ADAPTIVE DIGITAL PREDISTORTION LINEARISATION FOR RF POWER AMPLIFIERS

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Abstract

Development of linear modulation schemes has opened the way for spectrally efficient, high speed digital communication systems for voice and data applications. A trend has been to develop utra wide and wide bandwidth modulation formats, which has meant feedback linearisation schemes (both analogue and digital) are no longer effective. This has in turn lead to a number of approaches that involve predistorting the signal prior to amplification, with a characteristic that is the inverse to that of the power amplifier (PA). This paper presents a polynomial based predistortion for linearisation of an RF PA. The predistortion characteristic is adaptive, using the LMS algorithm to minimise the mean squared error between output of the PA, and a scaled version of the baseband signal. The simulation of this system indicate that this system can provide 40 dB decrease in ACPR by reducing the 3rd and 5th order IMD products.

Keywords: digital communications, linearisation, predistortion, RF power amplifier

1 Introduction

Recently proposed communication modulation formats have opened the way for high-data-rate wireless communication. In the implementation of digital radio, the effects of non-linearities can be observed in a multitude of forms. For example, mixers rely on non-linear behaviour to perform their function whereas non-linear behaviour exhibited by power amplifiers can restrict the performance of a system, causing in-band interference and out-of-band noise.

Generation of frequency components not present in the excitation is one effect a non-linear device can exhibit [1]. Of concern in communication systems is the amplitude and phase distortion which causes the signal spectrum to spread, interfering with other bands [2]. Power amplifiers (PAs) can be linearised somewhat by operating in the linear region. However, to increase output power levels and efficiency, they are often driven nearer the saturation region. Methods for reducing unwanted non-linear effects of PAs (while maintaining power efficiency) can be broken into three main categories: feedback [3], feedforward [4], and predistortion [5].

Predistortion linearisation, as depicted in Figure 1, can be used to linearise over a wide bandwidth. This is achieved by predistortion (PD) of the signal prior to amplification with the inverse characteristics of the distortion that will be imposed by the power amplifier. Thus, the output of the PA is a linear function of the input to the predistorter:

$$y(t) = f(x(t)) \tag{1}$$

$$y(t) = f[g(w(t))] = k \cdot w(t) \tag{2}$$

This paper presents the design and simulation of an adaptive polynomial predistortion linearisation scheme, designed with an end goal of implementation.

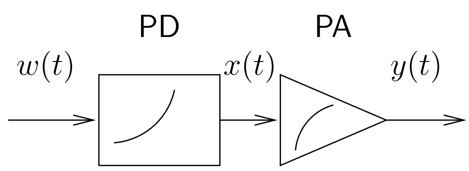

Figure 1: Basic system diagram of predistortion linearisation

Predistortion has been implemented to varying degrees, in a range of forms, and research has been done in the area of adaptive polynomial based predistortion. Many such systems look appealing in simulation [6][7][8][9], but have not been implemented. Thus, effects and complications that only become evident in implementation have not been investigated.

2 Proposed system

The proposed system is depicted in Figure 2. The input to the system will be a quadrature amplitude modulation (QAM) signal, but any baseband modulated signal can be used. Initially, the baseband signal will have a bandwidth of 150kHz. This baseband signal is distorted through a polynomial predistorter before being digitally modulated converted, to an analogue signal, and amplified. The baseband signal is converted into polar co-ordinates to allow predistortion of the AM-AM and AM-PM characteristics independently. The digital modulation and cartesian to polar conversion can be performed by a co-ordinate rotation digital computer (CORDIC) algorithm which can perform a number of trigonometric functions efficiently, and at high data rates [10]. The output of the PA is sampled using an analogue to digital converter (ADC), and used in conjunction with the predistorter input to update the predistortion algorithm. The least means squared (LMS) algorithm will be used to adjust the polynomial coefficients

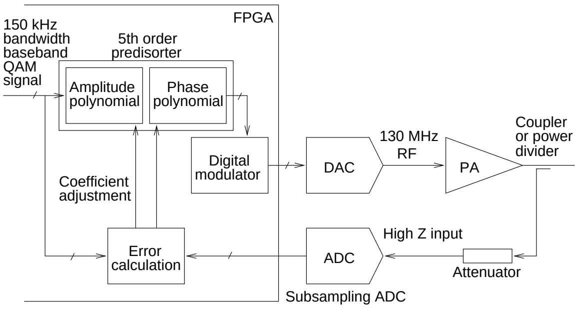

Figure 2: Diagram of the proposed system implementation

3 Amplifier modelling

In order to simulate a digital predistortion scheme, a model of a typical PA must first be obtained. For the purposes of this research, a ZFL-2000 amplifier available from Mini Circuits was chosen. The transfer characteristic of this amplifier was measured by performing a power sweep with a HP8753D network analyser. The HP8753D was configured to perform a power sweep at 130 MHz, measuring the amplitude and phase response of the ZFL-2000 amplifier as shown in Figure 3. PA models were developed by fitting a 5th order power series to the collected data using least squares fitting techniques.

Initial verification of the model transfer characteristics were made by comparing two tone test results of the polynomial models with data obtained from a two tone test of the ZFL-2000. The tests were

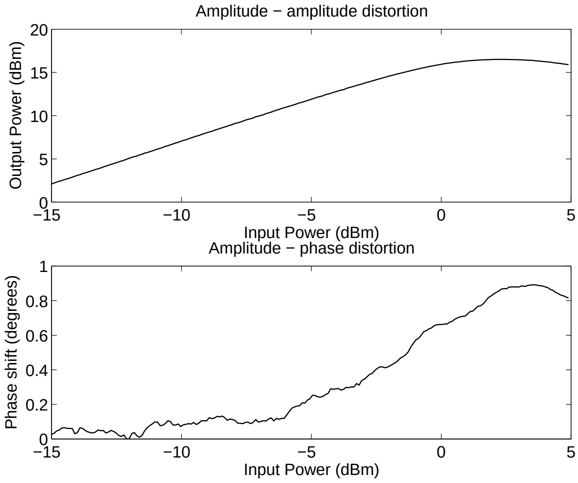

Figure 3: Measured Transfer characteristic of the ZFL-2000 amplifier

carried out at 130 MHz with a tone separation of 150 kHz to correspond to the target operating frequency and bandwidth of the implemented system. The combined input power level of the two tones was varied between -16 dBm and 0dbBm at intervals of 2 dB as the PA, and the extracted models were designed for this range of input power. Figure 4 shows the IMD levels of the PA and PA model. Note that the 5th order model produces the 3rd and 5th order IMD products accurately. This model cannot, however, predict the 7th and higher order IMD products. This is part of the limitations of using a 5th order polynomial model, however raising the order of the model increases the effect of quantisation effect on each IMD product leading to inaccurate modelling of all IMD products. For this reason a 5th order polynomial PA model was chosen. From Figure 4 we can see that these models are acurate for simulation of the ZFL-2000. The deviation at lower power levels is caused by the noise floor of measurement equipment.

4 Simulation

The LMS algorithm was used to minimise an error function by adapting the power series as described:

$$\mathbf{A}_{\mathrm{n,k+1}} = \mathbf{A}_{\mathrm{k}} + \mathbf{2}\mu\mathbf{e}_{\mathrm{k}}\mathbf{x}_{\mathrm{k}}^{\mathrm{n}} \tag{3}$$

Where n = coefficient order, at time = k, $\mathbf{A}$ is the coefficient vector, x is the input to the adaptive system, μ controls convergence and stability of the system, and e is the error calculated as follows:

$$e_{\mathrm{k}} = d_{\mathrm{k}} - y_{\mathrm{k}} \tag{4}$$

Where d_{k} is the desired (undistorted) output from the system, and y_{k} is the current output of the system. The functionality of this was tested by convergence on the known forward model of the PA, before using the system depicted in Figure 5.

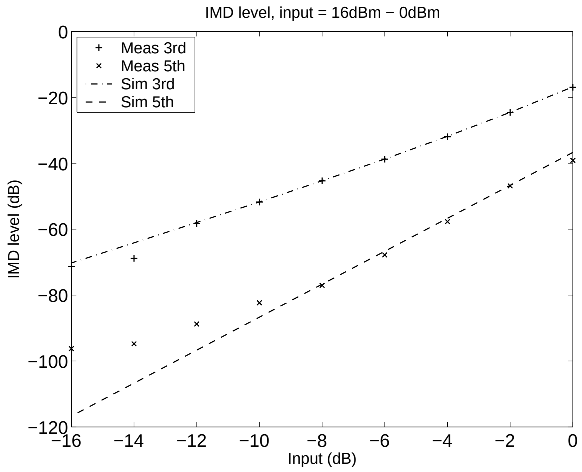

Figure 4: Two tone test comparison between the ZFL-2000 and power series model, with a input power range of -16 - 0 dBm.

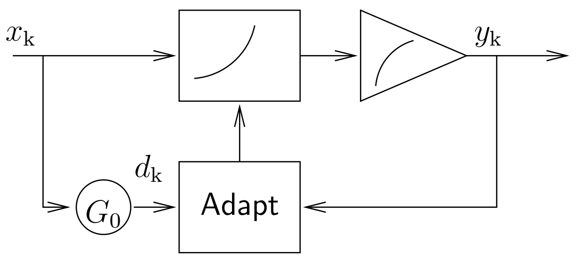

Figure 5: LMS diagram adaptive predistortion system

The incoming baseband signal x_k is predistorted with an amplitude expansion, to correct for the compression characteristic of the PA. The baseband signal is also scaled by the gain of the amplifier, to form a desired signal d_k. The output from the predistorter is distorted with the transfer characteristic of the PA by a power series to yeild y_k. The error is calculated using d_k and y_k. This error is then used to adjust the coefficients of the predistorter, as detailed above. The only 'knowledge' of the PA characteristics the system has, is the distorted output that is fed back and used for error calculation and adaption of the coefficients. To simplify the problem for initial investigation of adaptive predistortion, amplitude predistortion was investigated without the added complication of phase distortion.

Figure 6 shows the convergence of the coefficients of the polynomial power series adaptive predistorter. The transfer functions of both the amplifier and the predistorter are essentially the same as the amplitude transfer functions in Figure 9, and both the corrected and uncorrected spectrum are shown in Figure 7. IMD levels are shown in Table 1.

The above examples of adaptive predistortion deal only with amplitude distortion, however, the PA

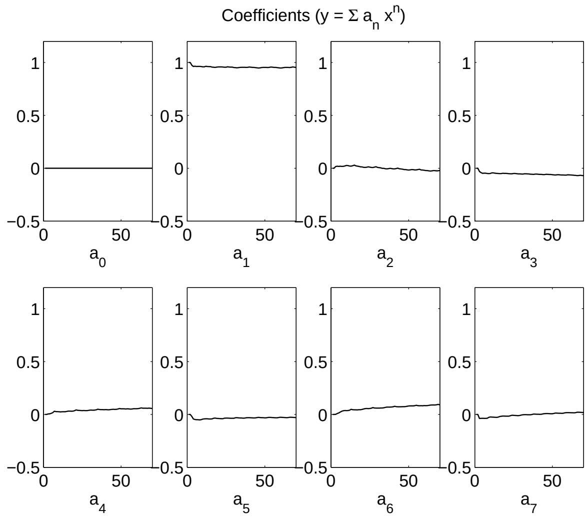

Figure 6: Convergence of the coefficients of an amplitude correcting adaptive predistortion linearisation system.

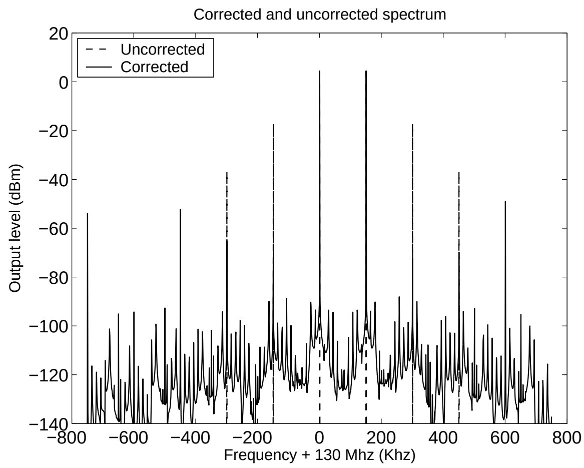

Figure 7: Corrected and uncorrected spectrum with amplitude predistortion.

IMD Levels		
	Uncorrected	Corrected
Fundamental	6 dBm	5 dBm
3rd order IMD	-17 dBm	-71 dbm
5th order IMD	-36 dbm	-65 dBm
7th order IMD	N/A	-52 dBm

Table 1: IMD levels with AM-AM predistortion correction.

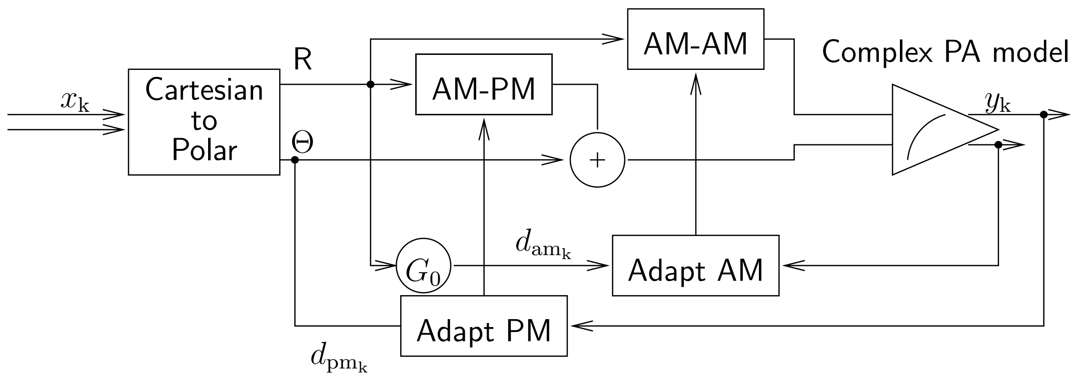

Figure 8: System diagram of an adaptive predistortion linearisation simulation to correct for both amplitude and phase distortion.

transfer characteristics will introduce both amplitude to amplitude (AM-AM) distortion, and amplitude to phase (AM-PM) distortion to the applied signal. Thus the predistorter must have facility to apply both an amplitude and phase corrective distortion. To simplify the implementation of this, the system has been designed around a polar representation of the signal, and independent AM-AM and AM-PM predistortion power series models. Figure 8 shows how the amplitude and phase predistortion is applied to the baseband input x_k. This system is very similar to the previous amplitude only system. The baseband signal is reduced to its magnitude and phase components, to allow for the amplitude and phase predistortion to be applied independently. The transfer functions after the system has had time to converge are shown in Figures 9, which lead to a reduction in the IMD products as shown in Figure 10. IMD levels are shown in Table 2.

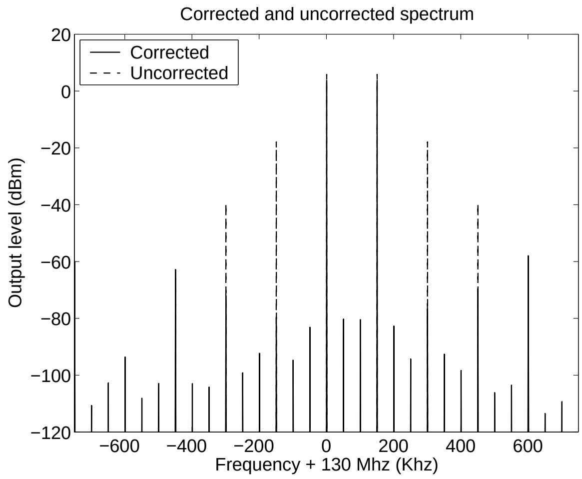

Figure 10: Corrected and uncorrected spectrum with amplitude and phase predistortion.

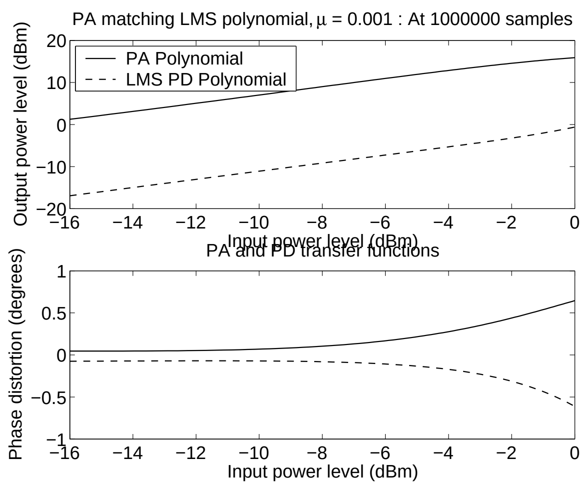

Figure 9: Transfer function of the PA and PD providing AM-PM correction

IMD Levels		
	Uncorrected	Corrected
Fundamental	6 dBm	4 dBm
3rd order IMD	-18 dBm	-85 dbm
5th order IMD	-39 dbm	-76 dBm
7th order IMD	N/A	-60 dBm

Table 2: IMD levels with AM-AM and AM-PM predistortion correction.

5 Performance

Digital adaptive predistortion implemented using lookup table (LUT) methods have been shown to reduce the 3rd order IMD by between 30 and 40 dB [11] [12]. As can be seen in Figures 7 and 10, 7th order digital adaptive polynomial predisortion can reduce the 3rd order IMD by up to 50 dB and the 5th order IMD by 35 dB. The 7th order predistortion creates 7th order IMD products that increase the total 7th order IMD level by 10 dB, which could be reduced by increasing the order of the predistorter. It should be noted however, that the simulations do not fully show the effects of quantisation. The main restriction of the hardware that will be used to implement the proposed system is a 10 bit ADC used to sub sample the RF signal. The effects of this have been simulated by way of 10 bit quantisation between the PA model and the error calculation, with minimal effects to performance. Data paths internal to the FPGA can be as wide as required, so quantisation within the FPGA should not be significant.

Typical LUT implementations have been seen to converge to a new amplifier, or after a channel switch over a time of around 10 seconds although some implementations have improved reduced this [11]. Simulations indicate that convergence to the inverse characteristics of the PA occurs over approximately 70,000 samples. For a system designed around a symbol rate of 150 k/samples, this corresponds to convergence within 0.5 seconds (3rd and 5th IMD products are corrected to below the 7th order IMD level).

6 Conclusion

Digital adaptive polynomial predisortion has a number of benefits over LUT based digital predistortion approaches. To provide fine resolution, LUT sizes become very large, which both increases memory requirements, and increases adaption time. Polynomial approaches, such as described in this paper, take advantage of current digital signal processing hardware to predistort the signal using a power series. This has significantly smaller memory requirements (only the coefficients for the power series and the current error must be stored) which means that the adaption time is quicker. Simulations indicate that polynomial based predistortion can provide around 40 dB decrease in ACPR, compared with 30 - 40 dB provided by a LUT based approach

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