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Digital Pre-distortion of Power Amplifiers using look-Up Table Method with Memory Effects

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Abstract
Digital pre-distortion techniques are widely used in linearization of RF power amplifiers. Due to frequency dependence of thermal constants of the active devices or components in the biasing network, power Amplifiers also exhibits memory effects. Thus digital pre-distortion technique should also be able to suppress these memory effects. In this paper Look-Up Table (LUT) type Adaptive Digital pre-Distortion (ADPD) is presented. In this algorithm, an output signal of the Power Amplifier (PA) is used as reference signal. This reference signal is used to update the coefficients of the LUT, so that characteristics of the PA, such as temperature dependence, do not have influence on the convergence performances. Simulation results have been presented.

Key Words: *Coordinate Rotation Digital Computer (CORDIC), Digital pre-distortion (DPD), Error Vector Magnitude (EVM), Look Up Table (LUT), Power Amplifier (PA).*

1. Introduction
Power amplifiers are mainly present in the transmitters, and are designed to raise the power level of the signal before passing it to the antenna. This power boost is crucial to achieve the desired signal to noise ratio at the receiver, and without which received signals would not be detectable. For the power amplifier it is necessary to have as high gain as possible, while adding as little distortion to the signal as possible i.e. be as linear as possible. For small and mobile transmitters there is usually another factor not less important; that is power efficiency since these devices are usually battery driven. Unfortunately, from a circuit design point of view, increasing the power efficiency would mean driving the device more and more into nonlinearity region which means that the amount of distortion will increase. The reason why the linearity is so important is the varying signal envelopes in spectrum efficient modulation types used in new generation mobile communication systems. If signals have constant envelopes like in FM (Frequency Modulation) or GMSK (Gaussian Minimum Shift Keying) then PA linearity is not an important issue because the instantaneous input power stays constant and therefore there are no gain and phase variations for a specific operation point. However, newer transmission formats, such as wideband code division multiple access (WCDMA) and orthogonal frequency division multiplexing (OFDM) used in 3G communication systems, the envelope of the signal continuously varies and hence the instantaneous input power changes continuously. As a result the signal at the PA output contains inter-modulation products, if the amplifier gain and phase response are not linear. Inter-modulation products interfere with adjacent and alternate channels and affects the Error vector magnitude (EVM) defined as the distance between the desired and actual signal vectors (error vector),normalized to a fraction of the signal amplitude.

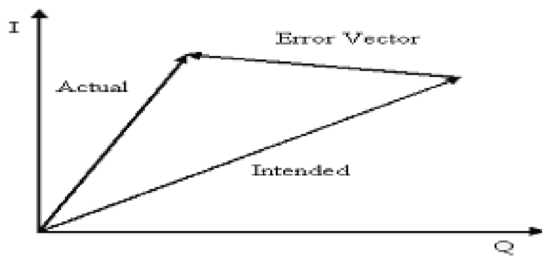

Figure 1: Error Vector Magnitude

Mathematically, the error vector can be written as

$$e = y - x \qquad (1)$$

Where y the modified is measured signal and x is the ideal transmitted signal. EVM can be defined as

$$EVM_{rms} = \sqrt{\frac{E\left[e^2\right]}{E\left[x^2\right]}} \qquad (2)$$

EVM level is strictly limited by FCC regulations [1]. To reduce the nonlinearity, the power amplifier can be backed off to operate within the linear portion of its operating curve. However signals like WCDMA and OFDM have high peak to average power ratios, i.e., large fluctuations in their signal envelopes. This means that the power amplifier needs to be backed off far from its saturation point, which results in very low efficiencies, typically less than 10%; i.e., more than 90% of the dc power is lost and turns into heat. Considering the large number of wireless base stations deployed worldwide, improved power amplifier efficiency can substantially reduce the electricity and cooling costs incurred to the service providers. To maintain linearity and power efficiency, one can apply linearization to the Power Amplifier (PA) through several techniques such as feed forward, feedback and more recently, digital pre-distortion (PD). Digital baseband implementations show higher efficiency at lower cost with greater pre-distortion bandwidth than traditional feed-forward techniques. Compared to feed forward linearization techniques, designs based on digital PD are showing higher efficiency at lower cost, and with recent advances in technology. The adaptation of wideband PD algorithms, such as least-mean squares (LMS) [2], requires sampling minimally 5 times the original signal bandwidth to accurately correct 3rd and 5th order intermodulation products or IMD3 and IMD5 respectively. For such implementations, system cost is largely driven by the high-performance analog-to-digital converters (ADC) in the feedback path. Less costly alternatives have been proposed which utilize only narrowband feedback to adapt the PD [3] thus reducing the cost of the ADCs.
The paper is organized as follows. Section 1 is an introduction. Section 2 presents linearization fundamentals emphasizing a digital pre-distortion technique. Section 3 introduces the architecture of proposed pre-distorter. Section 4 presents simulation results. A summary is given in section 5.

2. Linearization Fundamentals

In this section, we present some fundamental principles of digital pre-distortion, particularly the methods used to linearize a PA. Current linearization techniques employ feed-forward pre-distortion to meet EVM requirements. Technology advances have made it possible to use digital feedback **as** an alternate technique providing higher efficiency at a lower cost. Figure 2 shows an example of Feed-forward Technique to linearize a Power Amplifier.

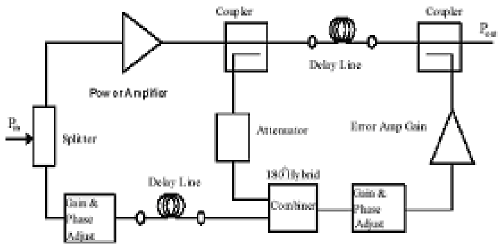

Figure 2: Illustration of Feedforward Technique to Linearize Power Amplifier

In the feedforward system the power amplifier is fed directly with the RF source signal. The delayed sample of the undistorted input RF signal is compared with an attenuated sample of the power amplifier output. The error signal is then amplified linearly to the required level and is recombined with the output, following a delay line in the main signal path, which compensates for the delay in the error amplifier. The error signal cancels the distortion present in the main path leaving an amplified version of the original signal. The distortion generated by the power amplifier is cancelled in the feedforward loop by subtracting the source signal from the power amplifier output. The resulting error signal is subtracted from the amplifier output RF components. Additionally, it does not require a phase-locked loop to maintain phase correction. The advantage of feedforward technique is the bandwidth is determined by frequency response of the couplers, delay lines, and phase shift components, which can be made to be very stable over a wide operating range [4][5]. The disadvantages are need for error amplifier which will be of a similar size as the main amplifier. Delay line in forward path needs to be rated for output power. Another method of reducing amplifier distortion is by some form of feedback. The Figure 3 illustrates the use of negative feedback around an amplifier with the effect of distortion $n(t)$, G is the gain of the amplifier and K is the feedback attenuation.

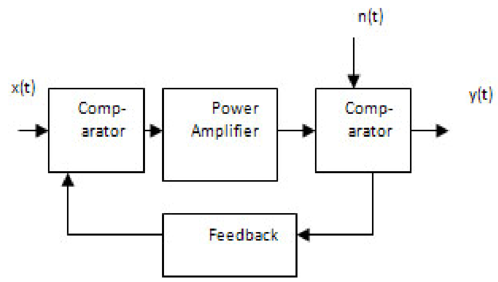

Figure 3: Illustration of Simple Feedback to linearize Power Amplifiers

Output: $y(t) = G.e(t) + n(t)$ (3)

Feedback: $f(t) = Ky(t)$ (4)

Error: $e(t) = x(t) - f(t)$ (5)

Therefore,

$$y(t) = (G.x(t) + n(t)) / (G + K) \qquad (6)$$

If the amplifier gain is much greater than the feedback ratio $G >> K$, then $K + G$ approximates to G . So

$$y(t) = K.x(t) + K.n(t) / G \qquad (7)$$

Therefore, the distortion produced by the main amplifier is reduced by a factor K / G. The disadvantage of this approach is that the improvement in distortion performance is at the expense of the gain of the power amplifier and also feedback needs more bandwidth than signal.
The digital pre-distortion method uses digital processing to synthesize the inverse transfer characteristic of a power amplifier. The digital pre-distortion is generally performed at baseband. The distorted baseband signal is translated to a convenient intermediate frequency (IF) and then the RF signal is generated by mixing the IF with a LO. An alternative to generating IF frequency is a direct conversion to RF signal using an Analog Quadrature Modulator (AQM). The digital pre-distortion parameters are stored in a look-up table or register table which can be updated with adaptive feedback. The pre-distortion scheme works on the orthogonal I and Q components of the input and the feedback signals, thus providing both Look-up table and register table which can be updated with adaptive feedback.

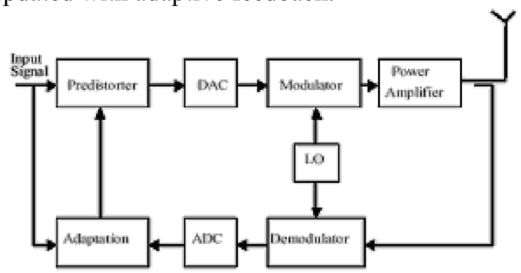

Figure 4: Basic steps of Pre-distortion

The pre-distortion scheme works on the orthogonal I and Q components of the input and the feedback signals, thus providing both amplitude and phase correction (see Figure 4). Furthermore, since the power amplifier's non-linearity is a function of power, frequency, temperature and aging the look-up tables must updated continuously, otherwise there will be degradation in IMD performance and these appear as interferers in the adjacent channels. The main advantages of this approach is that the correction is applied before the power amplifier where insertion loss is less critical and significant IMD reduction is achieved over a wide signal bandwidth.
To compensate for the amplifiers' nonlinearity, different linearization techniques are employed (shown in Table 1). Although feed-forward technique is commonly used today, digital pre-distortion (DPD) is better suited for 3G systems since it offers higher efficiency and greater flexibility at a lower cost.

Table 1: Comparison of different linearization Techniques

Technique	Correction *(1)*	Bandwidth *(2)*	Efficiency	Flexibility *(3)*	Cost
In-line Predistortion	2 to 3 dB	15 to 25 MHz	5 to 8%	Low	Very Low
Analog Predistortion	3 to 5 dB	15 to 25 MHz	5 to 8%	Low	Low
Cross-Cancellation	15 to 20 dB	10 to 20 MHz	10 to 12%	Medium	Medium
Feed-Forward	30 dB	25 to 60 MHz	6 to 10%	Medium	High
Digital Predistortion	15 to 20 dB	15 to 20 MHz	12 to 14%	High	Medium

There has been intensive research on pre-distortion techniques for memory less power amplifiers during the past decade. As the signal bandwidth gets wider, such as in WCDMA, power amplifiers begin to exhibit memory effects. This is especially true for those high power amplifiers used in wireless base stations. The causes of the memory effects can be attributed to thermal constants of the active devices or components in the biasing network that have frequency dependent behaviors. As a result, the current output of the power amplifier depends not only on the current input, but also on past input values. In other words, the power amplifier becomes a nonlinear system with memory. For such a power amplifier, memory less pre-distortion can achieve only very limited linearization performance. Therefore, there is need to design a robust pre-distorter model that is capable of linearizing power amplifiers with memory effects.

3. Pre-distorter Architecture

Pre-distortion requires the insertion of a nonlinear module before the RF power amplifier. The nonlinear module, called the pre-distorter, has the inverse response of the PA so the overall response at the output of the PA is linear. Adaptive digital pre-distortion involves the digital implementation of the pre-distorter and presence of a feedback loop adapting to the changes in the response of the PA due to varying operating conditions. The correction error functions computed using the adaptation algorithm are stored in a look-up table (LUT), and are dynamically updated to reduce errors between the pre-distorter input and the PA output. Figure 5 shows the simplified block diagram of the digital pre-distortion technique used in this paper. The proposed pre-distorter requires two; one-dimensional look up tables to store the polar coordinates.
The polar LUT table method also requires polar to rectangular (P/R) and rectangular to polar (R/P) conversions, which are carried out using CORDIC

algorithm. The complex envelope of the input (V_a) and the output (V_{pa}) of the power amplifier are related by

$$V_{pa} = V_a.(G|V_a|^2) \tag{8}$$

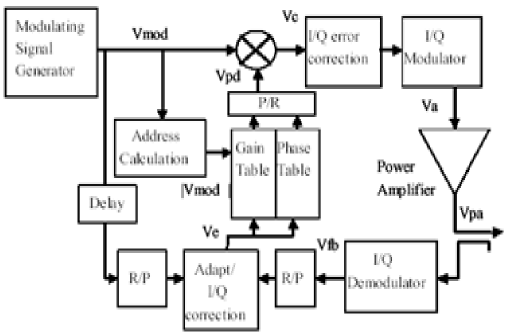

Figure 5: Digital Pre-distortion using gain and phase indexing of Look-Up Tables.

where $(G|V_a|^2)$ is the complex gain of the amplifier, and represents its AM/AM and AM/PM characteristics and is the pre-distorted signal [6].

The IQ table contains complex gain factors (see Figure 4) represented as,

$$V_e = F\{\mathrm{Re}(V_e), \mathrm{Im}(V_e)\} \tag{9}$$

The gain function from the look-up table is multiplied with modulated input signal. The resulting complex quantity based on the envelope of the input signal and is derived as

$$V_c(t) = V_{\mathrm{mod}}(t) * F\left\{|V_{\mathrm{mod}}(t)|^2\right\} \tag{10}$$

Where $F\left\{|V_{\mathrm{mod}}(t)|^2\right\}$ represents the inverse transfer characteristics of the power amplifier.

Also, $V_c(t) = V_{\mathrm{mod}}(t) * V_{pd}(t)$ (11)

The polar table can be represented as:

$$V_e = F\{\mathrm{R}(V_e), \phi(V_e)\} \tag{12}$$

Where $\mathrm{R}(V_e)$ and $\phi(V_e)$ represents gain and phase error respectively.

In order to generate $V_c(t)$, the output from the polar table is converted back to IQ representation using CORDIC algorithm. Therefore, the gain function obtained after polar to rectangular conversion from polar tables is identical to the gain function in IQ representation look-up table. This gain function is multiplied with modulated input signal.

Assuming a perfect modulator $V_c = V_a$, we can write,

$$V_a(t) = V_{\mathrm{mod}}(t) * V_{pd}(t) \tag{13}$$

The look-up table is updated on continuous basis. The input $V_{\mathrm{mod}}(t)$ is delayed to align with feedback $V_{fb}(t)$ from the power amplifier and the resulting difference, $V_{error}(t)$, which only contain the distortion is computed on sample by sample basis.

$$V_{error}(t) = V_{\mathrm{mod}}(t) - V_{fb}(t) \tag{14}$$

There are various adaptation techniques described in the literature for of look-up table entries, such as linear convergence, secant method, rotate and scale, and steepest decent method. The method of adaptation selected determines the speed of convergence, stability of the system and computation load on the DSP. The rotate and scale method of adaptation is used and equation 14 is used to calculate gain and phase error. Figure 3 shows the 3-D plot of the gain and phase look up table entries.

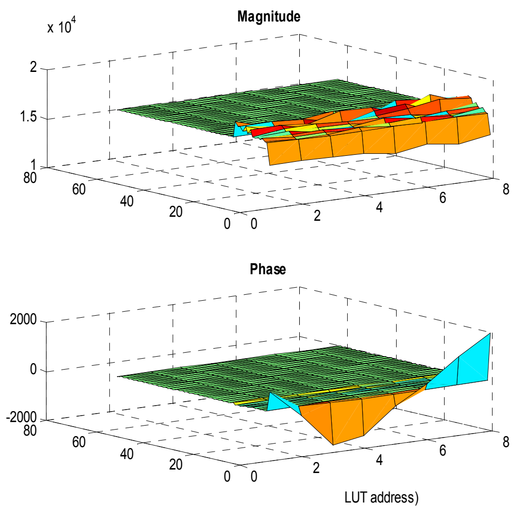

Figure 6: Gain and phase entries for Look-Up Tables.

4. Simulation Results

MATLAB and C++ are used to implement the pre-distorter architecture. Simulations are carried out and figure 7 and 8 show the performance of proposed pre-distorter. Figure 7 shows the calculation of magnitude and phase error and the results show that the average value of 3rd order IMD falls from -192.331 dB to -167.928 dB and the average value of 5th order IMD falls from -192.181 dB to -165.987 dB. Figure 8 shows the performance of proposed ADPD algorithm in suppressing the spectral regrowth. Results also show reduction of EVM from 10.715% to 10.1720% ie. a decrease of about 5.390% is noticed.

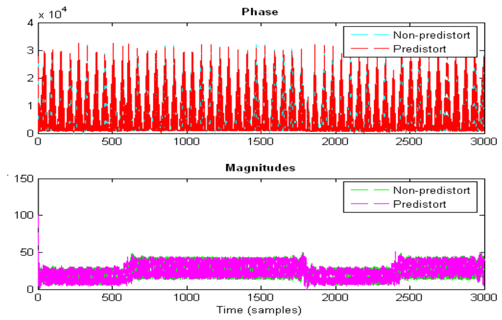

Figure7: Magnitude and phase errors with and without pre-distortion

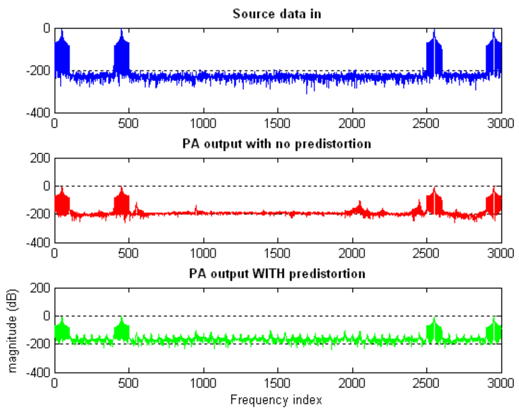

Figure 8: Pre-distorter Performance in suppressing spectral regrowth. Output without Pre-distortion and (2) Output with Pre-distortion.

5. Conclusions

The adaptive digital pre-distortion method is the most suitable in terms of bandwidth, correction achievable and complexity for the power amplifier linearization. A simulation of the adaptive digital pre-distorter with memory effects has been presented and shown to provide a significant improvement in the IMD performance of a power amplifier. Analysis of the simulated results shows that the pre-distorter has remarkable effect on the IMD performance of the power amplifier with memory effects. The algorithm is straightforward and robust.

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