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Mitigation of Non-Linear Impairments of W-CDMA Power Amplifier

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ABSTRACT

In this paper a non-linear Power Amplifier (PA) with memory effects is modeled and a Digital pre-Distortion algorithm is presented to mitigate non-linearity effects of a power amplifier. Look-Up Table approach is used to design the pre-distorter. Designs also take care of temperature dependence and memory effects of power amplifier. Simulation results have been presented.

Keywords: Digital Pre-distortion, Error Vector Magnitude, Look- Up Table, Power Amplifier

1. INTRODUCTION

The reason why the linearity of power amplifier is so important is the varying signal envelopes in spectrum efficient modulation types used in new generation mobile communication systems. If the signal envelope varies, then 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. An inter-modulation product interfere with adjacent and alternate channels and affects the Error vector magnitude (EVM) defined as the distance between the desired and actual signal vectors, normalized to a fraction of the signal amplitude and its level is strictly limited by FCC regulations [1].

To reduce the nonlinearity, the PA can be backed off to operate within the linear portion of its operating curve. However, newer transmission formats, such as wideband code division multiple access (WCDMA) and orthogonal frequency division multiplexing (OFDM), have high peak to average power ratios, i.e., large fluctuations in their signal envelopes. This means that the PA needs to be backed off far from its saturation point, which results in very low efficiencies, typically less than 10. Considering the large number of wireless base stations deployed worldwide, improved PA efficiency can substantially reduce the electricity and cooling costs incurred to the service providers. To improve the PA efficiency without compromising its linearity, PA linearization is essential. Among all linearization techniques, digital pre-distortion (DPD) is one of the most cost effective.

Most researchers approach the problem of PA linearization by first finding a good model for the PA. Volterra series is a general nonlinear model with memory [2] and has been used to model PAs with mild nonlinearities [3]. A serious drawback of the Volterra model is the large number of coefficients that must be extracted. One special case of Volterra model is the memory polynomial model proposed by Kim [4]. Similar to the Volterra model, an exact inverse of the memory polynomial is difficult to obtain, but another memory polynomial can be constructed as an approximate inverse. A variety of other PA models exist and it is difficult to judge which PA model is the best, since it could depend on the type of the PA, the data format being transmitted, etc [5]. In this paper our aim is not only to find a DPD model to approximate the inverse of the PA nonlinearity but also to model a easier to implement PA with memory effects, in the sense that parameter extraction and system implementation are straightforward and the pre-distorter model is robust.

2. MATHEMATICAL MODEL OF POWER AMPLIFIER

There has been intensive research on pre-distortion (PD) techniques for memory less PAs during the past decade. As the signal bandwidth gets wider, PA begins 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 PA depends not only on the current input, but also on past input values. In other words, the PA becomes a nonlinear system with memory. For such a PA, memory less PD can achieve only very limited linearization performance. Therefore, there is need to develop a straight forward and easy to implement mathematical model of PA with memory effects.

Nonlinear signal processing algorithms have been growing in interest in recent years [6- 9]. The Volterra model can be used to describe any nonlinear stable system with fading memory, with an arbitrary small error. However, its main disadvantages are the dramatic increase in the number of parameters with respect to nonlinear order and memory length, which causes drastic increase of complexity in the identification of parameters. This is the reason why it is highly unpractical to use volterra series for systems with high nonlinear orders and memory lengths. This model can be expressed mathematically as

$$y(n) = h_0 + \sum_{k_1=0}^{\infty} h_1(k_1)x(n-k_1) + \sum_{k_1=0}^{\infty}\sum_{k_2=0}^{\infty} h_2(k_1,k_2)x(n-k_1)x(n-k_2) + \\ ....+ \sum_{k_1=0}^{\infty}....\sum_{kp=0}^{\infty} h_2(k_1,....k_p)x(n-k_1)....x(n-k_p)+.... \tag{1}$$

Where h_0 is a constant and $\{h_j(k_1,....k_p)\ 1 \le j \le \infty\}$ is the set of jth-order Volterra kernel coefficients. Unlike the case of linear systems, it is difficult to characterize the nonlinear Volterra system by the system's unit impulse response. And as the order of the polynomial increases, the number of Volterra parameters increases rapidly, thus making the computational complexity extremely high. For simplicity, the truncated Volterra Series is most often considered in literature. The M-sample memory pth-order truncated Volterra Series expansion is expressed as:

$$y(n) = h_0 + \sum_{k_1=0}^{M-1} h_1(k_1)x(n-k_1) + \sum_{k_1=0}^{M-1}\sum_{k_2=0}^{M-1} h_2(k_1,k_2)x(n-k_1)x(n-k_2) + \\ ....+ \sum_{k_1=0}^{M-1}....\sum_{kp=0}^{M-1} h_2(k_1,....k_p)x(n-k_1)....x(n-k_p)+.... \tag{2}$$

There are several approaches to reducing the complexity. One approach is the basis product approximation [10-13], which represents the Volterra filter kernel as a linear combination of the product of some basis vectors to attempt to reduce the implementation and estimation complexity to that of the linear problem. Using the Volterra series, two major models have been developed to perform nonlinear signal processing. The first model is the nonorthogonal model and is the most commonly used. It is directly based on the Volterra series called the Volterra model. The advantage of the Volterra model is that there is little or no preprocessing needed before the adaptation. But because of the statistically nonorthogonal nature of the Volterra space spanned by the Volterra series components, it is necessary to perform the Gram-Schmidt/modified Gram-Schmidt procedure is crucial especially for the nonlinear LMS-type algorithms and also for the nonlinear RLS-type recursive Volterra adaptive algorithms. The second model is the orthogonal model. In contrast to the Gram- Schmidt procedure, the idea here is to use some orthonormal bases or orthogonal polynomials to represent the Volterra series. The benefit of the orthogonal model is obvious when LMS-type adaptive algorithms are applied.

Due to difficulty in the measurement of Volterra kernels and large eigenvalue spread issue which implies slow convergence speed and large misadjustment, especially for the LMS-type adaptive algorithm, alternative mathematical descriptions for nonlinear systems with memory are of interest. One such description is an alternative form of Volterra system called the nonlinear Wiener model. Wiener model consists of a linear time invariant (LTI) system followed by memory less nonlinearity as illustrated in Figure 1.

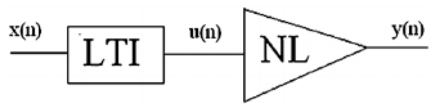

Figure 1: Wiener Model

The AM/AM conversion for a nonlinear system is the relation between the amplitude of the system's output and the amplitude of the system's input. The AM/PM conversion for a nonlinear system is the relation between the phase change of the system's input and output, and the amplitude of the input signal. The memory less AM/AM and AM/PM models of the PA proposed by [14] is:

$$A(r(t)) = \frac{\alpha_a r(t)}{1+\beta_a r^2(t)} \tag{3}$$

$$\phi(r(t)) = \frac{\alpha_\phi r(t)}{1+\beta_\phi r^2(t)} \tag{4}$$

The optimal parameters and mean-squared error for Saleh's model are reported as

$$\alpha_a = 2.1587;\ \beta_a = 1.1517;\ \alpha_\phi = 4.0033;\ \beta_\phi = 9.104. \tag{5}$$

As mentioned above Volterra series is unpractical for modeling power amplifiers in real time applications. This reason motivated researchers to investigate special cases of Volterra series. The memory polynomial model, [15] is a truncation of the general Volterra series, which consists of only the diagonal terms in the Volterra kernels. Thus, the number of parameters is significantly reduced compared to general Volterra series. Mathematically memory part of polynomial model can be represented as

$$Y(n) = \sum_{q=0}^{Q}\sum_{k=0}^{K} C_{(2q+1)k} * Z(n-q)\left|Z(n-q)\right|^{2k} \tag{6}$$

Where k = number of Volterra coefficients and q = size of memory.

If q = 0, the system described by (6) reduces to a memory less nonlinear system. Because all practical PA's shows memory effects.

But in our work a modified and easy to implement model, given by (7) is used, which is slight modification of (6).

$$y(n) = \sum_{q=0}^{Q}\sum_{k=0}^{K} C_{(2q+1)k} * Z(n-q)^{2k+1} \quad (7)$$

In our design we have selected $k = 2$ i.e. only 1st, 3rd and 5th terms are considered and $q = 2$ i.e. only previous two inputs are considered. In its expanded form (7) can be written as

$$\begin{aligned} Y(n) &= c_{10}z(n) + c_{11}z(n-1) + c_{12}z(n-2) \\ &+ c_{30}z(n)^3 + c_{31}z(n-1)^3 + c_{32}z(n-2)^3 \\ &+ c_{50}z(n)^5 + c_{51}z(n-1)^5 + c_{52}z(n-2)^5 \end{aligned} \quad (8)$$

(8) is implemented using the minimum-multiplier direct-form realization as shown in Figure 2.

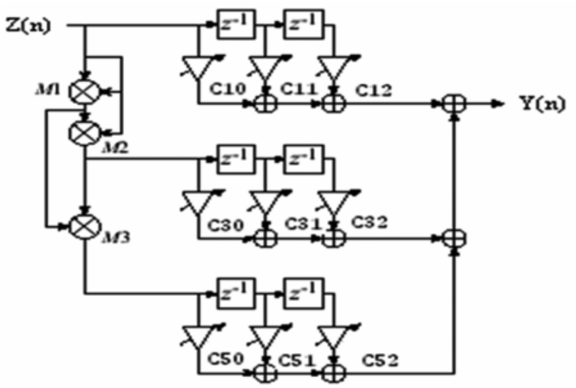

Figure 2: Direct form Realization of the Modified Memory Polynomial

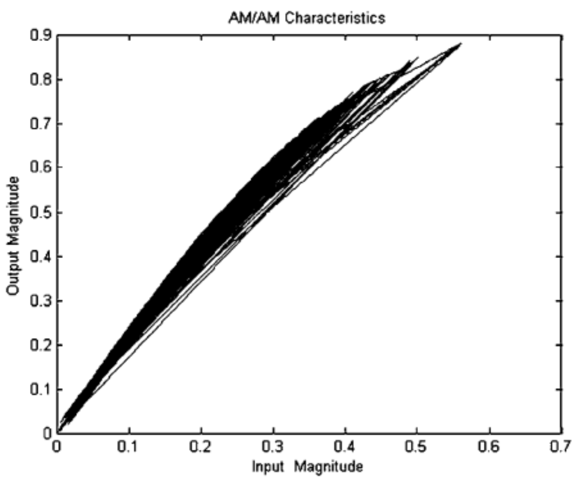

Figure 3: AM-AM Characteristics of the PA Model

The coefficients

c_{10} = 1.0513 + j0.0904

c_{30} = -0.0542 + j0.2900

c_{50} = -0.9657 - j0.7028

c_{11} = -0.0680 - j0.0023

c_{31} = 0.2234 + j0.2317

c_{51} = -0.2451 - j0.3735

c_{12} = 0.0289 - j0.0054

c_{32} = -0.0621 - j0.0932

c_{52} = 0.1229 + j0.1508 (9)

are extracted from the PA.

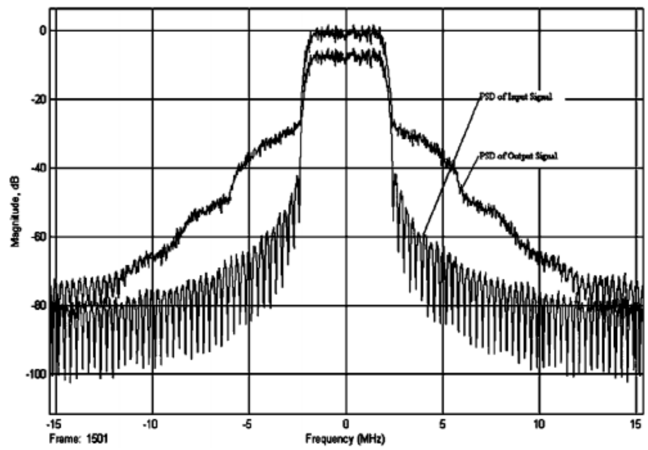

Figure 4: Power Spectral Density of Input and Output Signal

Figure 3 shows the AM-AM characteristics of the Power Amplifier and Figure 4 show the Power spectral density of input and output signal of the Power Amplifier. Memory effects can be seen very clearly in the diagrams.

3. PRE-DISTORTER ARCHITECTURE

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.

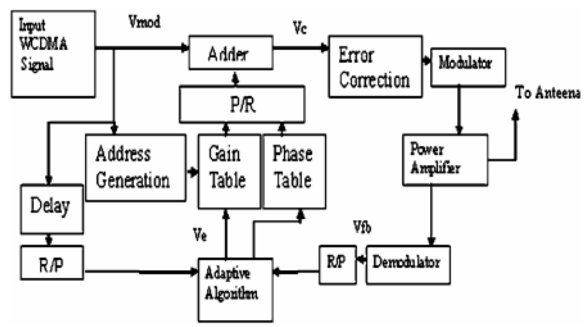

Figure 5: Block Diagram of Adaptive Digital Pre-distorter

Using gain and phase indexing of Look-Up Tables, the polar LUT table method requires polar to rectangular (P/R) and rectangular to polar (R/P) conversions, which are carried out using CORDIC algorithm.

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

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

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

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

The polar table can be represented as:

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

Where $R(V_e)$ and $\phi(V_e)$ represents gain and phase errors respectively.

In order to generate $V_c(t)$ the output from the polar table is converted back to IQ representation. 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,

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

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

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

4. SIMULATION RESULTS

Simulations were carried out using MATLAB and C++. Figure 6 show the performance of proposed pre-distorter in terms of magnitude and phase error.

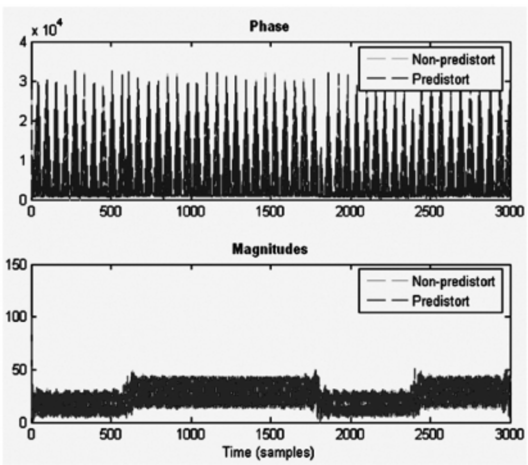

Figure 6: Magnitude and Phase Errors with and Without Pre-distortion

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.

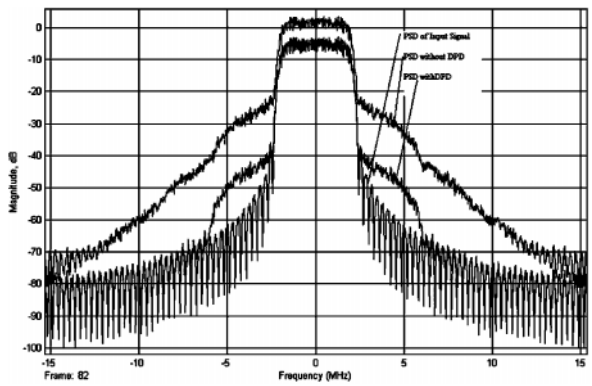

Figure 7: Performance of Pre-distorter in Suppressing Spectral Regrowth

Figure 7 show 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.

5. CONCLUSIONS

Memory effects of power amplifier is modeled using a truncated volterra series based memory polynomial function. Look up table based Adaptive Digital Pre-distorter model architecture is presented to model the inverse characteristics of the Power Amplifier. The gain and phase values of look-up tables are used to implement the pre-distortion function. The simulation results show performance of digital pre-distorter in improving the linearity of power amplifier.

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