Peak-to-Average Power ratio of IEEE 802.11a PHY layer Signals

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Abstract—**In this paper, we propose clipping with amplitude and phase changes of the signal points to reduce the peak-to-average power ratio (PAR) of orthogonal frequency division multiplexed (OFDM) signals in high-speed wireless local area networks defined in IEEE 802.11a physical layer. The proposed technique can be implemented with a small modification at the transmitter and the receiver remains standard compliant. PAR reduction as much as 4dB can be achieved by selecting a suitable clipping ratio and a correction factor depending on the constellation used. Out of band noise (OBN) is also reduced.**

Key Words:**OFDM, Peak-to-average power ratio, IEEE 802.11a PHY.**

I. Introduction

With a rapidly growing demand for wireless communications, much research has been expended on providing efficient and reliable high-data-rate wireless services. The IEEE 802.11 standard for wireless local area networks (WLAN) was first established in 1997, and it supported data rates of 1Mb/s and 2Mb/s in indoor wireless environments. In comparison to 100Mb/s Ethernet, the 2Mb/s data rate is relatively slow and is not sufficient for most multimedia applications. Recently, the IEEE 802.11 WLAN standard group finalized the IEEE Standard 802.11a, which has an OFDM physical layer for indoor wireless data communications [1]. The data rates of IEEE 802.11a range from 6Mb/s up to 54Mb/s. This new standard can provide almost all multimedia communication services in indoor wireless environments.

However, two limitations of OFDM based systems are often asserted. Firstly, due to the nonlinearities of transmitter power amplifiers, high PAR values of the OFDM signal generates high OBN. There are restrictions imposed by the Federal Communications Commission and other regulatory bodies on the level of these spurious transmissions. These restrictions impose a maximum output power limitation. This output power limitation corresponds to what is known as power amplifier back-off. Further more nonlinearities of amplifier cause inband distortion of the signal giving higher bit error rates (BER). 64-quadrature amplitude modulation (64-QAM) modulation is used in IEEE.11a PHY for 48Mb/s and 54Mb/s transmission. This modulation scheme is highly sensitive to distortions due small Euclidian distances between signal points. Thus IEEE 802.11a WLAN devices may need power amplifiers with large back off, which are inefficient and bulky. Overcoming this problem requires reducing the PAR of OFDM signals. Secondly, OFDM is highly sensitive to frequency off-set errors. However, frequency offset due to the mobility of the terminal is negligible in WLAN environments, owing to very low speeds of the mobile.

Clipping of high peaks increases the in-band distortion and the OBN. In [2] several modulation schemes are examined and effects of amplitude limiting is presented. A controlled amount of limiting is permissible in many cases. Clipping an oversampled signal produces less in-band noise but the OBN will increase [3]. Performance evaluation of clipped OFDM symbol with and without oversampling is presented in [4]. Two extra oversampled DFT operation are used in the transmitter to filter the OBN due to clipping. Oversampling is necessary to avoid peak regrowth after filtering. Similar PAR reduction scheme based on clipping and filtering an oversampled signal is presented in [5]. Two oversampled inverse fast Fourier transform (IFFT) operations are used to interpolate and perform frequency domain filtering after clipping. This reduces the amount of OBN. Increased BER due to clipping may be reduced using forward error correction coding. Thus, a system based on clipping and forward error correction is proposed in [6]. Decision aided reconstruction (DAR) is proposed in [7] for mitigating the clipping noise. The receiver is assumed to know the clipping level. DAR is an iterative reconstruction technique, which increases the receiver complexity. Several discrete Fourier transform (DFT) operations are performed at the receiver before reconstructing the original signal.

For baseband transmission, an approximation for the resulting increase in BER is given in [8], but spectral distribution of the distortion is not considered. References [9, 10] consider the spectral spreading but only for real valued discrete multitone (DMT) signals. The degradation due to clipping of an OFDM signal is analyzed in [11]. Extensive research has been undertaken to understand the effect of high power amplifier (HPA) nonlinear distortion in OFDM systems [12, 13]. Compared to other PAR reduction schemes clipping based techniques are simple to implement.

A PAR reduction using signal clipping and phase correction at the transmitter is proposed in [14]. The basic idea is as follows. Let the IFFT of the modulated symbol sequence $X_n, n = 0, 1, \ldots, N-1$ be $x_k, k = 0, 1, \ldots, N-1$. Here we assume quadrature phase shift keying (QPSK). The sequence x_k is clipped to a desired level, and the IDFT is taken $\hat{X}_n$. Because of the clipping $\hat{X}_n \neq X_n$. The key idea in [14] is to apply phase correction to $\hat{X}_n$ such that both $\hat{X}_n$ and X_n have identical phases. This is done by multiplying $\hat{X}_n$ with $e^{j(\theta_n - \hat{\theta_n})}$ where θ_n and $\hat{\theta_n}$ are the phases of X_n and $\hat{X}_n$. The idea of this phase correction is to limit OBN and BER degradation. Of course, we cannot make the amplitude $\hat{X}_n$ equal to the original signal magnitude. Then we would be back to the original input sequence. Finally, the IDFT of the phase-corrected sequence $\hat{X}_n$ is used to generate the transmitted signal. Note that only N samples per each OFDM symbols are generated. Clipping those to a low level does not guarantee that the peaks of the output signals are reduced to the same level.

This paper presents three enhancements to the method proposed in [14]. First, we oversample the OFDM signal by a factor of L. Oversampling will lead to greater robustness against peak regrowth. Oversampling is implemented using LN-length IDFTs. Secondly, the phase correction is controlled (additional parameter β) and is applied only if the difference between θ_n and $\hat{\theta_n}$ exceeds β . Third, if the amplitude deviates too much from the original signal amplitude (as measure by a parameter α), an amplitude adjustment is applied. The BER degradation caused is thus negligible and the OBN is reduced considerably. This approach is more general than [14]. For instance the special case in our scheme represented by $\alpha = \infty$ and β=0 corresponds to [14]. We then apply this new scheme in IEEE 802.11a PHY transmit signals and evaluate the performance.

II. An OFDM system and peak-to-average power ratio (PAR)

A block of N symbols, $X_n, n = 0, 1, ..., N-1$, is formed with each symbol modulating one of a set of N subcarriers with frequency, $f_n, n = 0, 1, ..., N-1$. The N subcarriers are chosen to be orthogonal, that is $f_n = n\Delta f = n/T$, where T is the OFDM symbol duration. The complex baseband signal can be expressed as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi f_n t}, 0 \leq t \leq T. \quad (1)$$

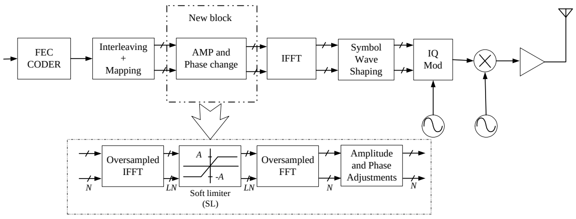

Fig. 1. IEEE 802.11a Transmitter.

This signal can be generated by taking an N point inverse discrete Fourier transform (IDFT) of the block X_n followed by low pass filtering. The actual transmitted signal is modelled as real$\left[x(t)e^{j2\pi f_c t}\right]$, where f_c is the carrier frequency. The PAR of the transmitted signal in (1) can be defined as

$$\xi = \frac{\max |x(t)|^2}{E[|x(t)|^2]} \quad (2)$$

where $E[x]$ is the expected value of x. The PAR of the continuous-time OFDM signal cannot be computed precisely by the use of the Nyquist sampling rate [15], which amounts to N samples per symbol. In this case, signal peaks are missed and PAR reduction estimates are unduly optimistic. Oversampling by a factor of 4 is sufficiently accurate.

III. IEEE 802.11a System description

The IEEE 802.11 transmitter with the proposed PAR reduction scheme is presented in Figure 1. Input data is first mapped into N symbols (X_n) and serial to parallel converted. Then a LN point oversampled IFFT is taken. The output of oversampled IFFT is clipped according the clipping ratio selected. A second LN point fast Fourier transform (FFT) is taken to get the clipped sample points back to frequency domain. We will now select N samples corresponding to the original signals (X_n). The clipping of the signal causes dispersion of the signal points. If we do not clip the signal, the original symbols (X_n) will be regenerated at this point. Next, we adjust the phase and the amplitude of these signal points $\hat{X}_n$ such that they are confined to a smaller region around the original signal points X_n.

Let us define an arbitrary signal point of the given constellation having amplitude and phase γ_n and θ_n as shown in Figure 2. Then phase, $\hat{\theta}_n$ and amplitude $\hat{\gamma}_n$ of each signal point $\hat{X}_n$ is adjusted according to the following rules. If the amplitude of $\hat{X}_n$ deviates from γ_n by more than α, the corrected amplitude will be adjusted as follows.

$$\hat{\gamma_n} = \begin{cases} \gamma_n + \alpha & \hat{\gamma}_n - \gamma_n > \alpha \\ \gamma_n - \alpha & \gamma_n - \hat{\gamma_n} > \alpha \\ \gamma_n & \text{else} \end{cases} \quad (3)$$

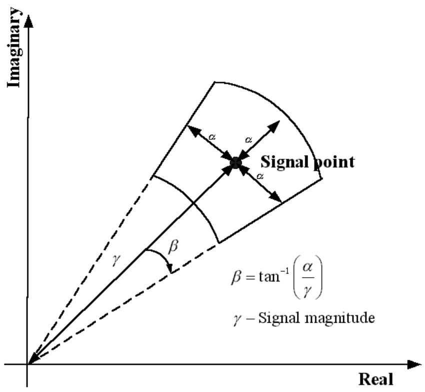

Fig. 2. Amplitude and phase adjustment parameters.

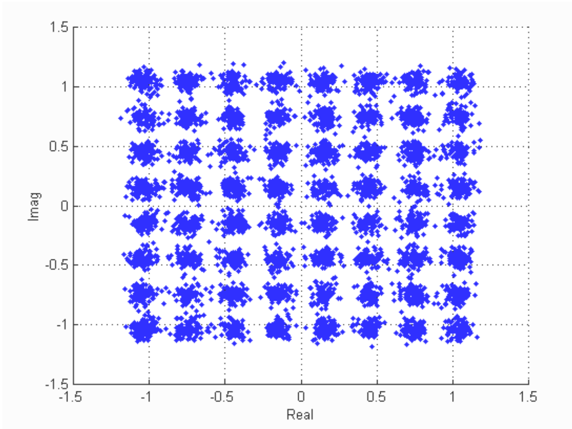

Fig. 3. Signal distortion at 4dB clipping of 48Mb/s Signals.

where $n = 0, 1, \ldots, N-1$. If the phase of the clipped signal deviates by β or more from the phase of the original signal points, the phase is also adjusted. β is calculated from the given α as follows

$$\beta = \tan^{-1}\left(\frac{\alpha}{\gamma_n}\right) \tag{4}$$

$$\hat{\theta}_n = \begin{cases} \theta_n + \beta & \hat{\theta}_n - \theta_n > \beta, \\ \theta_n - \beta & \theta_n - \hat{\theta}_n > \beta, \\ \theta_n & \text{else} \end{cases} \tag{5}$$

where $n = 0, 1, \ldots, N-1$. At this point we have a new symbol sequence optimized for lower PAR. This new scheme needs two extra oversampled-IFFT operations at the transmitter. *However, No modifications are needed at the receiver*.

TABLE I
IEEE 802.11*a* PHY PARAMETERS

Information data rate	6,9,12,24,36 48 and 54 Mb/s
Modulation	BPSK-OFDM QPSK-OFDM 16-QAM-OFDM 64-QAM-OFDM
FEC code	Convolutional rate 1/2, (K=7)
Code rates	1/2, 2/3,3/4
Total Number of sub carriers	52
Number of pilot subcarriers	4
OFDM symbol duration	4 μs
Guard interval	0.8 μs
Signal bandwidth	16.6 MHz

IV. Clipping High Peaks

A soft limiter (SL) described below is used to clip the signal peaks. The nonlinear characteristics of an SL can be written as

$$y_k = \begin{cases} x_k & |x_k| \leq A, \\ Ae^{j\varphi_k} & |x_k| > A \end{cases} \qquad 0 \leq k \leq 4N-1 \tag{6}$$

where A is the clipping level and φ_k is the phase angle of the sample x_k and y_k is the clipped output sequence. The clipping ratio is defined as

$$\text{Clipping ratio} = 10\log_{10}\left(\frac{A^2}{E[|x_k|^2]}\right) \text{dB}. \tag{7}$$

V. Results

Simulation results were obtained for different transmit signals. As IEEE 802.11a transmit signals utilize four constellations (binary phase shift keying (BPSK), QPSK, 16-QAM and 64-QAM), simulations are performed for data rates involving these constellations except for BPSK. Clipping has little effect on BPSK OFDM. Figure 3 depicts the constellation of a 48Mb/s transmitted signal passing through a SL with a 4dB back off. The distortion of the signal is clearly evident. Figure 4 shows the amplitude and phase corrected signal after 4dB clipping with correction factor $\alpha = 0.02$. The distortion of the signal reduces significantly depending on the value of the correction factor.

Figure 5 depicts the complementary cumulative distribution function of the PAR of the 48Mb/s signal. PAR is reduced by more than 4dB with the 4dB clipping, but with a severely distorted signal. Phase and amplitude correction reduces the distortion of the signal points but degrades the PAR statistics. A 3dB gain in PAR statistics is obtained when $\alpha = 0.05$, while this gain is around 2dB when $\alpha = 0.02$ at 10^{-3} of CCDF. Clipping with suitable phase and amplitude correction can achieve a significant PAR reduction.

We also examined the performance of other schemes. Figure 6 depicts the 36Mb/s signal constellation after passing through a SL with 2dB clipping. As 16-QAM

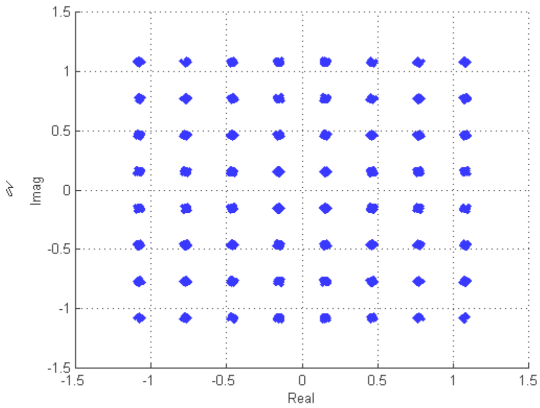

Fig. 4. Corrected signal constellation at 4dB clipping (48Mb/s and $\alpha = 0.02$).

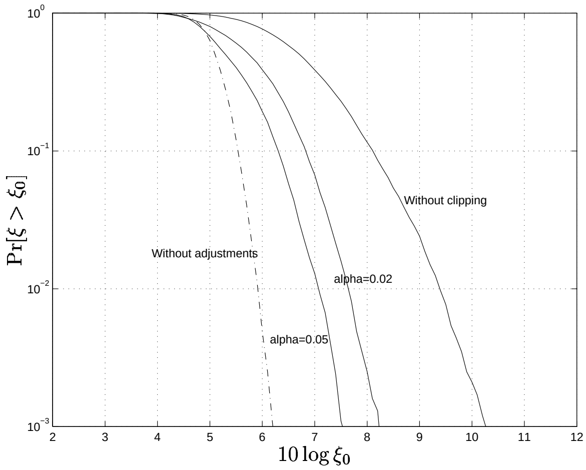

Fig. 5. CCDF of the 48Mb/s signals with 4dB clipping.

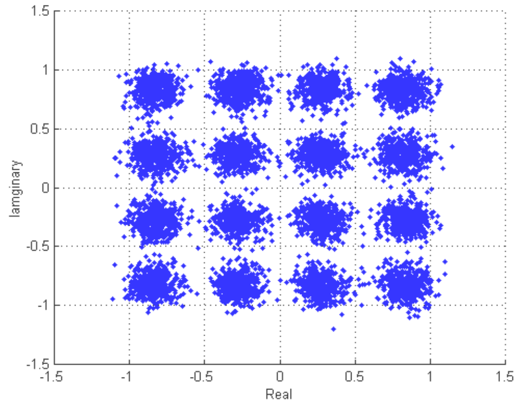

Fig. 6. Signal distortion at 2dB clipping of 36Mb/s Signals.

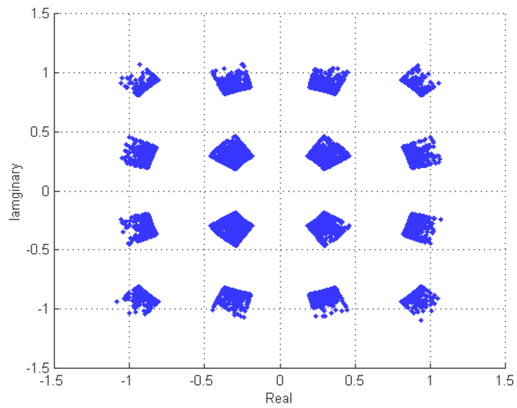

Fig. 7. Corrected signal constellation at 2dB clipping (36Mb/s and $\alpha = 0.1$).

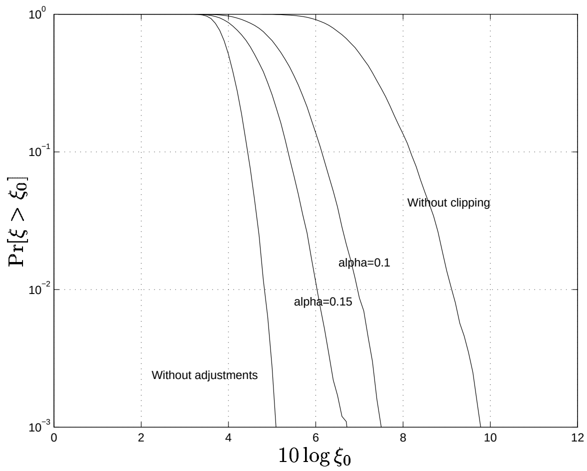

Fig. 8. CCDF of the 36Mb/s signals with 2dB clipping.

is less condensed than the constellation for 48Mb/s or 54Mb/s (64-QAM), we can allow for higher clipping ratios. Figure 7 shows the amplitude and phase corrected signal constellation. The amplitude and phase distortion is greatly reduced when the correction factor $\alpha = 0.1$. Figure 8 depicts the CCDF of PAR of the transmitted signals. The PAR statistics improve as before. The correction factor is chosen as $\alpha = 0.15$ and $\alpha = 0.1$ with clipping at 2dB. These parameters correspond to PAR statistics improvements of 3dB and 4dB respectively.

When the simulations are performed for 12Mb/s signals we could observe far better performance improvements. The constellation in 12Mb/s signal is less dense than the two other schemes before and allows greater flexibility in selecting correction factor α. High values of α give out high PAR reduction. When the $\alpha = 0.2$ about 5dB gain is observed while this was more than 3dB when $\alpha = 0.1$.

Next we observe the power spectral density (PSD) of the transmitted signal when passing through a non-

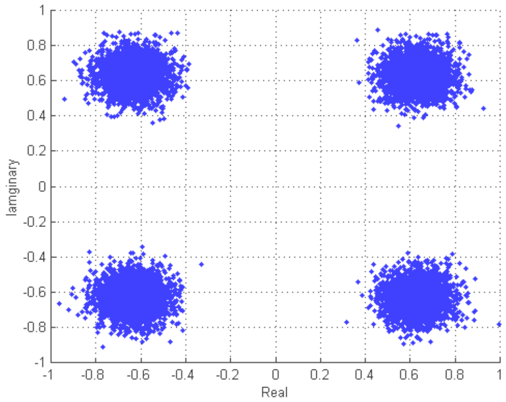

Fig. 9. Signal distortion at 2dB clipping of 12 Mb/s Signals.

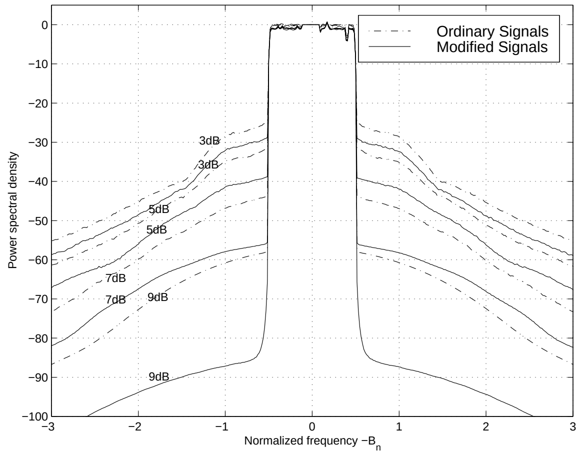

Fig. 12. Power spectral density when passing through a non-linear amplifier.

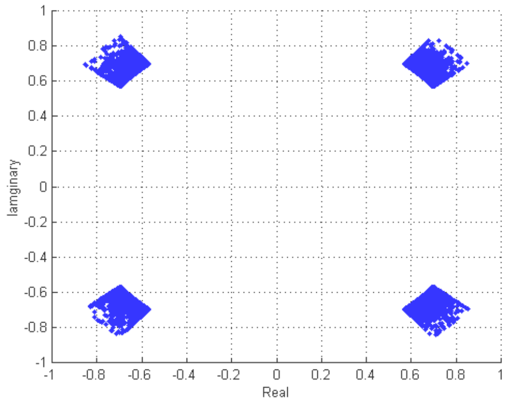

Fig. 10. Corrected signal constellation at 2dB clipping (12Mb/s and $\alpha = 0.1$).

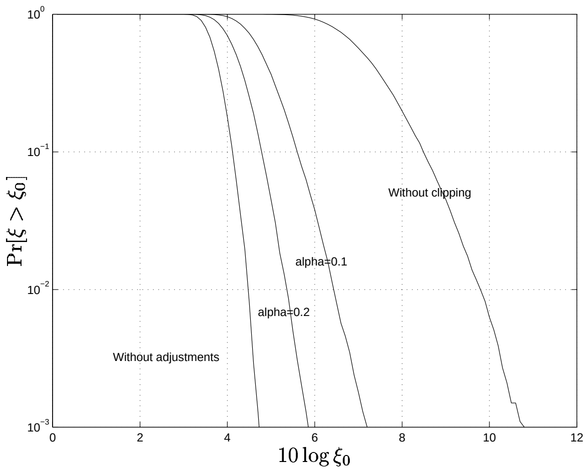

Fig. 11. CCDF of the 12 Mb/s signals with 2dB clipping.

linear power amplifier. The input output relationship of power amplifiers can be modelled as

$$F[\rho] = \frac{\rho}{[1 + (\frac{\rho}{A})^{2P}]^{\frac{1}{2P}}}$$
$$\Phi[\rho] = 0 \qquad (8)$$

where A is the clipping level, ρ is the amplitude of the signal input and F and Φ denote the amplitude and the phase at the output respectively. The parameter P controls the smoothness of the transition from the linear region to the limiting or saturation region. When, $P \rightarrow \infty$ this model approximates the SL characteristics. For PSD results, it is convenient to define the normalized bandwidth $B_n = f/(N\Delta f) = fT/N$, where T is the OFDM symbol duration.

In Figure 12, 12 Mb/s signal with 2dB clipping and correction factor $\alpha = 0.2$ is compared with an ordinary transmitted signal. The back-off of the power amplifier is set at different levels (3dB, 5dB, 7dB and 9dB). When the back off is very low (3dB) very slight improvement in OBN is observed. OBN is reduced by about 8dB when the back-off is at 5dB. Similarly, OBN reduces significantly with the increase in back-off at a faster rate compared to the ordinary signal. Therefore the back-off of the amplifier can be reduced significantly by using this technique.

Selection of initial clipping ratio and the correction factor depends on the signal constellation being used. Therefore, by selecting a suitable clipping level and a proper phase an amplitude correction factor significant PAR reduction is achieved without causing significant BER degradation. This is a desired feature in portable devices in WLANs, where power efficient transmitter power amplifiers are essential.

VI. CONCLUSION

A technique based on clipping with amplitude and phase changes to reduce the PAR of OFDM based WLAN signals defined in the IEEE 802.11a physical layer is presented in this paper. The proposed technique is capable of reducing the PAR by 3-4dB by selecting a suitable clipping level and amplitude and phase correction factor. It can be implemented with a slight increase in the complexity at the transmitter. This involves with insertion of two additional DFT operations and soft limiter at the transmitter. The receiver remains standard compliant.

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