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Quantifying the effect of Look up Table Size and Coefficients Complexity for Non-Linearity Compensation in Power Amplifiers

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Abstract: Power Amplifiers are the critical part of communication systems but they are nonlinear in nature. Look up Table (LUT) is one of the promising approaches for compensating the nonlinear effects of Radio Frequency (RF) power amplifiers. In this study we present a Memoryless Digital Predistortion (MDP) model to compensate the amplifier non-linearity based on updating the LUT coefficient iterations. Nowadays, the dual mode (Global System for Mobile communication (GSM) and EDGE (Enhanced Data rates for GSM Evolution) power amplifiers are in practice. In this work, we have proposed a single amplifier fulfilling EDGE specifications that can be implemented for base stations in order to compensate the required linearity and to improve overall system performance. MATLAB was used to simulate the proposed Class-B amplifier and a numerous simulation results were obtained and on that basis the best optimized LUT coefficient size complexity has been proposed. The proposed system also improves the maximum output power by optimizing the power at critical offset frequency. Moreover, Vector Magnitude (EVM) difference between estimated input and output results have also been calculated.

Keywords: Linearization techniques, Memoryless Digital Predistortion, Error Vector Magnitude, Look up Table, Critical offset

1. INTRODUCTION

Power amplifiers (PAs) are the promising part of any communication systems even though its natural nonlinear behavior is a valid concern (T, Du., 2012). This nonlinearity generate excess amount of spectral growth across the signal bandwidth which causes signal interfering between adjacent channels. At the same time due to distorted affect of nonlinearity signal bit error also disturbed. The linearity and efficiency are the two key requirements of efficient power amplifiers design (X, Hu., 2012). In order to achieve the linearity, PAs are operated with a back-off, which directly affects the system power efficiency. An optimum solution is to achieve maximum efficiency by operating PA in saturation region and then linearize them by means of any additional circuitry. Linearization techniques are adopted to enhance the linearity, reducing the saturated power at satisfactory level and improving the PAs system efficiency at desired level (Bruno *et.al.*, 2012). Several PA linearity compensation methods are proposed in literature such as feedback, feed forward and predistortion (Swaminathan, 2013).

Feedback linearization approach is a traditional method where PA output follows its input in the form of feedback concept. Feedback linearization approach normally suffers feedback delays which creates stability issues particularly in systems with discrete components. The feed forward linearization approach offers improved linearization characteristics, still widely accepted technique used in mobile base stations (Ming, Xiao., 2009). With this linearization technique, distortion is attenuated at the PA output, which is achieved by operating PA in opposite phase thus canceling the distortion. With predistortion linearization approach, PA input signal is amplified in a way that non-linearities can be compensated. With this method a nonlinear block is added across the nonlinear PA. The cascaded nonlinear blocks generate the linear response. Predistortion linearization technique can be adopted for two different approaches, Analog or Digital Predistortion approach. In this paper LUT based MDP is considered because a highly efficient PA can be design easily than desire amount of linearity can be achieved independently with MDP. Previous studies show that PA is a power consuming device but with MDP not only linearity of the system can be improved significantly but power consumption can also be restricted in acceptable ranges.

2. MEMORYLESS DIGITAL PREDISTORTION

The main object of Digital Predistortion (DP) is to linearize the nonlinear characteristics of a PA over a range of operating zones (Xiaoning, 2013). In digital predistortion system, an inverse characteristics of PA is

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generated and its amplitude and phase are merged to the input signal so that predistorted signal and the overall power amplifier response is rectified (Pooria, 2010) as shown in **(Fig-1).**

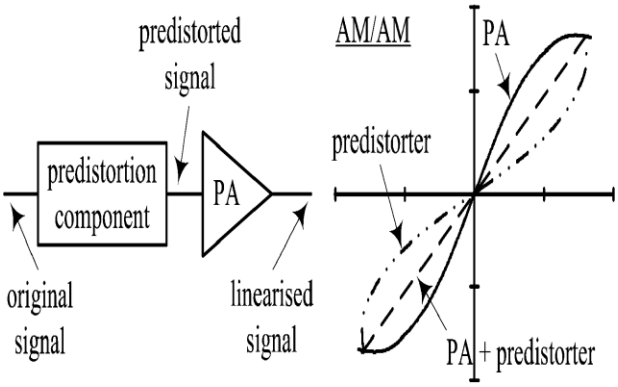


Fig-1: Predistortion linearization approach

This practice has to be implemented at high accuracy to achieve an acceptable and controlled compensation outcome. The inverse characteristics of PA are stored in a memory (LUT) and data is updated according to the error that is generated by the differentiation between output and input power amplifier signals. In a memoryless DP, power amplifier output only depends on the input value for new coefficient calculation. This coefficient calculation approach is very straightforward with possible small LUT size in contrast to memory PA systems.

2.1 Memoryless Adaptive Digital Predistortion Algorithm

The core function of adaptive DP algorithm is to acquire the inverse characteristic of the power amplifier. MDP is alienated into two paths: predistorted or forward path and the feedback signal path. (**Fig.2)** illustrates a generalized block diagram of adaptive digital predistortion system.

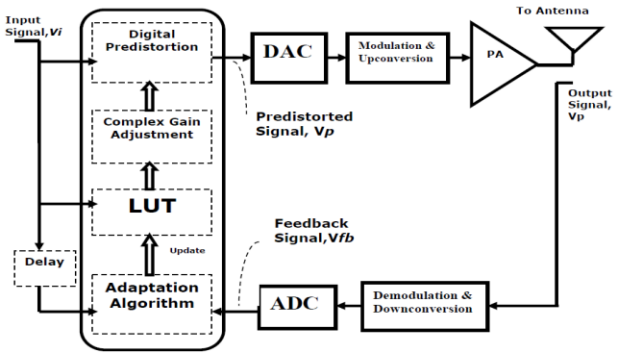


Fig-2: Generalized block diagram adaptive digital predistortion system

The transmitter of PA contains the forward path where predistortion block is applied. In order to update the predistorter to follow PA characteristics adjustments, the feedback path must contain analog feedback circuitry components like demodulator, signal conversion, envelope and a phase detector etc. With the DP function, the input signal samples of digital baseband are multiplied before being converted into the digital-to-analog converter (DAC) by series of complex coefficients generated from the LUT, where PD function is implemented through LUT coefficients. The adaptive PD function is derived by using a modulated input signal. The adaptation algorithm finds the coefficient values by evaluating the feedback signal and an input delayed signal (Laki , 2013). The adaptive PD system is executed using a address-generation block, LUT and a complex multiplier that choose the suitable coefficient from the LUT, according to the input signal magnitude. This relationship is illustrated in **(Fig.3),** where Output signal (***Vp***) is related as:

$$V_p = V_i . F(|V_i|) \quad (1)$$

Where *Vi* is the input signal, *F* is the Adaptive DP function, and ($|Vi|$) is the modulated signal magnitude.

The LUT size estimates the total amount of distributed points across which PD function is alculated. The divisions of the PD function points are determined as per squared or logarithmic relationship, so PD function points must be evenly distributed through the input signal magnitude (Wan-Jong, Kim., 2004).

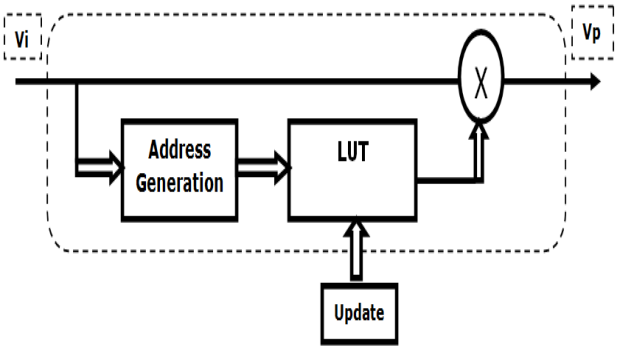


Fig-3: The address generations block with LUT coefficient updates

Fig-4 illustrates the basic concept of Predistorter and amplifier gain setup for adaptive DP algorithm. The predistorter algorithm function *(F)* relies on the predistorter open loop gain *(H)* and amplifier gain adjustment *(G)* which is updated after each LUT entry.

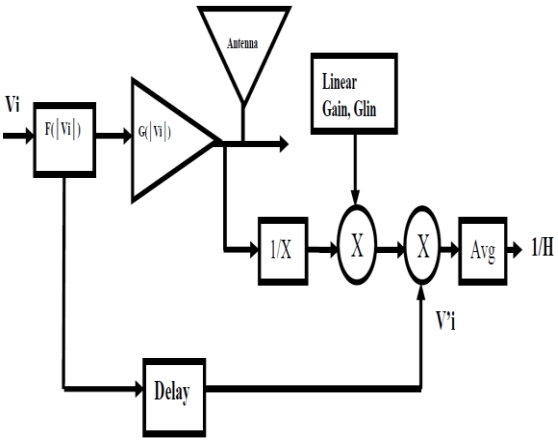


Fig-4: Predistorter and amplifier gain setup

The inverse function of open loop gain is defined as:

$$\frac{1}{H} = \frac{V'i}{V_{fb}} = \frac{G_{lin}}{F(|V_i|).G(|V_p|)} = 1 + jX0 \quad (2)$$

For the linear response, predistorter and cascaded amplifiers must entail that *F(|Vi|) G(|Vp|) = k* for all magnitude inputs, where *k* is the quantization level. For unity open loop gain, the linearized gain *(Glin)* must be equal to quantization level *k*. On the other side if system open-loop gain is deviated from unity, PD function must be attuned in a way to achieve the unity loop gain. For unity open loop gain, required system modification is illustrated in **(Fig-5).**

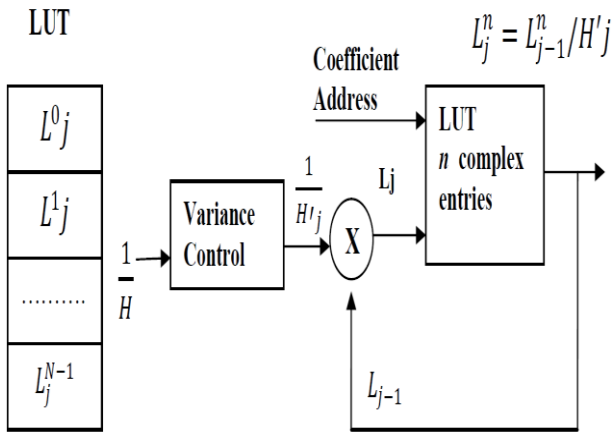


Fig-5: LUT coefficient address and variance control for unity open loop gain

The PD process is categorized by a series of LUT coefficients *Ln*, where *n represents the* input-signal magnitude which is considered as per LUT address. For unity open-loop gain requirements, the coefficients of PD functions are divided with calculated open-loop gain and then they are updated and mapped as a new coefficient entry. Meanwhile, the relationship between the input magnitude and the feedback signal is established to estimate the interruption in the feedback path. As the size of the block increases, system accuracy is estimated to increase at the cost of more time to adapt the changes.

3. MATERIAL AND METHODS

A LUT based predistorter part is comprised of coefficient address block, delay unit, LUT coefficient indexing and adaptation unit and a complex multiplier.

3.1 LUT Coefficient Calculation

With memoryless PA, the output is only linked with transitory input making LUT coefficient calculation and addressing very straightforward as opposite to memory based PA systems where pervious states are also considered making the LUT coefficient calculation and addressing a complex process. If we consider the Amplitude Modulation (AM) and Phase modulation (PM) characteristics of any power amplifier before and after the linearization as revealed in fig-6, than coefficients can be calculated easily. Fig-6 illustrates the nonlinear AM/AM characteristics of power amplifier with original behavior as *f*(*x*) and the linearized targeted response as *g*(*x*). The *y*1 and *y*2 points are defined as:

$$y_1 = f(x_1) \quad (3)$$

and $y_2 = f(x_2)$ (4)

The point's *xi* and *yi* represents the squared magnitude relationship of the PA input and output correspondingly. Where as

$$y2 = f(x_1) \quad (5)$$

represents the required linear response of power amplifier.

If we define the coefficient Cx_1 as

$$Cx_1 = x_2 / x_1 \quad (6)$$

multiply Cx_1 with function *x*1 and relate it to the defined function *f*, then a linear response (g) can be achieved as shown

$$y_2 = f(x_2) = f(C_{x1}x_1) = g(x_1) \quad (7)$$

This relates that for every *xi* function value a coefficient Cxi will be computed and stored in a LUT address unit for entire range of the input signal and linearize the PA consequently. The size and coefficient complexity of LUT entirely relies on input signal quantization levels.

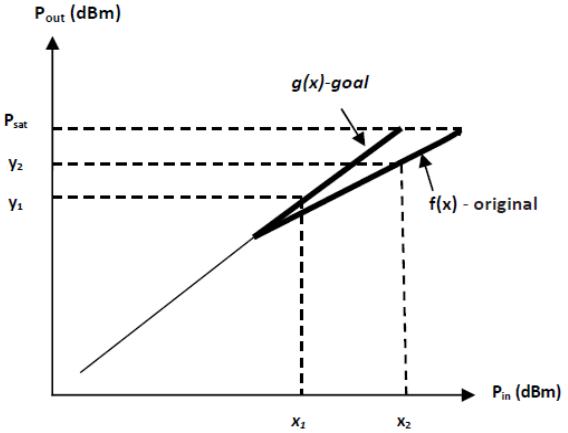


Fig-6: AM/AM characteristics before and after linearization

3.2 LUT Coefficient Updating

Once LUT coefficients are calculated it must followed by the coefficient updating process. Fig-7 illustrates the proposed square magnitude algorithm based coefficient updating model.

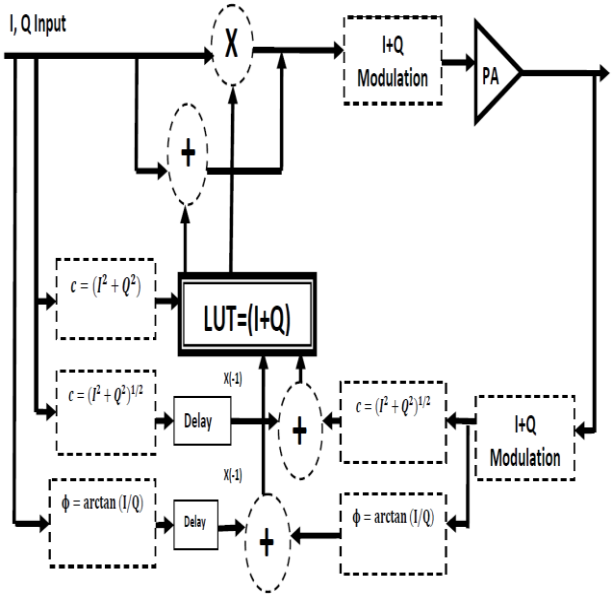


Fig-7: Proposed LUT based adaptive DP with coefficient calculation and updating model

The squared-magnitude relationship is estimated for the complex input signal across the addressing and multiplier units. The input predistorted coefficients values are stored in a LUT address unit and every received signal is multiplied sample by sample with originally stored coefficients, generating a new coefficient value. The next step is I (In-phase) and Q (Quadrature) coefficient comparison of the newly generated coefficient values of the demodulated PA with those generated earlier. The proposed system is a two dimensional mapped LUT predistorter in a way that with *k* quantization level for I and Q inputs, k^2 will be size of the LUT. With such system, the size of LUT to *k* can be reduce dramatically as amplifier nonlinearity only depends on its memoryless amplitude rather than input signal phase. This follows the amplitude calculation of addressing unit thus generating the new LUT entries and addressing them accordingly. With every new coefficient the target and original coefficient value can be compared for linearization compensation, quantization analysis and error vector magnitude (EVM).

3.3. Error Vector Magnitude Algorithm

EVM is a magnitude distance error vector between the intended signal and original signal. EVM is in in-band distortion which normally generates high bit error rates affecting the normalization of signal transmission. EVM must be limited as it is a major form of nonlinearity constellation point, which affects the linearity compensation. For the power amplifier linearity compensation and LUT size complexity analysis, EVM is used as a error updating symbol vector each quantization level (k), defined as:

$$EVM(k) = \frac{|E(k)|}{\sqrt{\frac{1}{N}\Sigma_{k=1}^{N}|S(k)|^2}} \quad (8)$$

Where $E(k)$ the symbol error vector for k, $S(k)$ is the symbolically idealized signal vector and N is cumulative number of updating vectors. Based on the Root-mean-square (RMS) value of EVM the percentage (%) offset linearity variation between targeted and original signal with respect to maximum output power can be calculated as :

$$EVM_{RMS} = \frac{\sqrt{\sum_{k=1}^{n}|E(k)^2|}}{\sqrt{\sum_{k=1}^{N}|S(k)|^2}} \quad (9)$$

The linearity offset variation in form of EVM_{RMS} values should not exceed 9% (Gregorio, 2013) with optimum defined output power level.

4. RESULTS AND DISCUSSION

The idea of the proposed algorithm is to analyze the effect of LUT size and coefficient complexity in order to develop a linearized system. The proposed algorithm improves the efficiency and performance based on leakage power at critical offset frequencies and error gap difference between original and observed results in form of EVM that will automatically linearize the system at greater deal.

4.1 LUT Coefficient Iteration Analysis

In this section the impact of LUT coefficients complexities and iterations at critical off set frequencies are analyzed with 14 bit constant wordlength. For the simulation purpose three critical offset frequencies (300 kHz, 450 kHz, 600 kHz) with different LUT coefficients iterations (60,120,240,480,960,1920) have been chosen with standard maximum output power level. It is observed that with smart design strategies the non-linearity in EDGE applications based handsets can be compensated having improved system efficiency with digital baseband predistortion. The corresponding performance of different scenarios with varying critical offset frequency and number of LUT coefficient iterations are illustrated in Figs 8, 9 and 10. It can be observed from figs-8 that for 300 kHz offset, with smaller LUT coefficients (60, 120, 240) the leakage power increases because minimum numbers of LUT iterations are being multiplied with input signal. As we increase the LUT coefficients the leakage offset power start to get improved. It can be seen that the performances of LUTs having 480, 960, 1920 coefficients are very much similar; as amplifier output leakage offset power hasn't being changed dramatically by increasing the LUT coefficient complexity to maximum level (1920 coefficients), so power amplifier with 480 LUT coefficients gives the optimal performance.

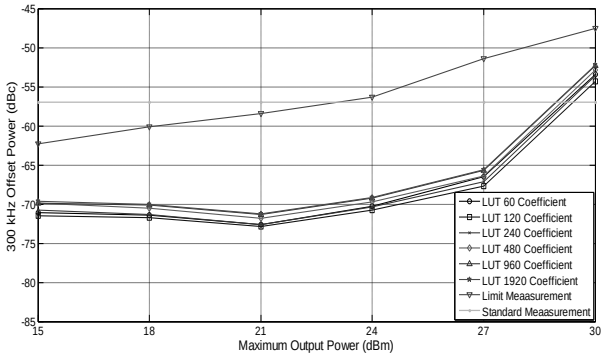


Fig- 8: Simulated output powers at 300 kHz offsets with variable LUT coefficients

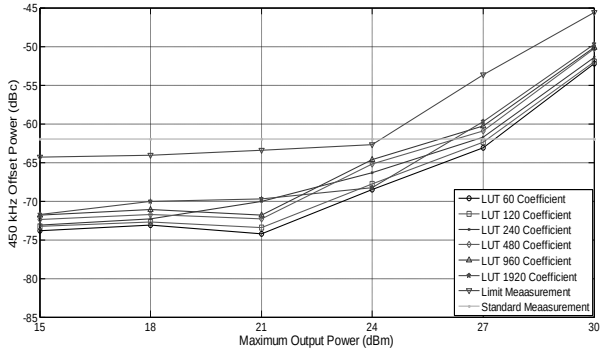


Fig- 9: Simulated output powers at 450 kHz offsets with variable LUT coefficients

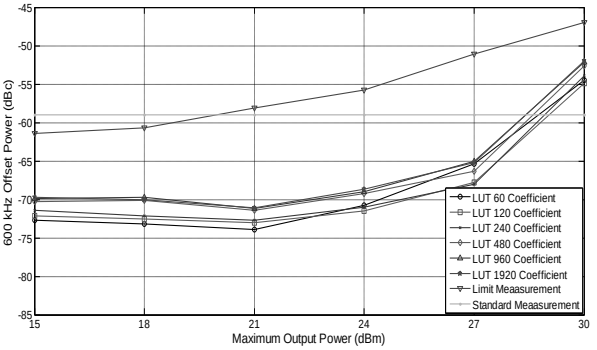


Fig- 10: Simulated output powers at 600 kHz offsets with variable LUT coefficients

Furthermore the performance characteristics at 300 kHz and 600 kHz are very much identical in terms of leakage offset power. However for the 450 kHz offset power, there is more linearized relationship between standard measurement and limit measurement offset power, and maximum output power (dBm) is also improved from standard 25dBm to 27.5dBm.

4.2 Error Vector Magnitude Factor

The simulation results without and with DP factor related to EVM are compared in Fig-11. For EVM factor calculation 27.5 dBm PA output spectrum is used. At 27.5dBm output power, EV*M* factor is reduced from 4.2% to 3.6%. As per specifications EVM_{RMS} values should not exceed 9%, which are successfully achieved with in proposed system even without DP.

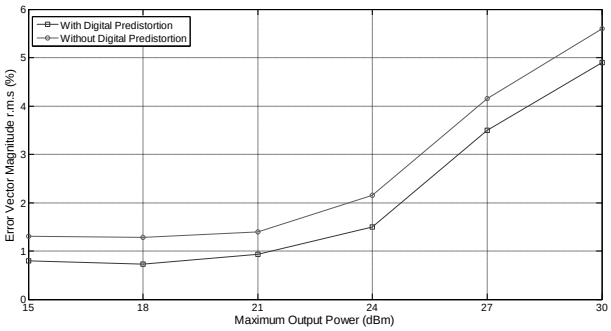


Fig -11: Simulated EVM_{RMS} with and without Digital Predistortion

5. CONCLUSION

In this work we have proposed a LUT based MDP system for 2nd to 3rd generation cellular applications. For the validation of results proposed model algorithm is applied to base station. Currently in handsets applications, 3rd or 5th order intermediation predistortion model is implemented which consider linearity compensation for leakage power traditionally at low frequency offset (200 kHz) which is not critical.

In this work, leakage power at different critical offset frequencies (300 kHz, 450 kHz 600 kHz) have been simulated and analyzed. With these specifications LUT size and coefficient complexity have been investigated. From simulation results it can be analyzed that 450 kHz offset power with 480 LUT coefficients gives best optimal results because any further increase in LUT coefficients have no significant improvement in the performance of digital predistortion. On the other hand with lower LUT coefficients leakage power increases accordingly and system performance gets worse. With proposed system model, once linearization is meeting, the amplifier linear output power improves linearly from 25dBm to 27.5dBm by a margin of 2.5 dBm.

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