Applying Digital Predistortion To Power Amplifiers Used in Third Generation Systems

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Efficient RF power amplifiers used in third generation systems (like wide-band WCDMA systems) require linearization in order to reduce adjacent channel inter-modulation distortion, without sacrificing efficiency. This paper presents a new adaptive digital base-band predistortion system based on look-up table (LUT) called the slope-dependent method, and compares it with the direct linear-LUT used by Cavers, by analysing their performance and convergence time when applied to a wide band signal (like W-CDMA) input.

INTRODUCTION

Spectrally efficient linear modulation techniques are used in the third generation systems such as the wide-band CDMA (W-CDMA) systems. Their performance is strongly dependent on the linearity of the transmission system. Also, the efficiency of the amplifier to be used has to be maximized; which means that it must work near saturation. The application of linear and efficient modulation technique with a fluctuating envelop to an efficient amplifier working near saturation introduces in-band distortions and spectrum spreading into adjacent channels.

A number of linearization techniques have been reported in recent years. Many of them suffer from limitations in bandwidth, precision or stability. One technique that can potentially compensate for power amplifier (PA) nonlinearities in such an environment is the adaptive digital predistortion technique. The concept is based on inserting a non-linear function (the inverse function of the amplifier) between the input signal and the amplifier to produce a linear output.

In this paper, the adaptive base-band predistortion technique based on LUT is firstly described. A new method of adaptation, called the slope-dependent is then introduced and compared with the direct method presented by Cavers (2) concerning their time of convergence and the residual error after convergence. Results (through simulations) of applying the proposed predistortion system applied to a wide band W-CDMA signal are shown with some conclusions. It is supposed that the power amplifier nonlinearities are memory-less.

PRINCIPLE OF THE ADAPTIVE BASE-BAND DIGITAL PREDISTORTION TECHNIQUE

The key components of the adaptive base-band digital predistorter system are shown in figure (1). The predistorter (P.D.) is implemented as a gain function (F) which is stored in the form of a look-up table (LUT) in rectangular form. The magnitude of the input signal (V_m) is quantized into (M levels) and is used as the address of the look-up table (LUT) . The predistorted signal (V_d) is the product of this gain function (F) and the input signal (V_m).

The adaptation of the predistorter is based on the error signal, which comes from subtracting the target signal [K. V_m], (where K is the target gain through the (P.D.) and the power amplifier), from the power amplifier's output signal (in a base-band form) during a specific iteration. The error signal is processed, and then is used to update the look-up table.

The following equations describe the important relationships depicted in the block diagram.

P.D. : $$V_d = V_m F(|V_m|) \quad (1)$$

P.A. output with P.D .: $$V_o = V_d G(V_d) \quad (2)$$

Where, V_m, V_d, and V_o, are the complex input, predistorted, and output signals, respectively. The values designated as (G) and (F) depict the complex voltage gains of the PA and predistorter, respectively, at a specific level. The forward path transfer function for the optimised predistorter is expressed by Cavers (2) as:

$$F_o(|V_m|) \times G(|V_m F_0(|V_m|)|) \tag{3}$$

When the predistortion is optimised, the value of the gain given in (3) should be constant and equal to the ideal gain through the linearizer and the power amplifier (K).

i.e. $$K = F_o(|V_m|) \times G(|V_m F_0(|V_m|)|) \tag{4}$$

Since equation (4) is highly non-linear and a closed-form solution is not possible, the problem can be solved iteratively by minimizing a L.S. criterion (J);

$$J = \sum |V_e(n)|^2 \tag{5}$$

Where the error function is given by:

$$V_e(n) = V_o(n) - K.\, V_m(n) \tag{6}$$

ALGORITHMS OF ADAPTATION

The need for the predistorter to dynamically adapt to changing system characteristics arises when either the signal characteristics or the P.A. characteristics (e.g. as a function of temperature and time) change. Two methods are evaluated and compared for the adaptation as shown in the next sections. The first is called the slope-dependent , which is suggested in this paper. The second is the well-known direct convergence method suggested by Cavers (2).

The Slope-dependent Method:

This is a simplified stochastic gradient adaptation algorithm. The motivation for this choice is its simplicity in implementation especially when dealing with high rate systems such as W-CDMA. It is based (as it's name indicates) on the slope of the P.A. characteristics shown in figure (2). It will be denoted in this paper as (b).

Applying the criterion of (5) to the proposed system yields the following iteration for updating the table at a certain level of input magnitude,

$$F(i+1) = F(i) - a\ .V_e(i) \tag{7}$$

Where, $F(i)$ denotes the ith. iteration of the table entry, and $Ve(i)$ denote the error signal.

When the complex input (V_m), is applied to the predistorter, the following sequence can be found;

$$F(i) = V_m(0) + i\,a\left(KV_m(0)\right) - a\sum_{j=0}^{i-1} V_o(j) \tag{8}$$

where $V_m(0)$ refers to initial value of V_m.

Similarly the successive values of the amplifier output can be found. Assuming the amplifier is linear in the vicinity of a certain magnitude with slope (b), which is a function of input magnitude, and using alimited approximation of order-1, the following equation can be found;

$$V_o(i) = KV_m(i) + V_e(0)\left(1 - \frac{a\,b}{K}\right)^i \tag{9}$$

In the limit, this system is convergent if the following condition is satisfied;

$$0 \le |1 - a.b| \le 1 \tag{10}$$

which can be written (if both a, b are positive) as;

$$a \le \frac{2}{b} \tag{11}$$

The slope of the power amplifier characteristics (b) is not constant; and at the start of the adaptation we could be operating around one region while at the end of adaptation we might be operating around another. Therefore, (a) has to be variable and for simplicity it can be considered to be constant and is taken as the maximum slope of the curve.

We have found by experiments and simulations (see following section) that a value of ($a = 0.1$) is a good choice.

Direct Adaptation Method, and Comparison With The Proposed Method:

This method had been described and used by Cavers (2). Based on equations (1-3), a root (F_o) of equation (4) is found by the method of successive substitution, for which an iteration for a certain magnitude is;

$$F(i+1) = \frac{K}{G(|V_m| \times |F(i)|)} \tag{12}$$

After some manipulations, the system converge to (F_o) if;

$$2.K|V_m|\frac{|G_o'||F_o|}{|G_o|^2}<.1 \qquad (13)$$

where G_o, G_o' denote the amplifier characteristics corresponding to (F_o), and its derivative, respectively.

Equation (12) leads to the following adaptation equation,

$$F(i+1)=F(i)-\frac{F(i)}{V_o(i)}.V_e(i) \qquad (14)$$

Comparing equation (14) to equation (7), one can prove that the two have similar forms if we consider :

$$\frac{F(i)}{V_o(i)}=a\ .$$

EXPERIMENTS AND RESULTS

Extensive simulation experiments have been performed using the AGILENT ADS software system. The power amplifier used is a built-in memory-less behavioural model , with an input-output characteristics shown in figure (2). The tests are done with the amplifier working at a 1-dB power back-off (PBO). All simulations are performed in base-band.

The tested signal is a wide-band W-CDMA signal of (2GHz) carrier frequency with a chip rate of 3.84 Mcps, and a band-width of (5 MHz).

One of the important task in designing the look-up table is how to calculate its address. Cavers (4) has shown that if the input is Gaussian then the best LUT address spacing is linear. Therefore, the linear spacing has been applied in our simulation.

Figure (3) shows the power spectral density of the input signal (W-CDMA) to the power amplifier and its corresponding output without predistortion (upper), and the output when applying the predistorter. From this figure, it can be shown that a (20 dB) improvement in spectral re-growth at both sides of the spectrum was achieved for the 5-MHz bandwidth W-CDMA signal using the proposed method .

In order to measure the convergence time of the adaptation methods mentioned in the previous section, the simulation is conducted by running the simulation until a certain level is reached. It is called the percentage relative mean square error and is defined as follows,

$$\mathrm{Re}lative\_error=\frac{\sum(error)^2}{InputPower*K}*100\% \qquad (15)$$

Since this error will be decreasing in average with time owing to the adaptation of the system, the point where this error reaches 5% as a percentage is taken as the reference point for the convergence time for a particular adaptation algorithm employed. Both tested methods are very close to each other concerning the time of convergence with better performance for the (slope-dependent method) as shown in table (1). Various values of (a) for a table size of (M=64) were investigated using the proposed adaptation algorithm, and (a =0.1) was found to be the best choice. Figure (4) clearly shows the relation between the convergence time and the relative-error with respect to the value of (a) respectively.

Assessment of a predistorter must takes into account both its performance (as discussed above) and complexity, which depends on the number of mathematical operations involved for a given LUT size. The complexity of the direct method described by Cavers (2) is of moderate complexity, since in each iteration there are three complex additions, and a complex multiplication with a division (equation 14). The slope-dependent method is a little less complex since it has no division but only two multiplications and one addition in each iteration.

CONCLUSIONS

In this paper, we proposed a new adaptive predistortion linearization method using a rectangular form of LUT technique for linearizing wide-band signals passing through an efficient power amplifier working near saturation.

The system is tested and evaluated using two adaptation methods. The two methods are compared concerning their speed of convergence and their relative error after convergence and the test shows very close results with a little superiority to the proposed method as shown in table (1).

An insertion loss of (4-5 dB) are noticed on the proposed system.

An improvement of (20 dB) in the ACPR was achieved for the W-CDMA signal on both sides of the spectrum.

The implemented linearizer is applicable to any wide-band signal and showed stable operation over output power variation, and at different output power back-off.

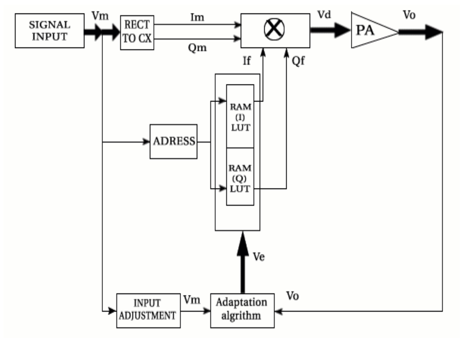

Figure (1):Block diagram of a base-band digital adaptive predistortion system.

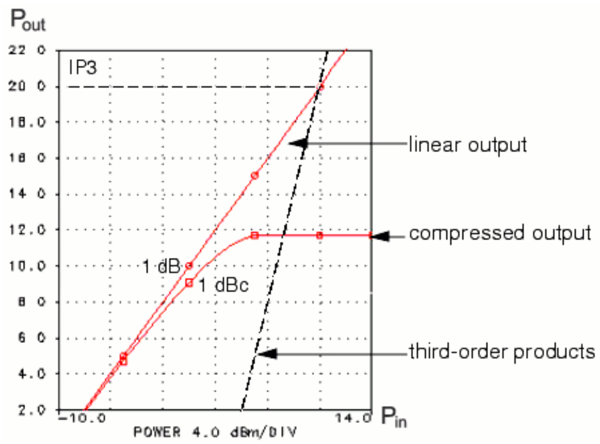

Figure (2): Input-Output power amplifier model characteristics as presented in the ADS system.

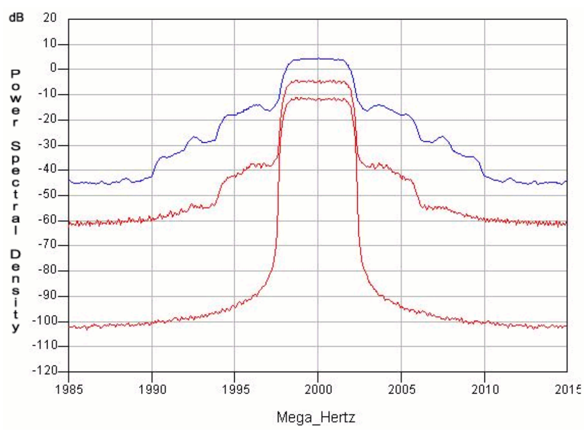

Fig (3) : Spectral Density Function of the W-CDMA at the input (lower), at the output of the power amplifier without predistortion(upper), and at the output of the proposed system with predistortion (middle).

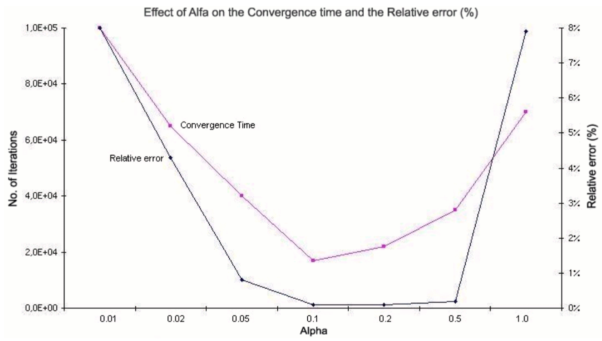

Figure (4): Effect of (α) on time of convergence (Upper), and on the relative error (%) (lower).

Table (1)

Comparison of convergence methods concerning the time of convergence and the relative-error (%) for a 5 MHz W-CDMA input

	Slope-dependent method	Direct method (Cavers)
Number of iterations till convergence	18500	20000
Relative-error (eq.11)	0.09%	0.098%

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