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An Improvement Method for Reducing Power Amplifiers Memory Effects Based on Complex Gain Predistortion

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Abstract: Efficient RF power amplifiers used in third generation systems require linearization in order to reduce adjacent channel inter-modulation distortion, without sacrificing efficiency. Digital baseband predistortion is a highly cost-effective way to linearize power amplifiers (PAs), but most existing architectures assume that the PA has a memoryless nonlinearity. For wider bandwidth applications such as wideband code-division multiple access (WCDMA) or wideband orthogonal frequency-division multiplexing (W-OFDM), PA memory effects can no longer be ignored. In this paper we proposed a technique for adaptation of digital predistorter that considers memory effects in power amplifiers.

Key words: digital predistortion, memory effect, ACPR, power amplifier, CDMA

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 inband distortions and spectrum spreading into adjacent channels.

Newer transmission formats, with wide bandwidths, such as multi carrier wideband code division multiple access (WCDMA), wireless local area network (WLAN), worldwide interoperability for microwave access (WiMAX), are especially vulnerable to PA nonlinearities, due to their high peak-to-average power ratio, corresponding to large fluctuations in their signal envelopes. In order to comply with spectral masks imposed by regulatory bodies and to reduce BER, PA linearization is necessary. A number of linearization techniques have been reported in recent years (Cripps, 1999; Kenington, 2000; Kim and Konstantinou, 2001; Ding *et al.,* 2004; Cavers, 1999; Wright and Durtler, 1992; Nagata, 1989; Woo *et al.,* 2007). 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. The digital predistortion (DPD) requires to be adaptive because of variation in power amplifier nonlinearity with time, temperature and different operating channels and so on. Another limitation of predistortion is the dependence of amplifier's transfer characteristic's on the frequency content of the signal or defined as changes of the amplitude and phase in distortion components due to past signal values, that is called memory effects. The memory effects compensation is an important issue of the DPD algorithm in addition to correction of power amplifier (PA) nonlinearity especially when the signal bandwidth increases. Many studies are involved in this technique but many of them suffer from limitations in bandwidth, precision or stability (Cavers, 1990; Wright and Durter, 1992; Nagata, 1989).

In this paper a new technique of adaptive digital predistortion that is a combination of two techniques, the gain based predistorter Cavers, 1990 and memory polynomial model (Ding *et al.,* 2004) is presented. Both previous techniques have demonstrated acceptable results but both have disadvantages. In memory polynomial predistortion the complexity of extracting the coefficients of predistortion function decrease the capability of linearization and so it needs to apply other method like (Raich *et al.,* 2003) for implementing it. In complex gain predistortion method the memory effects that cause dynamic AM-AM and AM-PM are not considered. So here the main objective is not only to demonstrate the capability of this new method to overcome for such

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disadvantages, but also to show that with applying this technique all the memory contents of power amplifier that is modeled with memory polynomial is compensated. For validating this technique several simulations are applied. The adaptation is based on linear convergence method in the simulations. For simplicity, the effects of the quadrature modulator and demodulator and A/D and D/A are not considered.

It will be shown that with applying this method all the memory contents of the power amplifier especially the one that cause dynamic AM-AM and AM-PM are compensated. Simulations and results are examined based on Motorola's MRF18085 1.9 GHz LDMOS PA with 13.5 dB gain and 85W output power. To demonstrating the results several tests are shown with Mobile WiMAX signal.

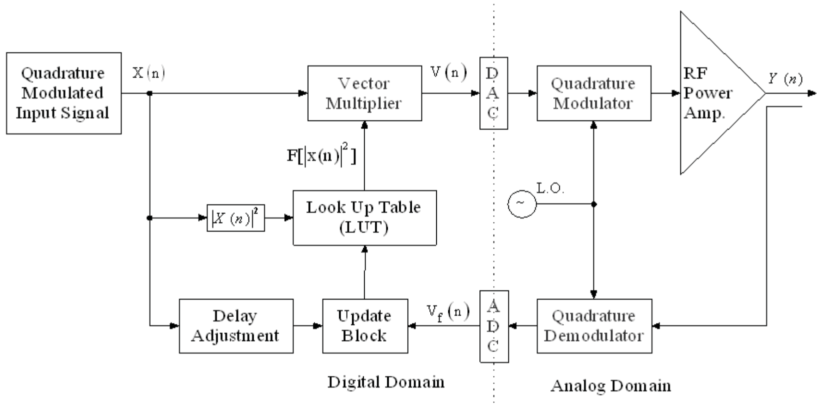

Fig. 1: Adaptive digital predistortion block

2. Predistortion Technique:

Fig. 1 shows a block diagram of the adaptive predistortion proposed in (Cavers, 1990). A fully adaptive digital predistortion system requires the addition of a predistortion circuit consisting of a digital predistorter and look up table (LUT) to the transmission path in addition to a feedback path consisting of a demodulator , analog to digital converter (ADC) and adaptation circuit for updating the LUT. The block diagram assumes that all components of the system except the predistorter and high power amplifier (HPA) have a linear response and hence can be ignored in the analysis. In this paper also these effects are ignored. The predistorter is equivalent to a nonlinear circuit with gain expansion response that is inverse of the power amplifier gain compression AM-AM (Amplitude dependent gain) and a phase rotation that is the negative of the Power Amplifier phase rotation AM-PM (Amplitude Dependent Phase Shift).

In this figure x(n)=1+jQ is the quadrature modulated input signal and $v_f(n)$ is the quadrature demodulated feedback signal. These signals are sampled synchronously, and their values are used to generate a predistortion vector function $F[|x(n)|^2]$ which is stored in polar or rectangular form in a look-up table (LUT). The input signal x(n) is predistorted according to $F[|x(n)|^2]$, so that the predistorted signal v(n) produced the linearized output from the RF amplifier. Here the LUT is 10bit and the absolute of input signal is used for addressing it.

The main objective of this paper is to study the electrical memory effects that cause dynamic AM-AM and AM-PM (Ku and Mckinley, 2002). The previous studies (Kim and Konstantiou, 2001; Ding *et al.,* 2004; Cavers, 1990; Raich *et al.,* 2003; Wangnyong *et al.,* 2004l; Ku and Kenny, 2003; Ku and Mckinley, 2002; Bosch and Gatti, 1989; Nagata, 1989; Woo *et al.,* 2007a; 2007b; Morgan *et al.,* 2006) were all restricted to calculation of the coefficients of the power amplifier. This way needs a lot of computation and therefore takes a lot of processor time and also never can be implemented when the number of coefficients increases. The technique that is proposed here doesn't have that drawback. It even claims that can compensate the dynamic memory effects in wideband applications. This method will be discussed in details in next section. One of the other important things in studying the predistortion method is that the predistortion attempts to add 3^{rd} and 5^{th} order intermodulation products to the input signals that cancels out the 3^{rd} and 5^{th} order intermodulation products added by the PA, thus the bandwidth of the predistorted signal must be three times greater than the bandwidth of the input signals to be able to represent up to 5th order intermodulation products. In the real world the predistorted signals are fed into a DAC and then low pass filtered at the Nyquist rate (half the input sample rate), the predistorted signal must have a sample rate of at least six times that of the original input signals. Thus in simulations the input signals are interpolated by a factor of six before being fed into the predistorter. In the next section the new technique of predistortion is discussed.

3. Complex gain predistortion:

Fig. 2 shows the predistortion function $F[|x(n)|^2]$ that cascades with power amplifier that has shown with $G[|v(n)|^2]$ function. $F[|x(n)|^2]$ and $G[|v(n)|^2]$ are complex gain functions of predistortion and power amplifier. As proposed in (Ding *et al.,* 2004) the equivalent discrete baseband PA model considering memory effects and bandpass nonlinearity can be represented with a memory polynomial model which is a special case of Volterra series.

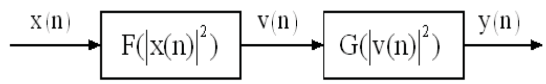

Fig. 2: Cascade of predistortion and power amplifier

This model can be presented as below:

$$y(n) = \sum_{\substack{k=1 \\ \text{Odd}}}^{K} \sum_{q=0}^{Q} a_{kq} v(n-q) |v(n-q)|^{2(k-1)} \tag{1}$$

where v(n) is the discrete input complex signal of power amplifier after predistortion block and y(n) is the discrete output complex envelope signal, K is the order of nonlinearity and Q is the memory length.

This model considers only odd-order nonlinear terms due to bandpass nonlinear characteristics that cause intermodulation distortion. In (1) v(n) also can be represented as below:

$$v(n) = x(n) F[|x(n)|^2] \tag{2}$$

where x(n) is the discrete input complex and $F[|x(n)|^2]$ is the complex gain of the predistortion block. Equation (1) can be simplified as below:

$$y(n) = \sum_{q=0}^{Q} v(n-q) \sum_{\substack{k=1 \\ \text{Odd}}}^{K} a_{kq} |v(n-q)|^{2(k-1)} \tag{3}$$

Where the function $G_q(|v(n-q)|^2)$ can be represented as:

$$G_q[|v(n-q)|^2] = \sum_{\substack{k=1 \\ \text{Odd}}}^{K} a_{kq} |v(n-q)|^{2(k-1)} \tag{4}$$

Then (3) is as below:

$$\begin{aligned} y(n) &= \sum_{q=0}^{Q} v(n-q) G_q[|v(n-q)|^2] \\ &= v(n) G_0[|v(n)|^2] + v(n-1) G_1[|v(n-1)|^2] + .. \end{aligned} \tag{5}$$

This equation demonstrates that the memory contents of the power amplifier are not only in the coefficients a_{kq} of the (1), but it also can be shown as the complex function, which means that the memory effects are in the function $G_q[|v(n)|^2]$. Previous efforts only tried to extract the a_{kq} to compensate for such memory effects but here it will be shown that without having the coefficients also the memory effects can be compensated and even the compensation is better and includes all the memory (Varahram *et al.,* 2007).

From (2) for finding the function $F[|x(n)|^2]$, first it is assumed that Q=0 or the power amplifier is memoryless thus from (5) it can be conculded:

$$y(n) = v(n) G_0[|v(n)|^2] \tag{6}$$

Ideally the power amplifier should satisfy the below condition for having the linear output.

$$y(n) = Gx(n) \tag{7}$$

Where G is the linear gain of power amplifier.

replacing (5) in (7) then:

$$y(n) = \sum_{q=0}^{Q} v(n-q) G_q[|v(n)|^2] = Gx(n) \tag{8}$$

With assuming Q=0 and replacing the v(n) in (6) and with considering that the quadrature modulator is a perfect unity gain device the optimum predistorter characteristic, denoted by $F[|x(n)|^2]$, would satisfy:

$$x(n) F[|x(n)|^2] G_0[|x(n) F[|x(n)|^2]|^2] = Gx(n) \tag{9}$$

Then the optimum value of the predistortion complex gain is calculated from below iterative equation:

$$F_{i+1}[|x(n)|^2] = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n) G_0[|v(n)|^2]} V_{error}(n) \tag{10}$$

where

$$V_{error}(n) = y(n) - Gx(n) \tag{11}$$

Now assume that the power amplifier includes one memory or Q=1 then after some simplification, equation below will be generated:

$$F(|x(n)|^2) = \frac{G}{G_0[|v(n)|^2]} - \frac{v(n-1) G_1[|v(n-1)|^2]}{x(n) G_0[|v(n)|^2]} \tag{12}$$

The second fraction of (12) indicates the memory effects of the power amplifier. If Q increases then the elements in (12) also will increase.
The iterative solution for (12) is:

$$\begin{aligned} F_{i+1}(|x(n)|^2) = {} & F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n) G_0[|v(n)|^2]} V_{error}(n) \\ & + \frac{F_i[|x(n)|^2] v(n-1) G_1[|v(n-1)|^2]}{v(n) G_0(|v(n)|^2)} - \frac{v(n-1) G_1[|v(n-1)|^2]}{x(n) G_0[|v(n)|^2]} \end{aligned} \tag{13}$$

This equation can be simplified as below:

$$F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)\,G_0[|v(n)|^2]} V_{error}(n)$$

$$+\frac{v(n-1)\,G_1[|v(n-1)|^2]}{G_0[|v(n)|^2]}\left(\frac{F_i[|x(n)|^2]}{v(n)} - \frac{1}{x(n)}\right) = \tag{14}$$

$$F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \frac{F_i[|x(n)|^2]}{v(n)\,G_0[|v(n)|^2]} V_{error}$$

The function $F[|x(n)|^2]$ in (14) is similar to (10) when the power amplifier has no memory. This formula can be extended to more memory and is still valid. Simulations and results will prove the validity of this equation later. Memory polynomial method was very complicated and it couldn't calculate all the coefficients in the volterra series and only could compensate for 2 or 3 memory length but this method proves that it can compensate all the memory contents of the power amplifier.

The important parameter in (14) is the gain factor which is the only difference between (10) and (13) and it is the $F[|x(n)|^2]$ over $v(n)\,G_0(|v(n)|^2)$. In the case of having memory, $G_0[|v(n)|^2]$ can not be found and also (6) can not be assumed except the case of memoryless power amplifier. As it is shown in (Cavers, 1990; Wright and Durtler, 1992) the gain factor can be a constant number between zero and one and it indicates the stability and convergence rate. If the gain factor sets to the larger value then the convergence is faster but the probability of convergence is low. For controlling and making the convergence slower and reach to the highest linearity especially at saturation point, (13) can be written as below:

$$F_{i+1}(|x(n)|^2) = F_i[|x(n)|^2] - \alpha \frac{F_i[|x(n)|^2]}{v(n)\,G_0[|v(n)|^2]} V_{error}(n) \tag{15}$$

In (Cavers, 1990) α is a constant between 0 and 1. This parameter indicates the convergence rate and stability and its value should be allocated with considering the linearity requirements. In (Cavers, 1990) the condition for convergence of (15) is shown. For calculating the function $F[|x(n)|^2]$ in (15) first the error vector should be calculated and then the gain factor which involves the division and then these values multiply together. $F[|x(n)|^2]$ is initially one then after some iteration the optimum value will be found. Finding the appropriate gain factor is possible as described below.

The parameter $v(n)\,G_0[v(n)]$ in the gain factor is the power amplifier output without memory and it can be modeled with the block diagram in Fig. 3. for finding the $v(n)\,G_0[v(n)]$ parameter, it is possible to initially calculate the coefficients of the power amplifier without memory and save it in LUT and then calculate the gain factor.

With doing this a lot of processor time and hardware resources will be compensated. It is important that if the feedback in Fig. 3 comes from the output of the amplifier with memory which is y(n) rather than that the one which is shown in this figure this method will not linearized the power amplifier and (15) will not convergence. The value of α in (15) should be considered accurately to have a convergence in the loop. The only drawback that is still remained, is calculating the inverse of $v(n)\,G_0[v(n)]$ which after finding it and multiplied with error vector and predistortion function $F[|x(n)|^2]$ the LUT contents could be updated. So in implementation the main concern is the division part. One solution for this is to convert the division to multiply and this could be done with Newton Raphson method but it leaves for future work.

In (15) with two or three iterations convergence is achieved and it will be shown that as compared with memory polynomial method the efficiency improves more and it is less complex. The only time consuming part for implementing this method is the calculation of the gain factor which requires the division of the complex gain of predistortion block to the $G_0[|v(n)|^2]$. The predistorter is assumed to be implemented as a lookup table (LUT) of complex gain values (Cavers, 1990) that here the size is 10bit, and is indexed by the squared magnitude, as shown in Fig. 1. It is also possible to index by magnitude, or any other monotonic function of magnitude, depending on the regions of amplifier characteristic that need the greatest accuracy of representation. However, these considerations do not enter the analysis of the present paper. Also to help evaluate the performance of the DPD a figure for in-band distortion as well as out of band distortion which is measured with adjacent-channel-leakage-ratio (ACLR) is calculated. This involves calculating the error vector magnitude (EVM) in transmitter, which is given by the following equation:

$$EVM = \frac{rms(|V_{error}(n)|)}{rms(|(x(n)|)} \tag{16}$$

where $V_{error}(n)$ is from (11) and x(n) is the input signal

4. Simulations and Results:

In order to validate the proposed method several simulations are done. MATLAB is applied for simulations. The power amplifier is Motorola MRF18085 1.9GHz 85W LDMOS class AB power amplifier suitable for CDMA applications. First the power amplifier is designed in Microwave Office 2007. The input and output matching are designed accurately. The results of input and output matching are shown in Fig. 3. The amplifier is designed to cover the 60 MHz bandwidth from 1.93 GHz to 1.99 GHz. the gain parameter S21 which is 13.5 dB should be flat in all the bandwidth. It is always a trade off between the gain parameter S21 and input and output matching that represent with S11 and S22. For having the flat gain in all the bandwidth one of the parameter S11 or S22 should be scarified. Here as it is shown in Fig. 3 the S22 is around -4 dB to -10 dB and it is higher than S11 which is at less than -20 dB range. After the matching results are confirmed, then the AM-AM and AM-PM characteristics of this power amplifier are generated and then the 4096 input and output data samples are brought to MTLAB for further analysis. These samples are used to model the power amplifier based on (1) which is the memory polynomial method. It is assumed that Q=2 and K=3. In Fig. 4 the AM-AM and AM-PM characteristics of this power amplifier are shown. These characteristics are extracted with two carrier WCDMA signal with 10 MHz carrier spacing that is generated from Microwave Office 2007. In Fig. 5 the AM-AM and AM-PM of this power amplifier with memory effects is shown. It can be seen the scattering of samples that is because of the dynamic memory effects and it should be compensated. It can be shown that when the amount of memory effects is more, these samples will be scattered more, and then the digital predistortion technique should be more powerful. It is obvious in Fig. 5a that the AM-AM characteristic is not linear when the input amplitude is increased. And also in Fig. 5b the curve bends too. This is because of the nonlinear characteristics of power amplifier. All the input and output samples in the simulations are normalized.

For modeling the memory effects of the power amplifiers authors in (ku and Kenney, 2003) proposed a method for modeling the power amplifiers with memory. This method that is based on the spars delay taps is actually able to take into account all the memory effects of power amplifier. The memory effect modeling ratio (MEMR) was used to show the amount of memory that this method can model. The power amplifier that is designed here has MEMR=0.45 and the one in (ku and Kenney, 2003) has MEMR=1. previous researches could present the comparison of the power amplifier with MEMR that is less than one. Here the presented method is successfully tested with these two types of PA models. In all the simulations the input back off is 3 dB. In simulations, it is avoided to reach to 1 dB compression point which increases the complexity of this method and also the effects of analog imperfections are not considered.

In Fig. 5 and Fig 6 the Mobile WiMAX signal that is compatible with IEEE 802.16e with 10 MHz bandwidth is applied for simulations. The power amplifier is with MEMR=0.45. In Fig. 5 the power amplifier is memoryless and has only 3. In Fig. 6 the power amplifier includes memory. In this case the nonlinearity order is three and memory length is two. According to the Fig. 6. the amount of reduction in ACLR is averagely -49.3dB when applying the memory polynomial method and with the new technique is reduced to -57.4 dB which is around 8 dB improvement in ACLR.

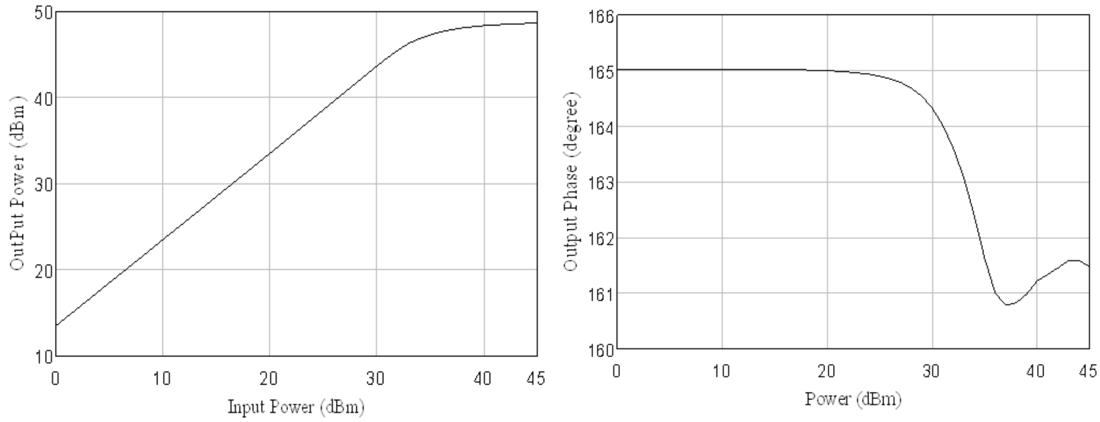

Fig. 3: AM-AM and AM-PM characteristics of the 1.9 GHz LDMOS PA without memory effects when a 2-carrier WCDMA signal is applied (a) Input power versus output power. (b) Input power versus phase difference

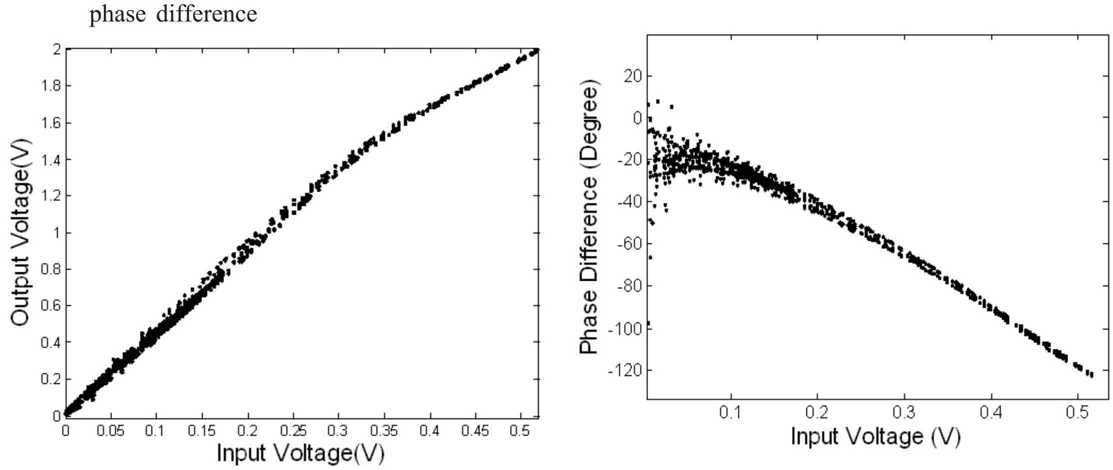

Fig. 4: AM-AM and AM-PM characteristics of the 1.9 GHz LDMOS PA with memory effects when a 2-carrier WCDMA signal is applied (a) Input power versus output power. (b) Input power versus phase difference.

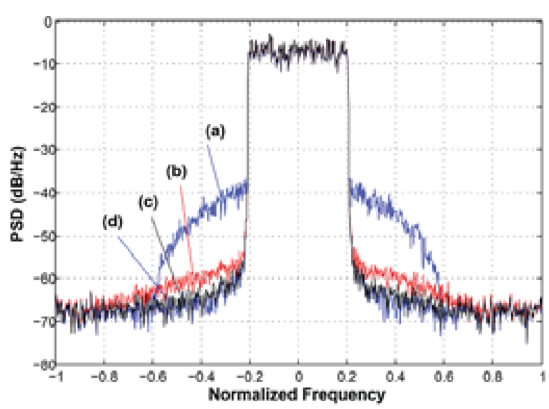

Fig. 5: Comparison of the power spectral density (PSD) between memory polynomial predistorter and gain predistortion for power amplifier without memory and Mobile WiMAX signal. (a) Output without predistortion (b) Output with memory polynomial predistortion (c) Output with gain predistortion (iteration=5) (d) Input data

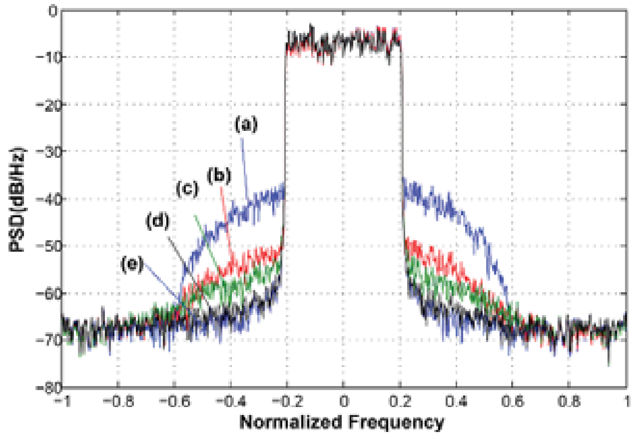

Fig. 6: Comparison of the power spectral density (PSD) between memory polynomial predistorter and gain predistortion for power amplifier with memory and Mobile WiMAX signal. (a) Output without predistortion; (b) Output with memory polynomial predistortion (Q=0, K=3) (c) Output with memory polynomial predistortion (Q=2, K=3) (d) Output with gain predistortion (iteration=5,) (e) Input data

In this paper we introduce the combination of two techniques that improve the performance of linearization of power amplifiers, the memory polynomial predistortion and the slope-dependent method. Simulations and results are examined then we simulated this PA with short term memory effects with memory polynomial method. Results are approved. Simulations and results are examined with 1.9 GHz LDMOS PA with 12.5 dB gain and 85W output power. And Mobile WiMAX is used for validation of the results. The results show the improvement of 13 dB in ACLR and improvement of 3 % in EVM. The future research should be more on the implementation of this technique using FPGA and DSP and measure the effects of analog imperfection that cause reduction in efficiency in practical implementation and add that effects in the simulations.

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REFERENCES

Bosch, W. and G. Gatti, 1989. "Measurement and simulation of memory effects in predistortion linearizers," IEEE Trans. Microwave Theory Tech., 37: 1885–1890.

Cavers, J.K., 1990. "Amplifier Linearization Using a Digital Predistorter with Fast Adaptation and Low Memory Requirements", IEEE Transaction on vehicular technology, 39(4): 374-382.

Cripps, S.C., 1999. *RF Power Amplifiers for Wireless Communications*. Norwood, MA: Artech House.

Ding, L., G.T. Zhou, D.R. Morgan, Z. Ma, J.S. Kenney, J. Kim and C.R. Giardina, 2004. "A robust predistorter constructed using memory polynomials," IEEE Trans. Commun., 52: 159–165.

Kenington, P.B., 2000. *High-Linearity RF Amplifier Design*. Norwood, MA: Artech House.

Kim, J. and K. Konstantinou, 2001. "Digital predistortion of wideband signals based on power amplifier model with memory," Electron. Lett., 37(23): 1417–1418.

Ku, H. and J.S. Kenney, 2003. "Behavioral modeling of nonlinear RF power amplifiers considering memory effects," *IEEE Trans. Microw. Theory Tech.*, 51(12): 2495–2504.

Ku, H. and M.D. McKinley, 2002. "Quantifying Memory Effects in RF Power Amplifiers," IEEE Trans. Microw. Theory Tech, 50:12.

Morgan, D.R., Z. Ma, J. Kim, M.G. Zierdt and J. Pastalan, 2006. "A generalized memory polynomial model for digital predistortion of RF power amplifiers," IEEE Trans. Signal Process., 54(10): 3852–3860.

Nagata, Y., 1989."Linear amplification techniques for digital mobile communications," in Proc. IEEE 39th Veh. Technol. Conf., pp: 159–164.

Raich, R., H. Qian and G.T. Zhou, 2003. "Digital baseband predistortion of nonlinear power amplifiers using orthogonal polynomials," in Proc. IEEE Int. Con f. Acoust, Speech, Signal Processing, pp: 689–692.

Varahram, P., S.S. Jmauar, S. Mohammady, M.N. Hamidon, S. Khatun, 2007. "power amplifiers linearization based on digital predistortion with memory effects used in CDMA applications," 18th European Conference on Circuit Theory and Design ECCTD, pp: 488–491.

Wangnyong, W., Marvin Miller and J. Stevenson Kenney, 2004. "Predistortion Linearization System for High Power Amplifiers", IEEE MTT-S Digest, pp: 677-680.

Wright, A.S. and W.G. Durtler, 1992. "Experimental performance of an adaptive digital linearized power amplifier," IEEE Trans. Veh. Technol., 41(4): 395–400.

Woo, Y.Y., J. Kim, S. Hong, I. Kim, J. Moon, J. Yi and B. Kim, 2007. "A new adaptive digital predistortion technique employing feedback technique," in IEEE MTT-S Int. Microw. Symp. Dig., pp: 1445–1448.

Woo, Y.Y., J. Kim, J. Yi, S. Hong, I. Kim, J. Moon and B. Kim, 2007. "Adaptive digital feedback predistortion technique for linearizing power amplifiers," IEEE Trans. Microw. Theory Tech., 55(5): 932–940.