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Impact of Nonlinear Power Amplifier on Link Adaptation Algorithm of OFDM Systems

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Abstract—The impact of non linear distortion due to High Power Amplifier (HPA) on the performance of Link Adaptation (LA) - Orthogonal Frequency Division Multiplexing (OFDM) based wireless system is analyzed. The performance of both Forward Error Control Coding (FEC) en-coded and uncoded system is evaluated. LA maximizes the throughput while maintaining a required Block Error Rate (BLER). It is found that when OFDM signal, which has high PAPR, suffers non linear distortion due to non ideal HPA, the LA fails to meet the target BLER. Detailed analysis of the distortion and effects on LA are presented in this work.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is widely used as physical layer technology for its tolerance to harsh wireless channel conditions as well as for its high spectral efficiency [1]. The time and frequency selectivity of wireless channel also provides the opportunity to improve the link quality and system throughput. LA is one technique which exploits the time and frequency variability of the wireless channel.

LA is used to introduce a real time balancing in the link budget in order to increase the spectral efficiency of a system over fading channels [2]. Parameters like transmitted power level, modulation scheme, coding rate, or any combination of these can be adapted according to the channel conditions. Channel conditions are estimated at the receiver and the Channel state Information (CSI) is sent to the transmitter to adapt the transmission accordingly. These schemes are used in multi-carrier systems where the adaptation is done based on the channel state for each subcarrier.

Despite many advantages, OFDM suffers from high (Peak to Average Power Ratio) PAPR problem. OFDM symbol is generated by superimposing several carriers when Fast Fourier Transform (FFT) is done at the transmitter. These carriers may add up constructively which results in high PAPR. When this signal with high PAPR passes through the High Power Amplifier (HPA), which has nonlinear transfer function [1], in-band and out-band regrowth occurs [3]. This in turn causes Block Error Rate (BLER) degradation and Adjacent Channel Interference (ACI) [1], [2].

Backing off the operating power of the amplifier by a certain amount helps to reduce the non linear distortion effect [3]. The larger the power Back Off (BO), higher the reduction of the distortion effect. On the other hand, BO reduces the total available transmit power which affects the coverage

area and achievable throughput of the system. Therefore it is aimed that minimum BO is used while optimizing the BLER performance by limiting the signal distortion. It is also known that the amount of BO needed for optimum performance varies for different modulation and coding schemes [4]. Since LA uses varying modulation, power and coding rate, hence fixed value of BO power will not optimize the performance. So, it becomes important to analyze the impact of nonlinearity in OFDM system that uses rate, modulation and power adaptation.

There has been a little focus on the performance of OFDM based LA systems under the effect of non linear distortion. In [4], the authors' have analyzed performance of uncoded system for a first hand analysis where significant influence of PAPR has been found on LA schemes. Although the implementation of FEC with interleaver improves the BLER performance significantly, the effect of nonlinear distortion can not be overcome completely with it. It is therefore important that OFDM systems using LA with FEC and interleaver be investigated for practical implementation in WiMAX and/or 3GPP-LTE system which is the focus of this work.

The impact of HPA non linearity and the required power BO on the BLER studied in this work is based on the Solid State Power Amplifier (SSPA) model of the HPA. The total degradations (TD) due to transmitter non linearity and signal distortion for different combinations of modulation with coding schemes is shown. The Distortion plus Noise Ratio (SDNR) at the transmit side is shown to be independent of modulation and coding rate while it is shown to be dependent on BO. Based on these analysis it is identified that threshold values for switching between modulations need to be updated. Accordingly, new threshold values have been found for mitigating the HPA impacts. These results will serve as an indication on how to design the LA thresholds when the PAPR impairments are considered.

The rest of this paper is organized as follows. Section II briefly describes the LA algorithm used for this work. Section III describes the impact of HPA on LA in Additive White Gaussian Noise (AWGN) channel. Section IV summarizes the performance in fading channel. Finally, conclusion is given in Section V.

II. LINK ADAPTATION PROCESS

The Figure 1 shows the block diagram of OFDM system with LA. On the received side the channel estimation is done. This channel state information (CSI) is fed back to the transmitter, which uses this information in LA block to decided which modulation and power it will use for next frame transmission. There are several LA algorithms for OFDM

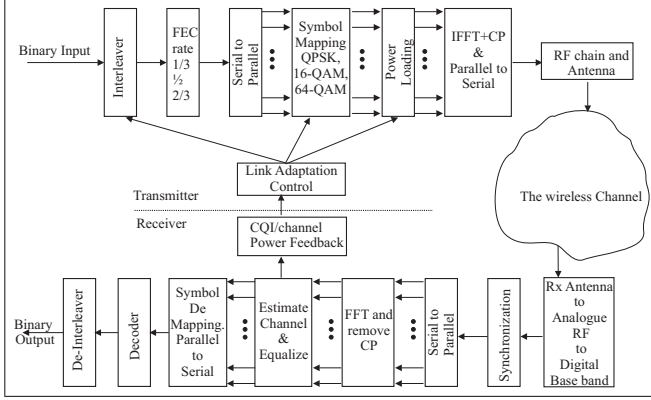


Fig. 1. Block Diagram of Link Adaptation System

systems. The algorithm used in this work is developed by the authors' [4] which is referred to as SAMPDA.

III. INTERACTION BETWEEN PAPR AND LINK ADAPTATION

A. Effect of HPA on signals with High PAPR

The HPA model used in this work is according to Rapp's Model [5]. The HPA model for AM/AM conversion is simulated using the relation in [1],

$$g(x) = \frac{|x|}{(1 + |x|^{2p})^{\frac{1}{2p}}}, \quad (1)$$

where x is the signal amplitude and the variable p is used to tune the amount of nonlinearity. A good approximation of existing HPA can be obtained by choosing p in the range of 2 to 3. For large values of p , the model converges to a clipping amplifier. This clipping amplifier is perfectly linear until it reaches the maximum output power level, which is very hard to achieve in practical system. Available literatures suggests that the AM/PM conversion for SSPA is small enough to be neglected [1].

OFDM symbol can be written as

$$X_n = \frac{1}{N} \sum_{k=0}^{N-1} A_k e^{jnk \frac{2\pi}{N}} \quad (2)$$

PAPR is defined as

$$\text{PAPR} = \frac{\max[|x(t)|^2]}{E[|x(t)|^2]}. \quad (3)$$

The signal is fed to the input of the HPA. The output of the HPA depends on the nonlinearity parameter p given by the equation 1. Output of the HPA can be written as

$$y(t) = \alpha \cdot |x(t)|^2 \cdot e^{j\angle x} + n(t) = f(|x|^2, \alpha) \quad (4)$$

where, α is an attenuation constant depending on power BO value and $x(t)$ and $n(t)$ are uncorrelated. Variance of the distortion caused by the amplifier is given by,

$$\sigma_D^2 = E[|x(t)|^2 - f(|x|^2, \alpha)]. \quad (5)$$

The transmitter side SDNR is given by,

$$\text{SDNR}_{\text{Tx}} = \frac{f(|x|^2, \alpha)}{\sigma_D^2 + \sigma_w^2} \quad (6)$$

where σ_w^2 is the variance of white gaussian noise. SDNR in transmit side takes distortion due to amplifier into account. Since this distortion is due to nonlinearity of power amplifier, it is independent of modulation scheme used.

Figure 3 shows the SDNR plots when 64-QAM modulation is used. We can see that, when the BO is reduced, then the SDNR reaches the highest value quite speedily, i.e. with increasing transmit SNR, the SDNR also increases until a certain value, after which the SDNR saturates. Thus increasing the SNR after some value does not improve the performance. Since with different BO, the SDNR behaves differently, the selection of BO needs to done carefully to achieve optimum performance.

The Figure 2 shows the relation of distortion with power BO of the HPA. It is clear from the figure that with increasing power BO, the signal operates more in the linear region and hence decreases the amount of distortion. For LA based system, threshold values are the function of SNR distribution [6]. And since the Eq.(6) shows that the SDNR is function of α , which depends on the BO, the threshold values are expected to be dependent on α as well. This means the Look Up Table (LUT), which contains the threshold values for different modulation and coding rate at certain BLER constraint, needs to be updated. For uncoded system, it is possible to obtain analytical expression for revised threshold. However, this is not applicable to coded system. Since almost all practical system, as well as system under investigation, i.e. 3GPP-LTE and WiMAX, uses FEC coding, analytical expression obtained for uncoded system will not be usable. Therefore, computer based simulations are used in this work in order to find the additional margin needed to update LUT in order to maintain the Quality of Service (QoS) constraint.

B. Impact of HPA on Coded and Uncoded OFDM System

From Figure 3 and it is clearly seen that the impact of BO on symbol error probability is severe which justifies the further investigation into the impact of HPA and BO on LA system performance.

In the forthcoming discussions, the non-linearity tuning parameter $p = 2$. Following the HPA affected constellations diagrams, the Bit Error Rate (BER) and BLER of uncoded and coded OFDM system are shown.

The authors in their previous work [4] obtained uncoded performance and here in Figure 5 gives the coded ($\text{FEC} = \frac{1}{2}$) performance. In both coded and uncoded system there is impact of HPA, however there is some performance improvement due to FEC coding gain. Coding rate in conjunction

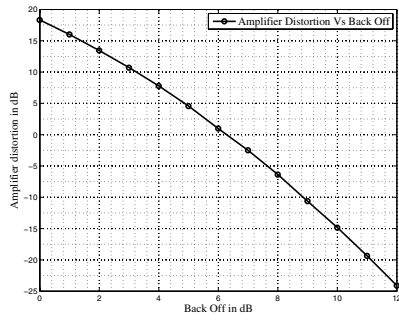


Fig. 2. Amplifier Distortion with Power BO

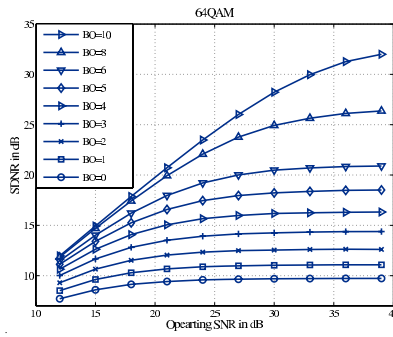


Fig. 3. SDNR plot for 64-QAM in AWGN.

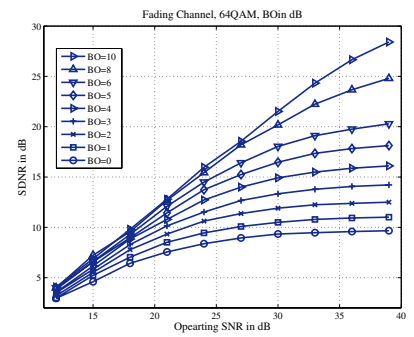


Fig. 4. SDNR for 64QAM in fading channel

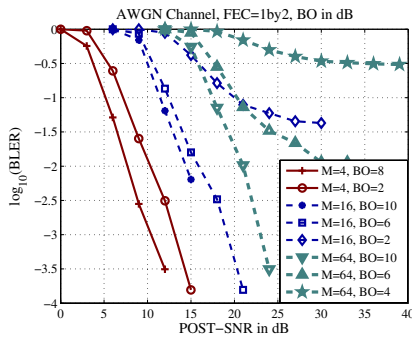


Fig. 5. Effect of HPA and BO on coded system

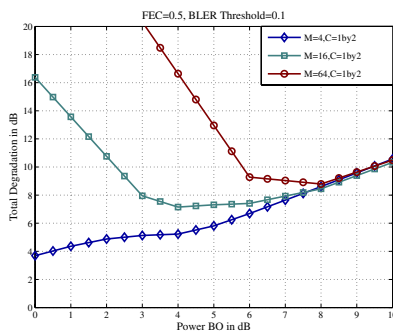


Fig. 6. TD Plot for BLER Threshold of 0.1

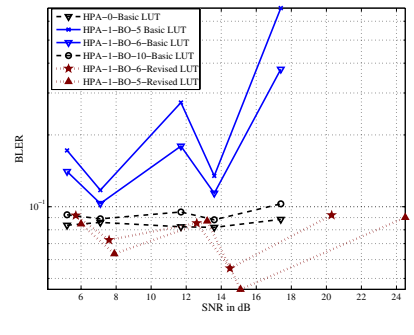


Fig. 7. BLER Performance of Link Adapted System with and without HPA

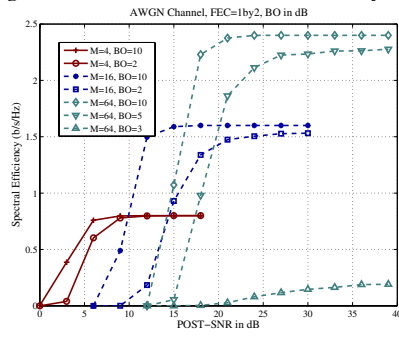


Fig. 8. Spectral Efficiency Comparison for different BO values

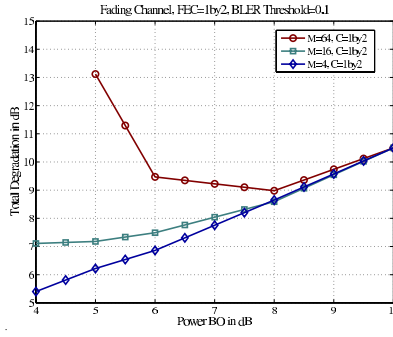


Fig. 9. TD Plot for BLER Threshold of 0.1 in fading channel

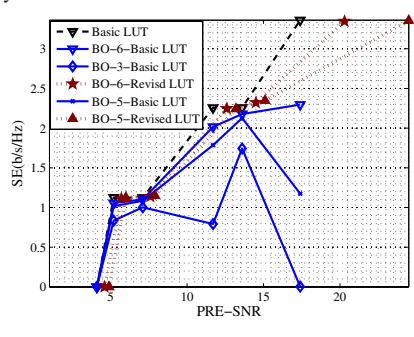


Fig. 10. Spectral Efficiency for Link Adapted System

with different modulation scheme has different impacts on performance. The higher the modulation rate, the greater the impact of BO values. Figure 5 also shows that FEC tries to compensate the distortion effect. For uncoded case, 16-QAM and 64-QAM schemes show error floor. At lower modulations like QPSK, coding does not improve the performance. At higher modulation rate, for example at 64-QAM, coding rate gives significant gain though there is throughput reduction due to FEC.

From Figure 5, it is clear that low modulation order does not require BO at all, since there is almost no performance improvement when 8 dB BO is used in comparison to the case with 2 dB BO. However for 16-QAM modulation, 2 dB power BO gives almost the same performance as no BO. This is inline with [4] and in other available literatures [1]. In those works, it is reported that increasing the BO values for more than the mean of PAPR (which is nearly 6dB) does not make

much difference, as the cdf of PAPR is quite steep.

Since different modulation and coding rate shows different behavior for variation in BO power, the choice of suitable BO point for different modulations are different. It is highly complex, if not impossible, to change the BO power frequently with the change in modulation and coding rate in link adapted system. So finding an optimum BO point considering modulation with coding rate becomes necessary for optimum performance.

Total Degradation (TD) for a certain BLER threshold is defined as the amount of BO plus the SNR degradation due to non-linearity in BLER performance as compared to the performance in basic system [3]. TD curve is very useful to find this optimum operating BO. The Table I shows how the TD values are calculated. For a certain value of BER or BLER, the corresponding SNR for without HPA system is used as the basic reference point. Then for that BER or BLER threshold,

corresponding SNR values for different BO values are noted. The difference between these values and basic reference values represent the degradation. The TD is defined as the sum of degradation and corresponding BO. Figure 6 represents the TD curve for BLER threshold of 0.1. The amount of degradation can vary for different modulation, coding as well as for BLER threshold. From Figure 6, it is seen that for 64-QAM, 16-QAM and 4-QAM, optimum BO is 6 dB, 4 dB and 0 dB respectively. So, it becomes important to draw TD curves for different BLER threshold as well as different coding and modulation rate to find the best operating BO.

The SDNR at receiver is defined as:

$$\text{SDNR}_{\text{Rx}} = \frac{1}{N} \sum_{i=0}^{N-1} \frac{|X_i|^2}{|X_i - \hat{X}_i|^2}, \quad (7)$$

where, X_i is the transmitted constellation point, \hat{X}_i is the received constellation point and N is the number of subcarrier.

C. Link Adaptation with HPA in Coded OFDM System

The first row of the Table II shows the threshold for ideal system. i.e. without HPA for LA system at BLER threshold of 0.1 with code rate = $\frac{1}{2}$. It also shows the additional margin required to satisfy the BLER threshold when HPA is used and since decreasing BO leads to increase in distortion, higher additional margin is required for lower BO values.

Figure 7 shows the performance of LA with ideal system clearly satisfies the BLER threshold. However, when HPA is added to the system, using the same LUT the BLER requirement can not be met except with a very high Power BO of 10 dB. However, this can not be used as a solution since it will reduce the coverage drastically. Obviously alternative solution is to modify the LUT by adding some extra margin to satisfy the threshold. For uncoded system the new LUT is already found in [4].

For coded system the Table II shows the margin required to satisfy the BLER requirement. The LA performance with the updated LUT is shown in Figure 7 where it clearly satisfies the BLER requirement. The zigzag nature of the curves when HPA is used is due to the power adaptation algorithm used in the system. For each subchannel, SNR is measured and checked which modulation scheme threshold it satisfies. And power for that subchannel is reduced to the threshold level. However, reducing power of the subchannel is in a way, backing off power by that amount which means it is operating in more linear region that definitely improves the performance. So for two different operating SNR, amount of power reduction is different and therefore BLER performance for same LUT is different accordingly.

D. Effect of HPA on Throughput

Throughput is a very important parameter to measure performance. Figure 8 shows the spectral efficiency of the system with HPA. With low modulations as QPSK, there is almost no effect of BO. However it gradually increases with increase in modulation and coding rate. At low SNR for 16QAM rate $\frac{1}{2}$, throughput for BO of 3 dB is lower than that without HPA. The

impact is severe for 64QAM. For example, Spectral Efficiency (SE) at 22 dB SNR with BO of 10 dB, 5 dB are 2.4 b/s/Hz and 2 b/s/Hz respectively. And for 3 dB BO, SE falls almost to zero. It is therefore very much important to carefully select the BO point considering throughput as well as BLER and other parameters which again shows the importance of TD curves for different threshold.

For LA based system, if it fails to maintain the target BLER, then throughput performance is severely affected. Thus it becomes very important to maintain the target BLER. Figure 10 shows the spectral efficiency of the system for different conditions. The figure also shows that if the revised LUT with added margin is used, then the system can have nearly the same spectral efficiency of the basic system.

IV. RESULTS FOR FADING CHANNEL

The discussion and results presented so far is based on AWGN channel. To use the results found for AWGN channel into the real system, it is very important to investigate the performance in the fading channel.

The Figure 11 show the basic system performance in fading channel with different modulation and power BO. It is worth mentioning that in all the figures the performance is shown against post SNR, i.e. the SNR measured at the receiver for each subchannel.

The performance with power BO of 10 dB can be considered as the basic system performance as with this amount of BO the system mostly operates in the linear region. However, this will reduce the coverage of the system significantly. Like AWGN channel, the effect of HPA gradually increases with the increase in modulation rate.

The first row of the Table III shows the basic LUT for fading channel. In link adaptation system, channel information is extracted from one symbol of a frame and is used not only in the next one symbol but also over the whole next frame. Thus a certain amount of error due to delay and averaging is introduced. To compensate for this effect margin is added to the threshold values, which is shown as addition within the bracket. With this LUT basic system maintains the target BLER as shown in Figure 13. However, when HPA is used, the behavior is same as in AWGN channel and it fails to meet target BLER which results in a severe reduction in SE at high SNR which is shown in Figure 12. Hence extra margin is required to satisfy the QoS constraint. The smaller the power BO, higher the degradation and hence more margin is required which may make some higher modulation and lower coding rate invalid.

Figure 4 shows SDNR plot which shows that for higher order modulation with low BO it SDNR saturates at certain value. This means increasing SNR beyond this value will not improve performance. So SDNR plot plays a vital role in choosing the highest operating SNR and thereby saves power. On the other hand, increase in BO causes decrease in the cell coverage. So a trade off between this two should be made. Total degradation curve, in Figure 9, can help to find the optimum BO value.

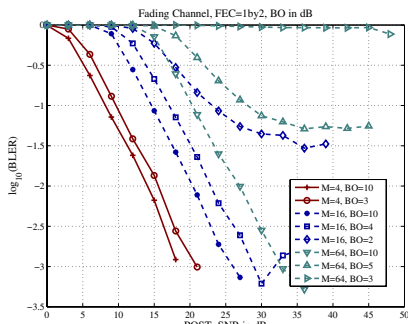


Fig. 11. Effect of HPA and BO in Fading Channel

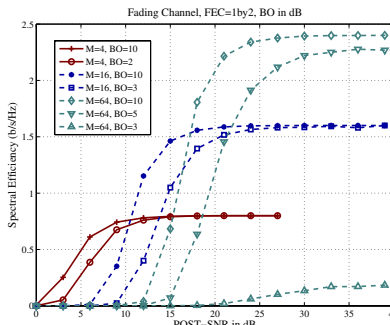


Fig. 12. Spectral Efficiency Comparison for different BO values in Fading Channel

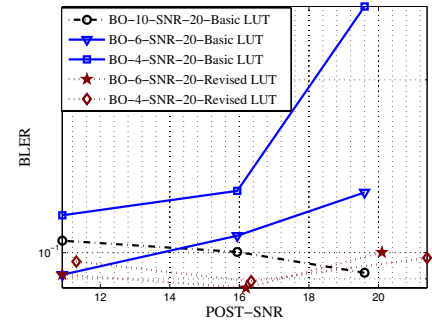


Fig. 13. BLER Performance of Link Adaptation with and without HPA

TABLE I

TABLE FOR CALCULATION OF TOTAL DEGRADATION IN dB

BO Values	Ideal	10	8	6	5	4
Measured SNR	5.1	5.67	5.7	5.79	5.91	6.33
Degradation	0.0	0.57	0.6	0.69	0.91	1.33
TD	-	10.57	8.60	6.69	5.91	5.33

TABLE II

LUT WITH BASIC AND UPDATED VALUES (dB) FOR AWGN CHANNEL

Power BO	None	QPSK	16QAM	64QAM
Ideal	0	5.1	11.6	17.3
6	0	5.1+0.5	11.6+0.9	17.3+2.9
5	0	5.1+0.8	11.6+1.5	17.3+7.1

TABLE III

LUT WITH BASIC AND UPDATED VALUES (dB) FOR FADING CHANNEL

Power BO	None	QPSK	16QAM	64QAM
Ideal	0	8.31+1.6	14.34+0.6	18.6
6	0	(8.31+1.6)+0.0	(14.34+0.6)+0.2	18.6+0.5
4	0	(8.31+1.6)+0.4	(14.34+0.6)+0.4	18.6+1.8

V. CONCLUSION

It is shown that the LA algorithms fail to meet BLER requirement if the non linear distortion from HPA due to high PAPR is not considered which has severe impact on throughput performance. A solution to this problem is proposed where the SNR LUT is adapted. It is shown that with the new threshold values, the LA meets the target BLER, though, this change affects the throughput performance.

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