# System Analysis of a W-CDMA Base-Station PA Employing Adaptive Digital Predistortion

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***Abstract*** **— An analysis is presented of the implementation requirements for a linear power amplifier (PA) incorporating a predistortion lineariser. It is shown that the statistical distribution of the W-CDMA envelope affects the linearity requirement of the PA when viewed as a function of instantaneous power. Where there is a low probability of a given level, the acceptable non-linearities are higher than at the most probable level. Consequently, a minimum linearity profile is derived that is consistent with meeting the ACLR, PCDE and EVM system requirements. This can be exploited to produce a simpler and more efficient PA while still meeting its specifications.**

## I. INTRODUCTION

The overall performance objective of a W-CDMA base-station PA is primarily to meet its linearity requirement at a desired output power level. A secondary objective is achieving a reasonable efficiency, especially approaching maximum operating power. This objective may be realized by a combination of output device choice, careful input and output matching, and some form of linearisation hardware. This paper considers the strategy of using Automated Load Pull to optimize the output device for best Adjacent Channel power Leakage Ratio (ACLR), and to complement this with a relatively simple adaptive predistortion lineariser.

The design of the PA requires an interpretation of the overall system requirement into a different form in order to specify the performance required from the individual components. This paper addresses the question of how small the residual linearity errors have to be, in terms of AM/AM and AM/PM components, in order to meet the 3GPP linearity specs of ACLR, Peak Code Domain Error (PCDE) and Error Vector Magnitude (EVM).

## II. 3GPP PA SYSTEM REQUIREMENTS ANALYSIS

There are three predominant parts of the 3GPP specification [1] that determine the linearity requirements of a PA:

?? ACLR at +/- 5 MHz must be < -45dB, and < -50dB at +/- 10 MHz.
?? PCDE must be < -33 dB at spreading factor 256
?? EVM must be < 17.5 %.

The amount of these distortion artifacts actually produced depends upon the amplitude distribution of the modulation as well as the linearity of the PA. It is well-known that constant-envelope modulation formats do not require a linear amplitude transfer function from the PA.

Testing of 3GPP base-stations and their components is done with test models prescribed by the standard [2]. A different test model is used for each test, having appropriate information content and signal statistics for the tests to be representative. The relative severity of each of these tests is examined in the following analysis.

For example, Test Model 1 specifies 64 traffic channels randomly distributed to create a realistic traffic scenario having a high peak to average ratio. This is to be used when testing ACLR and maximum output power. The statistical distribution of the modulation amplitude is shown in Fig. 1.

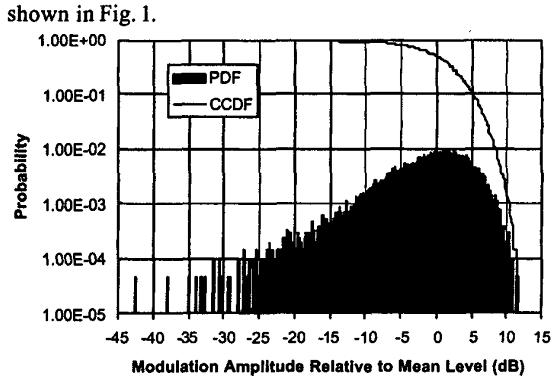


Fig. 1 Probability Density Function (PDF) and Complementary Cumulative Distribution Function (CCDF) of 3GPP Test Model 1 with 64 traffic channels

The peak to mean ratio is approximately 10.5 dB and the most probable level is 0.5dB below the mean. The median level is at 1.7dB below the mean.

### *A. ACLR Requirements*

In order to establish an upper bound on the linearity required to achieve the desired adjacent channel power leakage, let us assume that all deviation from an ideal PA transfer function is translated into power in the two adjacent channels. If each adjacent channel has -45dB of



0-7803-7246-8/02/$10.00 © 2002 IEEE

leakage, or -42dB total leakage power, this is equivalent to all parts of the modulation having a vector error $E_v$ of 0.794%. This is of course pessimistic (too small), because it does not allow for products that are generated in other channels, or indeed in the wanted channel. However, it avoids making assumptions yet about the types of non-linear mechanism and their spectral components.

The next step is to show how a non-uniform distribution of $E_v$ can have the same potential ACLR as a uniform value. The first special case is to weight the permissible error according to the PDF of the modulation envelope. Fig. 2 shows how an overall error of 0.794% can be distributed according to probability of occurrence such that the overall contribution from each level is the same.

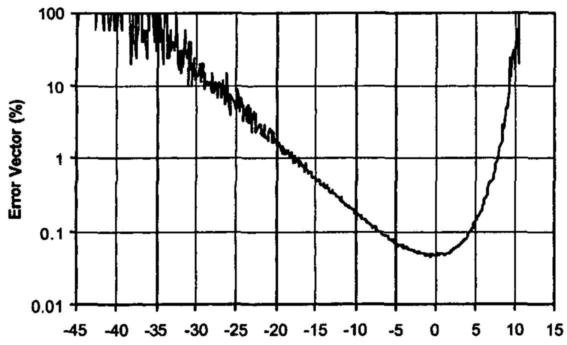


Fig. 2 Modulation Error Vector, weighted according to Test Model 1

This suggests that it is critical to achieve good linearity in the region of 5 dB above and below the mean level, and that the extreme peaks and troughs are considerably less important. The lowest point of the graph at 0.04% also suggests that in an IQ modulator or digital predistorter implementation, an effective DAC resolution slightly better than 11 bits would be required. Even with a more comprehensive relationship between ACLR and linearity that would show that this graph could move upwards, the conclusion still holds that the most sensitive part of the transfer function to linearity errors is at the mean operating level.

Although Fig. 2 is a special case profile, it is useful to consider a non-uniform error profile in a practical implementation. Allowing larger errors at the extremities of the modulation mitigates against noise and offset error at low levels and PA compression at high levels.

Another special case is also useful to analyze, where the amplifier has perfect linearity except for a region of hard clipping, above which no further increase in level is possible. This will help to predict how much amplifier compression is permissible. A simulation was set up where the onset of hard clipping was varied until the ACLR was only just meeting spec. It was found that the peak to mean ratio could be reduced by 2.7dB to 7.8dB under these conditions. Fig. 3 shows the clipped Probability Density Function (PDF) and Complementary Cumulative Distribution Function (CCDF) curves. The first adjacent channels are at a level of -45dB and the second adjacent channels are at -56.5dB.

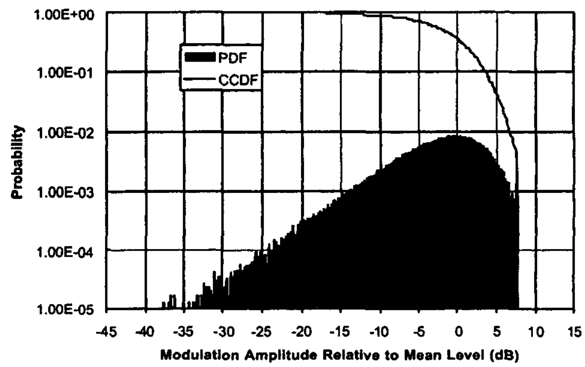


Fig. 3 Probability Distribution of 3GPP Test Model 1 with hard clipping

The missing part of the PDF function was used to calculate the proportion of power missing from the overall waveform. The result showed that 0.33% of the power was not delivered as a consequence of hard clipping the modulation to 7.8dB peak to mean ratio. This can be expressed as a -24.8dB residual modulation error. Given that -42dB would have been the result if all the error power fell into the adjacent channels, we conclude that this example causes predominantly in-band errors.

## *B. PCDE Requirements*

Peak Code Domain Error is tested with Test Model 3. The difference between each frame of the measured modulation and an ideal numerically reconstructed version is analyzed in the code domain. The PDF and CCDF of the test modulation are shown in Fig. 4.

As with Test Model 1, a simulation was conducted where hard limiting of the upper power level was varied until a value of -33dB PCDE was observed. This corresponded to clipping the modulation at a new peak to mean ratio of 2.7dB. This test is therefore considerably more tolerant than the ACLR test, and is likely to be easily passed if the ACLR requirements are met.

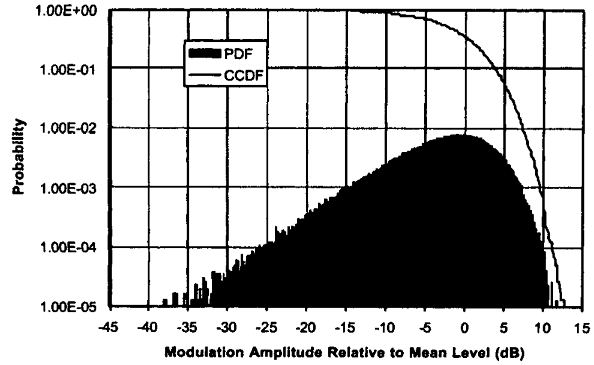


Fig. 4 Probability Distribution of 3GPP Test Model 3

*C. EVM Requirements*

Error Vector Magnitude is tested with Test Model 4. This specifies a relatively simple configuration, having one channel carrying PCCPCH + SCH and optionally a second channel carrying Primary CPICH. Consequently the PDF shows a relatively low peak to mean ratio of 5.45dB, as shown in Fig. 5. Although it is possible to show how the results of the EVM test can be progressively degraded by increasing amounts of hard clipping, it is not necessary in this analysis, since the majority of the modulation envelope lies within the critical area covered by the ACLR requirements. This EVM test will pass the specification if the ACLR test passes.

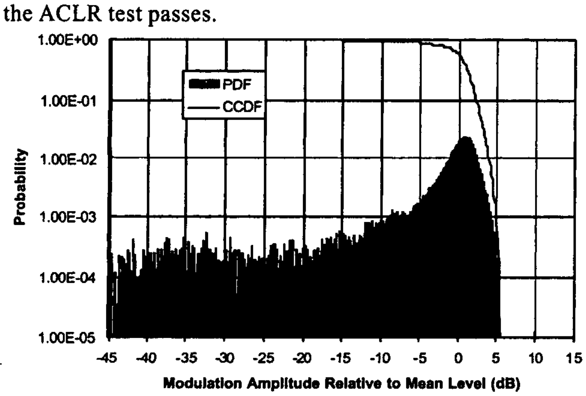


Fig. 5 Probability Distribution of 3GPP Test Model 4

## III. LINEARISED PA ARCHITECTURE

This work builds on the established art of applying a digital compensation to the IQ waveform such that the characteristics of the PA are cancelled out [3, 4, 5].

Fig. 6 shows the architecture of a lineariser and PA. The modulation waveform to be transmitted is passed through a predistortion block while still in the digital domain. This has the appropriate inverse characteristic to compensate for the PA's non-linearity. The compensation is applied through an IQ lookup table, although this is a representation of a polar format AM-AM and AM-PM correction characteristic.

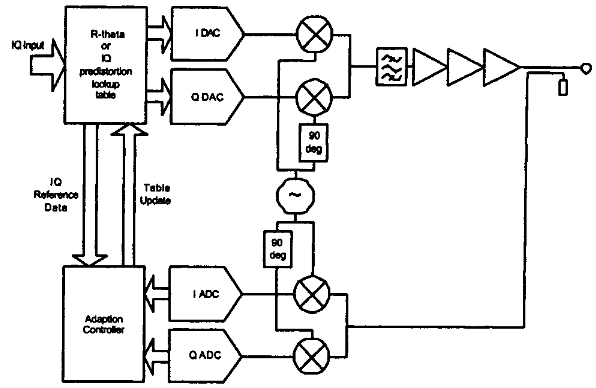


Fig. 6 Adaptive Predistortion PA Block Diagram

The correction to be applied is determined by analyzing the output of the PA. This is sampled with a coupler and downconverted such that it can be digitized by the lineariser hardware. The architecture shown measures the IQ trajectory of the output, effectively allowing the EVM of the modulation to be measured. Alternative architectures that measure the output envelope with a detector, or the adjacent channel power have also been considered, but the overall performance requirement derived from Section II still applies.

*A. Weighted Adaptive Predistorter*

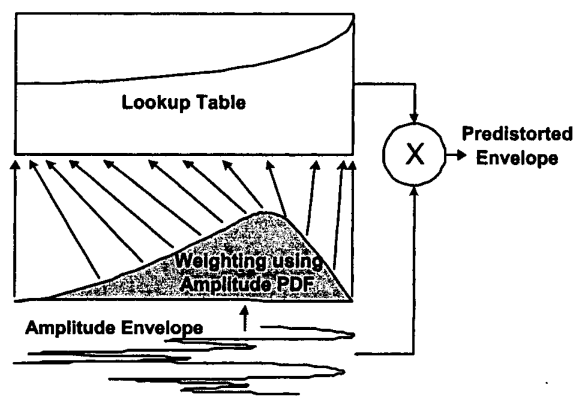


Fig. 7 Weighted Adaptive Predistortion Lookup Table

In particular, the lookup tables and the adaptation algorithm make use of the statistical distribution of the modulation. The linearisation effort is weighted towards the part of the characteristic that gives the best ACLR payback. The adaptation algorithm has access to the statistical history of the transmitted modulation and this is used to weight the optimization of the predistortion tables.

Fig. 7 shows how this can be achieved by mapping the amplitude envelope onto the elements of the lookup table according to the modulation amplitude PDF. This technique can be extended to artificially impose hard clipping. By restricting the amount by which the PA is overdriven, excess heating, peak AM to PM and peak current are moderated, helping to reduce thermal and biasing effects that take significant time to recover from.

*B. PA Design Using Automated Load Pull*

The design of a PA for a W-CDMA can be approached in a number of ways. Critically, the source and load impedances presented to each transistor determine their linearity as well as their gain and efficiency. Automated load pull measurements are particularly revealing, where contours of constant ACLR can be plotted on a Smith chart. An example showing ACLR, gain and drain current contours is given in Fig. 8.

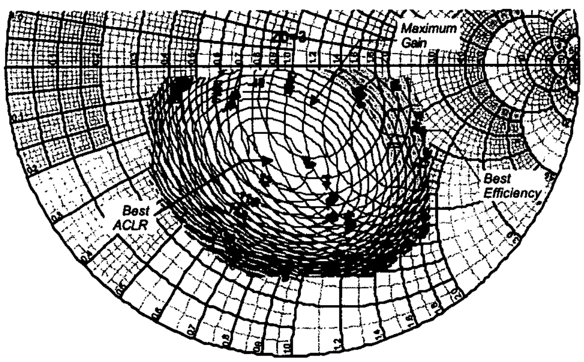


Fig. 8 Load plane contours for MRF21125 at 41.2 dBm using Test Model 1, 64 traffic channels stimulus

This design information was used to specify the matching networks for each stage in the amplifier, such that it has been optimized for best ACLR performance prior to linearisation.

*C. Measured Results of Linearised PA*

Fig. 9 shows the characteristics of the PA after load-pull design for best ACLR but prior to linearisation. A small amplitude droop is present at lower levels and predominantly AM compression occurs at large signals. The lineariser was programmed to flatten the response up to 7.5dB above the mean level. Initial performance with conjugate matching was limited to 8.8W at -45dB ACLR. Following load pull, 12W at -45dB ACLR was achieved. With the lineariser active, 20W output was possible. The output stage Power Added Efficiency (PAE) was 17%.

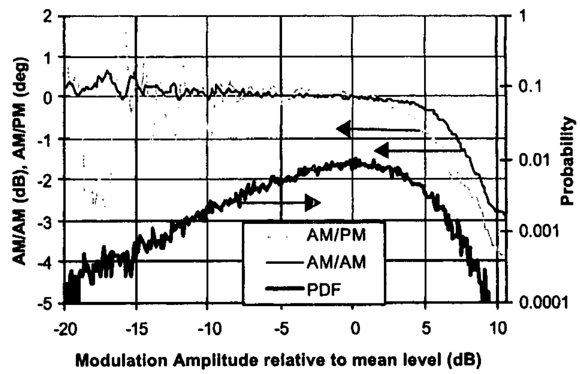


Fig. 9 LDMOS AM/AM and AM/PM characteristics compared with Test Model 1 PDF. Optimum load pull, 43dBm

## IV. CONCLUSION

The analysis shows that the overall performance of the linearised PA depends on several critical factors. In particular, the linearity requirements of the PA vary as a function of the instantaneous power level, and this can be exploited to focus the design task in the area that has the greatest payback. The unlinearised RF performance can be maximized by careful attention to the load and source match presented to the RF power transistors. The predistortion function complements this by focusing on the linearity at the median power level, and permits a degree of clipping at the envelope peaks. Consequently, a transistor with a given saturated output capability can be operated at a higher rms output level, with the potential to deliver better efficiency.

## ACKNOWLEDGEMENT


The author wishes to acknowledge the assistance and support of the staff of the PA Design Centre at Tality UK.


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