSK OFDM signal, the power efficiency can be improved by 55% without increasing the bit error rate.**

Keywords-OFDM; Clipping; Power amplifier; Power efficiency

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) modulation is an attractive technique for transmitting information efficiently within a limited bandwidth [1]. This modulation scheme has been applied in many wireless transmission standards, such as wireless LAN's, and digital broadcasting. However, since the OFDM signal consists of a number of independently modulated subcarriers, it therefore produces higher peak-to-average power ratio (PAPR) than single-carrier signals. The PAPR in decibels is defined by (1), where *Peak* is the maximum peak power of the signal and *Pave* is the average power of the signal.

$$PAPR = 10\log(Peak / Pave) \text{ (dB)} \quad (1)$$

As the numbers of subcarriers are increased, the higher the PAPR becomes. A typical PAPR for a 64-subcarrier OFDM signal is around 8-13 dB. When the numbers of subcarriers are increased to 2048, the PAPR will also be increased from 11 to 16 dB. Although an OFDM signal has a very high PAPR, the large peak envelopes occur with very low levels of probability. Figure 1 shows the envelope distribution of the OFDM signals, which exhibits a Rayleigh distribution. In Figure 1, the dashed line and solid line represent a distribution of a 64-subcarrier and a 2048-subcarrier OFDM signals respectively, which corresponds with IEEE802.11a standard and 2k mode of DVB-T standard respectively.

Such high PAPR signals require a large linear dynamic range of the power amplifier. To maintain the linearity, the power amplifier has to operate with large levels of back off,
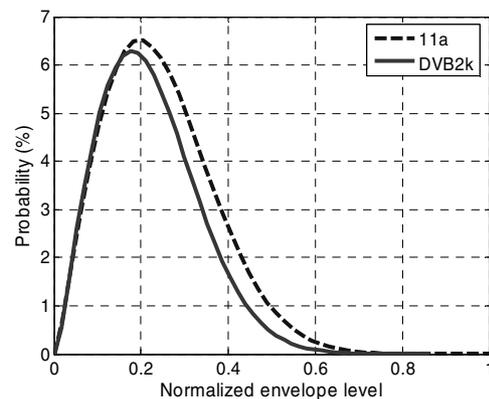

Figure 1. Envelope distribution of a 16QAM OFDM signal

which seriously reduces the power efficiency [2]. The input back-off (IBO) in decibels is defined by (2), where P_{1dB} is the input power level at the 1 dB compression point and the P_{in} is the input mean power [3].

$$IBO = 10\log(P_{1dB} / P_{in}) \text{ (dB)} \quad (2)$$

A typical power efficiency of a class AB power amplifier is around 18% for an IEEE802.11a system and around 8% for DVB 2k mode system. Such poor efficiency drastically reduces the operation time of portable equipment.

To reduce the PAPR, many PAPR reduction techniques have been proposed. These solutions can be classified as coding [4][5], using signal correction functions [6][7], and clipping[8][9]. Coding techniques do not generate any out-of-band distortion. However, they reduce the transmission bit rate. Using correction functions to limit the PAPR will generate in-band interference. The clipping technique is a simple way to reduce the PAPR, but heavy clipping will cause serious out-of-band and in-band distortion.

The clipping ratio (CR) is usually used to estimate the amount of clipping that has been applied, which is defined in decibels using (3), where *A* is the amplitude of the clipping level and $E[|x|^2]$ is the mean power of the input signal. The lower the value of CR results in an increase in the number of peaks that will be removed.
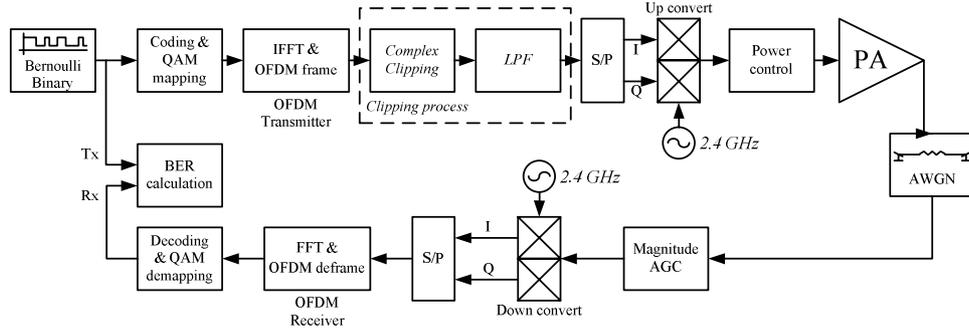
Figure 2.   Simulation procedure

$$CR = 10\log(A^2 / E[|x|^2]) \text{ (dB)} \qquad (3)$$

If there are no re-construction functions in the receiver, any clipping method will increase in-band noise and thus cause a reduction in the resultant BER. In this paper, baseband clipping and filtering techniques were exploited to reduce the PAPR. When the PAPR is reduced, the power amplifier can operate with less IBO, and therefore the overall power efficiency can be increased. The paper will investigate the impact that clipping has on the resultant power efficiency and BER.

Figure 2 illustrates the simulation procedure, an OFDM signal was implemented using an IFFT from a coded and mapped QAM signal, and then clipped and filtered at baseband. The quadrature modulator up-converts the baseband signal to a carrier frequency. Then the RF signal was controlled dynamically and then amplified by the power amplifier. The characteristics of the power amplifier were imported into MALAB from the circuit simulation results of a class AB amplifier carried out using Agilent's circuit simulation tool, ADS. Finally the receiver down converts the transmitted signal and calculates the BER.

II.   SYSTEM DESCRIPTION

A.   Clipping and Filtering

The clipping technique is used to limit the amplitude of the peaks to a particular clipping level and fix the phase when the peaks are higher than the clipping level. The clipping process used in the simulation is shown by (4), where x is the over-sampled complex OFDM signal [8], φ is the signal phase, y is the clipped signal, and A is the clipping level.

$$y = \begin{cases} |x| \cdot e^{j\phi}, & |x| \le A \\ A \cdot e^{j\phi}, & |x| > A \end{cases} \qquad (4)$$

If a digital OFDM signal implemented by an IFFT is clipped directly, the clipping noise will all fall in-band and cannot be removed. To solve this problem, over-sampling of the digital OFDM signal is necessary [9]. In the simulation, the digital OFDM signal is over-sampled by a factor of 8. In addition, since clipping is a nonlinear process, the out-of-band spectrum of the clipped signal will exhibit spectral re-growth, which can result in an Adjacent Channel Power Ratio (ACPR) as high as -20dBc. Filtering after the clipping process is used to reduce the spectral re-growth. However, the filtering process
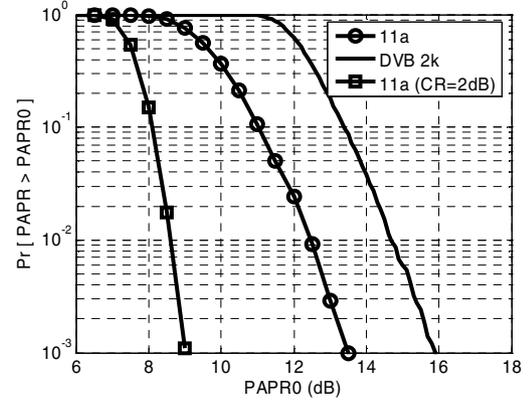

Figure 3.   The CCDF of the IEEE802.11a and DVB-T 2K mode

causes peak re-growth. To filter out much of the spectral re-growth, a 100 tap equiripple FIR low pass filter was used, which has 1dB ripple at pass band, 40dB attenuation at stop band, and 10MHz bandwidth. The clipped and filtered OFDM signal removes the out-of-band spectrum re-growth but the in-band noise cannot be removed, which will result in BER deterioration. Figure 3 shows the Complementary Cumulative distribution function (CCDF) of the PAPR, where the line with circles represents the IEEE802.11a signal and the solid line is the DVB 2k mode signal. It can be observed that the IEEE802.11a OFDM signal has a PAPR from 8-13 dB, and the DVB 2k mode OFDM signal has a PAPR from 11-16 dB. The lines with squares represents the clipped and filtered IEEE802.11a OFDM signal which is clipped using a CR=2dB. It can be observed that the PAPR of the clipped signal has been reduced to around 7-9 dB.

B.   Power Amplifier

The system simulation is implemented within a MATLAB environment. However, to estimate the power efficiency of the amplifier, a circuit simulation of a class AB power amplifier is necessary [10]. The circuit simulation was carried out by using the Advanced Design System (ADS), which is a commercially available circuit simulation tool from Agilent technologies. The characteristics were then imported into MATLAB to evaluate the impact that clipping has on the resultant power efficiency. Figure 4 shows the major characteristics such as output power level (Pout), DC power consumption (Pdc), power gain (Pagin)
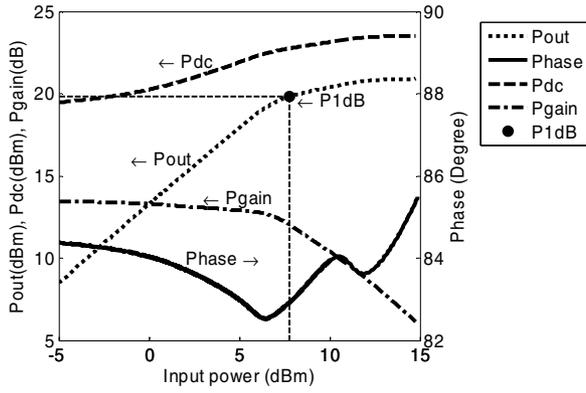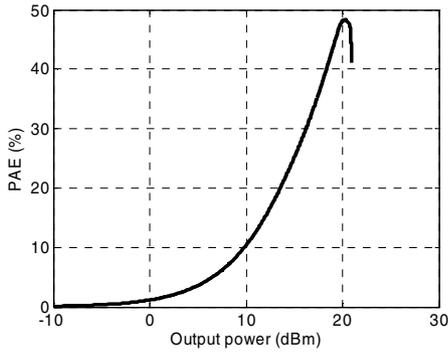
Figure 4. The characteristics of the class AB amplifier

Figure 5. PAE of the class AB amplifier

, 1 dB compression point (P1dB), and output phase, where the Pin represents input power levels. This class AB amplifier has its 1 dB compress point at around 20dBm output power level, and the power gain is around 14 dB. The class AB amplifier operates with low amounts of AM to PM distortion, from the graph this is less than 3 degrees.

The power efficiency can be calculated by using the characteristics shown in Figure 4. A precise definition of power efficiency is called power added efficiency (PAE), which is defined as (5).

$$PAE=(Pout-Pin)/Pdc. \qquad (5)$$

The instantaneous PAE characteristic is shown in Figure 5. The maximum PAE which can be achieved is 48% when the amplifier is driven to the 1 dB compression point. The average PAE of an OFDM signal is dependent on the average output power level. Because the OFDM signal has very high PAPR and requires large back-off to maintain the linearity, therefore the average PAE of the class AB amplifier will be reduced to around 18% for IEEE802.11a OFDM signal.

III. SIMULATION RESULTS

In the simulation, both of the IEEE802.11a and 2k mode of DVB OFDM signals with convolutional coding were applied as input signals. The coding and interleaving processes corresponded to the respective standards and the coding rate is set to ¾ rate. Since this paper investigated the clipping effect
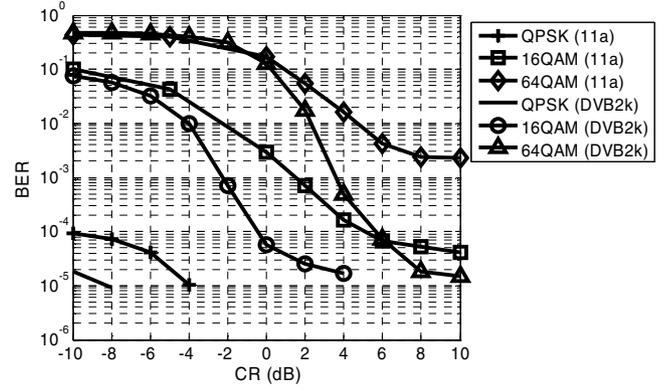

Figure 6. The BER with different CR (64 & 2048 subcarriers)

an the resultant power efficiency, a real radio channel was not simulated. So a simple additive white Gaussian noise channel was used. In addition, the equalizer is also simulated to correct the constellation position, which can reduce the BER.

To increase the power efficiency, an input power controller can be used to regulate the IBO dynamically in every OFDM symbols to achieve the specific required ACPR. In the simulation, the ACPR level is set to fit in with the transmission mask of the IEEE802.11a and DVB 2K mode standards.

Figure 6 shows the BER against CR levels, for OFDM signals with different constellations and different numbers of subcarriers. It can be observed that the signals operating in the QPSK constellation mode can be more heavily clipped, i.e. a lower CR value, results in the BER being less than 10^{-4}. Comparing the 16QAM mode of OFDM signals, it can be observed that at the same clipped ratio the 2k mode DVB signal has lower BER than the IEEE802.11a signal. This is because the DVB signal has higher PAPR, but the peaks occur with a very low level of probability, so the DVB 2K mode can tolerate more clipping.

Figure 7 shows the PAE with different CR levels. The dashed line and the solid line represent the IEEE802.11a and 2K mode of DVB OFDM signals respectively. Since the DVB OFDM signal has a higher PAPR, it results in a requirement for more back off to maintain the linearity of the power amplifier. So the average PAE of the unclipped DVB OFDM signal is
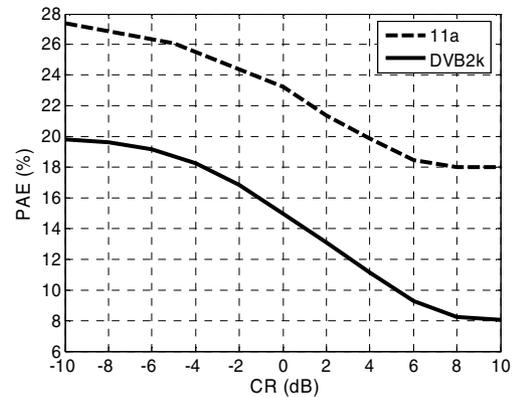

Figure 7. The PAE with different CR (11a & DVB2k)

around 8%, which is lower than the average of the unclipped IEEE802.11a OFDM signal having 18% PAE. It can be observed from Figure 7 that the PAE can be increased when heavier clipping is used. In the case of CR setting at 0dB (the clipping level is the same as the mean power level), the PAE of the DVB and IEEE802.11a OFDM signals can be increased by 7% and 5% respectively, which is an overall 87.5% and 27.8% improvement for the two cases respectively.

Although heavily clipping the OFDM signals can result in an increase in the PAE, the BER will worsen because of the clipping process. Table 1 summarizes the PAE improvement for the different constellation modes of OFDM signals, where the CR represents the permitted CR level when the BER criterion is set at 10^{-3}. The table shows that the lower order constellation signals can yield more PAE improvement. Also, the clipping technique produces greater improvements in PAE for OFDM signals with larger numbers of subcarriers. In the case of IEEE802.11a with QPSK constellation, the CR can be tolerated to -10 dB and thus the PAE can achieve by more than 55%. In the case of DVB, the PAE can be improved by 150% operating in QPSK mode, even the 64QAM mode of DVB can achieve a 37.5% improvement in efficiency performance.

TABLE I. PAE IMPROVEMENT COMPRISON

BER<=10^{-3}		
	CR	*PAE improvement*
11a (QPSK)	<< -10	>>55%
11a (16QAM)	2	16.7%
11a (64QAM)	> 10	0%
DVB (QPSK)	<< -10	150%
DVB (16QAM)	-2	112.5%
DVB (64QAM)	4	37.5%

IV. CONCLUSION

The simulation results show that the clipping technique can be used to increase the power efficiency. Heavy clipping can result in high levels of power efficiency being achieved. However, the clipping scheme is a non-linear process, which results in BER increase. The higher order constellation modes of the OFDM system are more sensitive to large Clipping Ratios than the lower order constellation modes. Besides, systems which operate with larger numbers of subcarriers such as DVB can tolerate heavier clipping than systems such as IEEE802.11a which have fewer subcarriers.

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