From September 2006 *High Frequency Electronics*

Adaptive Digital Baseband Predistortion for RF Power Amplifier Linearization

By Rahul Gupta, Saad Ahmad, Reinhold Ludwig, and John McNeill
Worcester Polytechnic Institute

By manipulating the input signal to compensate for the inherent distortion of a power amplifier, a low-distortion output signal can be achieved

Power amplifiers (PAs) are vital components in many communication systems. To be transmitted wirelessly, a signal must be amplified with high fidelity so as to account for attenuation through the channel or propagation medium. The linearity of a PA response constitutes an important factor that ensures signal integrity and reliable performance of the communication system.

Unfortunately, PAs are inherently non-linear due to their technology limitations. A significant manifestation of this non-linearity is the excessive distortion of the transmitted signal which can result in symbol recovery errors at the receiving end. Overcoming the PA's non-linearity therefore poses a major engineering challenge. A popular approach to PA linearization is to use *predistortion* [1-3]. This concept implies the creation of a function that represents the inverse of the PA transfer function in order to linearize the overall gain from the input to the output.

There are a plethora of linearization techniques that have been reported in literature. Feedforward linearization is a commonly used technique where the spurious, distorted PA output spectrum is modified via two complementary circuits: a) an input signal cancellation circuit, and b) a distortion or error-cancellation circuit [4]. Unfortunately, feedforward linearization has generally moderate power efficiency and suffers from limited bandwidth. Contemporary analog radio-frequency (RF) techniques such as diode predistortion that are primarily operated in an open-loop configuration are only moderately effective, but relatively simple to implement [5]. Currently, digital baseband adaptive predistortion is the popular choice as it permits application of a variety of corrective algorithms and ensures reasonable bandwidths for common cellular phone standards such as Code Division Multiple Access (CDMA) and Global System for Mobile Communications (GSM).

Background

The demand for high data rates and stringent Federal Communications Commission (FCC) requirements have driven the need for spectrally-efficient modulation techniques such as *Quadrature Phase Shift Keying* (QPSK) and *Quadrature Amplitude Modulation* (QAM). These modulation schemes result in a fluctuating envelope of the baseband modulating signal on the RF carrier, which are degraded by the distortion performance of PAs. Intermodulation distortion (IMD) tends to further complicate signal recovery at the receiver end due to the presence of undesirable odd-order IMDs of the fundamental harmonics; they are the by product of the PA non-linearity. Odd-order IMD products are close to the fundamental frequencies where filtering is not viable because of the required extremely high quality factor [6].

PA distortion is typically characterized in the form of its amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) modulation curves, which reflect, respectively, the amplifier gain and phase progression as a function of the input power. Figures 1 and 2 depict typical AM-AM and AM-PM characteristics.

At low input power levels, the output is a

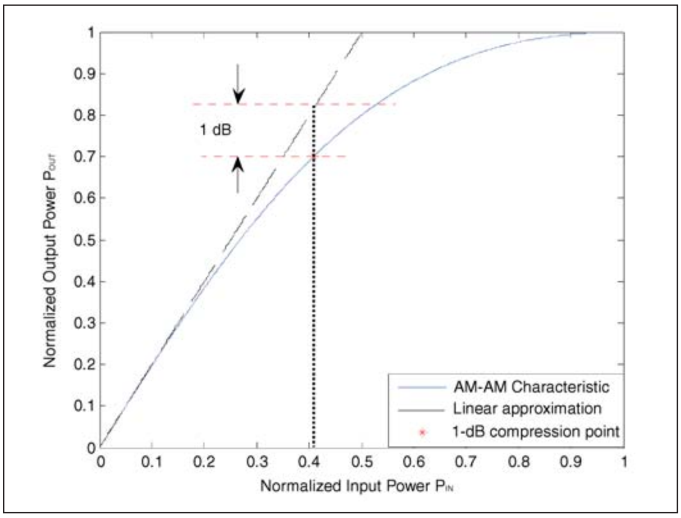

Figure 1 · Normalized output response of PA as a function of normalized input power.

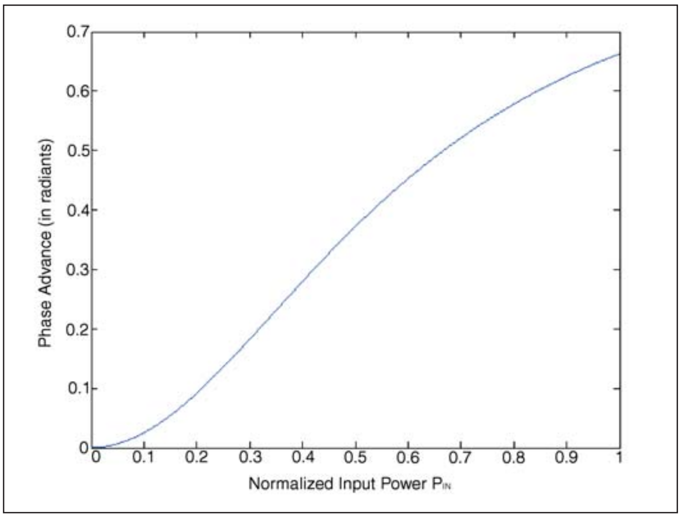

Figure 2 · Normalized phase response of PA as a function of normalized input power.

linearly scaled version of the input, which can be inferred from Figure 1. However, as the power increases, the amplifier gain starts decreasing and eventually the PA is driven into saturation. The operating point where the gain of the amplifier deviates from the linear small-signal gain by 1 dB is called the *1-dB compression point.* Additionally, varying input power levels also affect the phase of the output signal, as is illustrated by the PA's AM-PM characteristic, see Figure 2. Both these characteristics are a key stepping-stone in understanding symbol recovery errors that occur on the receiver end as a result of PA non-linearities, particularly with respect to warping of the entire signal constellation diagram.

The Predistortion Concept

The main idea behind the concept of predistortion is the aim of introducing inverse nonlinearities that can compensate the AM-AM and AM-PM distortions of the PA. A key assumption made here is that the amplifier is memoryless, implying that the output is only a function of the instantaneous input. Consequently, every instance of the PA output signal can be mapped to a unique input value without hysteresis. In this scenario, amplitude and phase distortions introduced by the PA may be regarded as functions of the input level $r(t)$ alone. If we consider an input signal v_{in} with carrier frequency ω_c and phase $\theta(t)$ such that

$$v_{in}(t) = r(t)\cos\left(\omega_c t + \theta(t)\right) \tag{1}$$

then, the corresponding PA output voltage $v_{out}(t)$ is given by

$$v_{out}(t) = \xi\left[r(t)\right]\cos\left(\omega_c t + \theta(t) + \Phi\left[r(t)\right]\right) \tag{2}$$

Here, $\zeta[r(t)]$ and $\Phi[r(t)]$ represent, respectively, the AM-AM and AM-PM transfer characteristics as a function of the input envelope, while $\zeta[r(t)]$ is the AM-PM response.

The predistorter operates on the input to yield an output signal that is distorted in a precisely complementary fashion to the distortion produced by the RFPA. Thus, if $\nabla[r(t)]\exp[\Psi\{r(t)\}]$ is the complex predistorter function, then the predistorter output v_d will be given by

$$v_d(t) = \nabla\left[r(t)\right]\exp\left[\theta(t) + \Psi\left\{r(t)\right\}\right] \tag{3}$$

where the function $\nabla[\ldots]$ and $\Psi\{\ldots\}$ satisfy criteria that invert the nonlinearities created by the PA:

$$\xi\left\{\nabla\left[r(t)\right]\right\} = \lambda r(t) \tag{4}$$

$$\Psi\left\{r(t)\right\} + \Phi\left[\nabla\left\{r(t)\right\}\right] = 0 \tag{5}$$

The expected linear gain is given by the constant λ in equation (4). The predistorter must comply with the conditions of predistortion, as stated in equations (4) and (5) by making decisions based on the values of AM-AM and AM-PM coefficients that can be computed and stored as a function of the input power (or envelope) in a look-up table (LUT).

Predistorter Architecture and Algorithm

A block diagram of our proposed for the linearization scheme is shown in Figure 3.

The complex baseband input signal, represented by its I_B and Q_B components, is digitally modulated using a 64-QAM scheme. During the calibration mode of the predis-

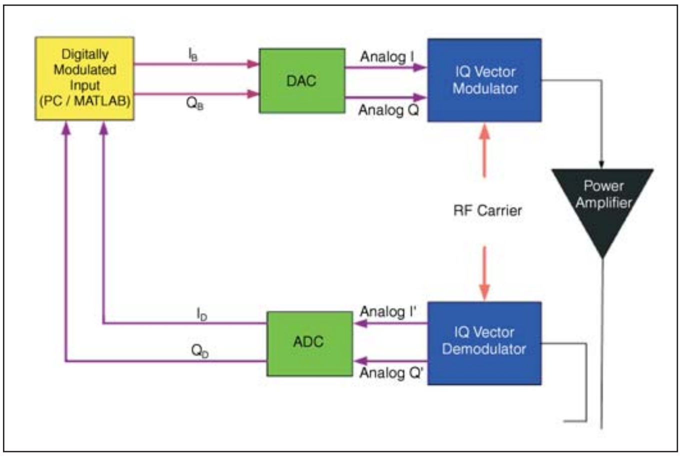

Figure 3 · Functional block diagram of the proposed digital baseband PA predistorter.

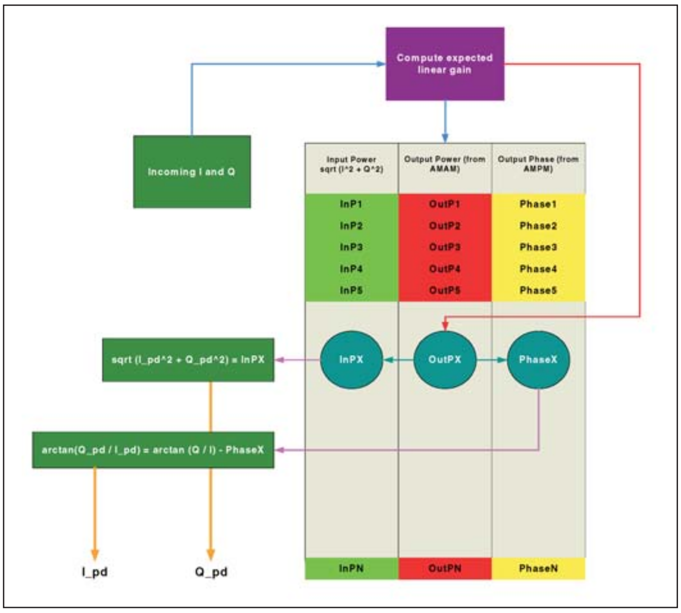

Figure 4 · Overall predistortion algorithm and LUT structure, where column one represents the input power, column two the resulting output power and column three the resulting output phase.

torter, these symbols are sampled using dual-channel analog-to-digital converts (ADCs) to feed into a MATLAB code. The code then computes the input power and transmits the signal unaltered to the vector IQ modulator, which performs the upconversion to the RF carrier frequency. The modulated RF carrier propagates through the PA and a part of the output is coupled off and downconverted to baseband using an IQ vector demodulator which splits the signal into I_D and Q_D channels. These channels propagate through an adjustable phase shifter that can be calibrated to align the distorted I_D and Q_D signals with respect to the baseband inputs I_B and Q_B. Alternatively, this alignment could be performed digitally in the MATLAB code, thereby eliminating the need for an external phase shifter. In this manner the input power can be swept and the corresponding AM-AM and AM-PM distortions can be recorded in a LUT as a function of the baseband input power.

In the actual mode of operation, the MATLAB code would compute the power of the incoming signal represented by I_B and Q_B. This input power would then be scaled by the appropriate linear gain set point (λ) to compute the expected value of the output power (or envelope), based upon linear gain prediction. Thereafter, this value would be compared against the LUT coefficients depicting the AM-AM conversion and the input power closest to the theoretical linear prediction, provided this value is not beyond the saturation value of the PA. This would be the input power of the predistorted signal that can ultimately be fed into the IQ modulator, which determines the constraints that I_{PD} and Q_{PD}, the predistorted (PD) in-phase and quadrature components, would satisfy. The second constraint would be determined by the AM-PM conversion at the selected predistortion input power. This can then be calibrated out from the original input signal phase, given by $\tan^{-1}(Q_B / I_B)$, such that once the predistorted symbol undergoes phase translation by the PA, the initial input and the final output (derived from the PA after feeding in the predistorter output) possess the same phase. The structure of the algorithm discussed is described in Figure 4.

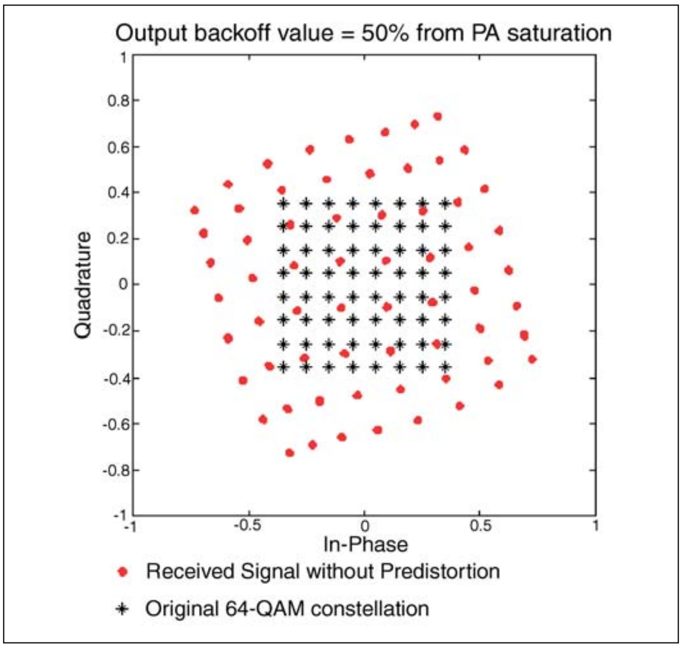

Figure 5 · Constellation warping due to nonlinear PA response in the absence of predistortion.

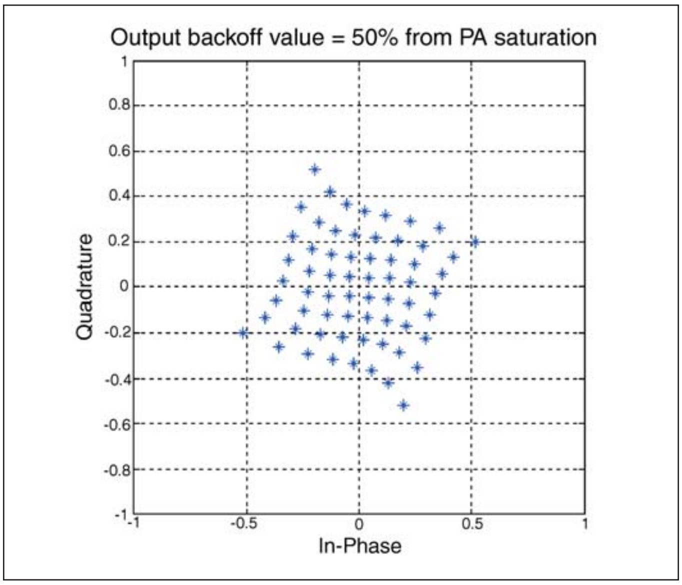

Figure 6 · Signal representation for the predistorted constellation.

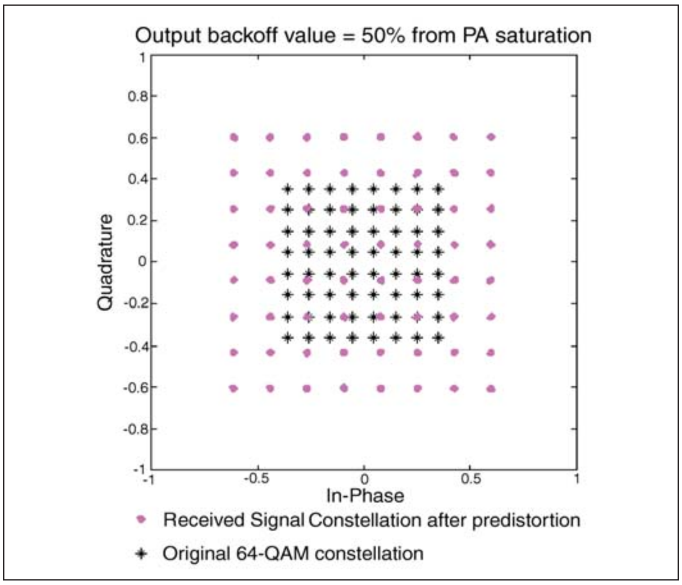

Figure 7 · Nearly linear scaling of the transmitted constellation after predistortion.

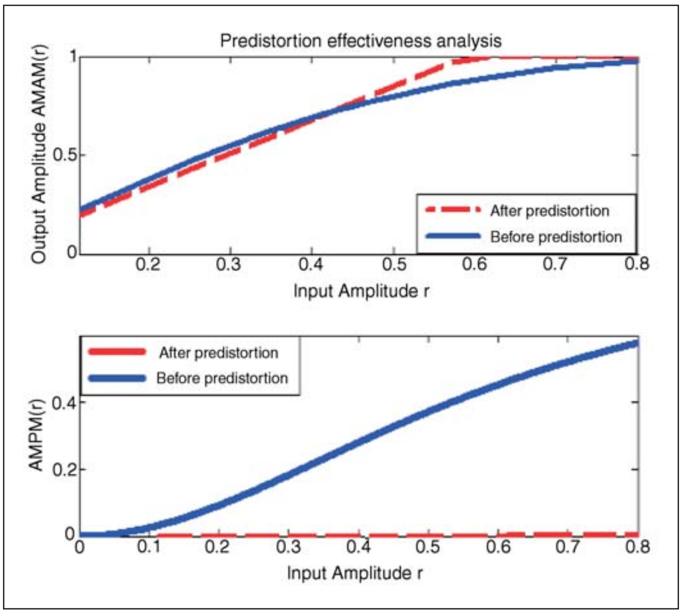

Figure 8 · I/O transfer characteristic after predistortion.

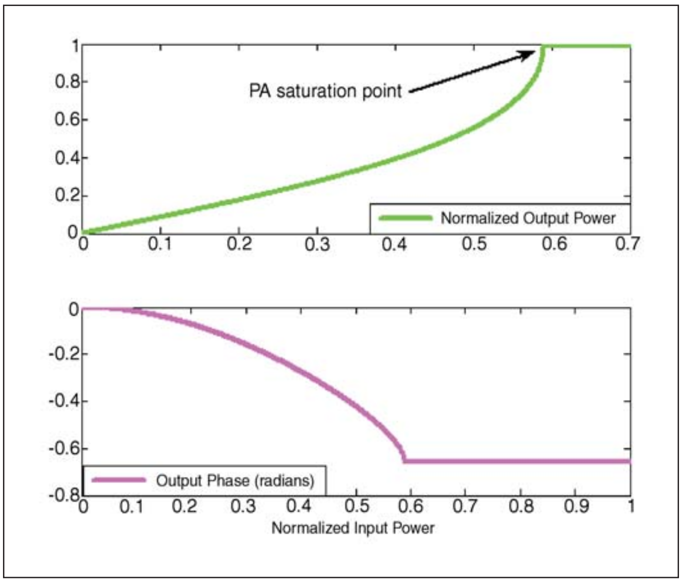

Figure 9 · Amplitude and phase characteristics of the predistorter block.

Evaluation of Constellation Warping Using Predistortion

The proposed algorithm was implemented in MATLAB, and its effectiveness was analyzed by evaluating the performance on a 64-QAM constellation that was transmitted through a highly nonlinear Travelling Wave Tube (TWT) PA. Detailed characteristics are described by the Saleh model [4]. The results are presented in Figures 5, 6, 7 and 8 for peak constellation power backoff values within 50% from the absolute saturation region.

As illustrated in Figure 7, the constellation appears well linearized with respect to the original input 64-QAM constellation. Obviously, this exceptional performance can only be derived for peak signal values well below the compression region of the PA. As this backoff value (from the compression region) decreases, the end points of the constellation eventually begin to buckle inwards.

Intermodulation Distortion (IMD)

The level of intermodulation distortion can be regard-

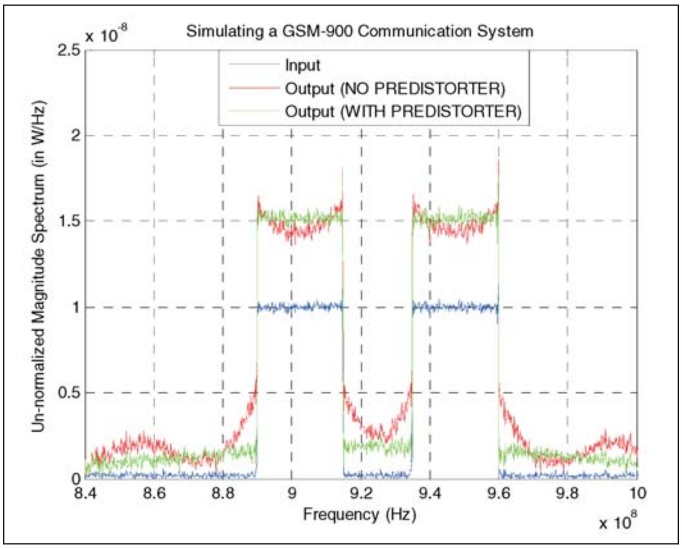

Figure 10 · Simulating predistortion for a GSM-900 communication system.

ed as a measure of the spectral integrity of the transmitted signal and thus the effectiveness of the predistortion algorithm. We modeled GSM-900 to verify that the side lobes are indeed considerably reduced as a consequence of linearization approach. The resulting predistortion block characteristics are shown in Figure 9 and the GSM-900 spectrum is shown in Figure 10.

Figure 10 documents the significant reduction in the level of the spurious IMD products. Additionally, restoration of the amplitude at the fundamental tones, verifies that the predistorter operation is indeed successful.

Conclusion

This paper outlines an efficient digital baseband predistortion scheme that is stable, robust and capable of adapting to changing PA characteristics that affect power gain as a function of frequency. Specifically, the effect of non-linearities in active devices, such as PAs in communication systems, is explored with special emphasis on IMD and warping of the signal constellation diagram.

We have introduced an efficient predistortion concept as part of a linearization technique, which involves manipulation of the input signal prior to amplification in a manner that counteracts the distortions introduced by the PA. A digital LUT is generated which can be calibrated using the PA's AM-AM and AM-PM information obtained after performing an input RF power sweep. The simulation results illustrate that the developed algorithm is capable of linearizing the PA entirely up to saturation, at which point it becomes physically impossible to generate any significant gain.

Since the predistorter is calibrated in a closed-loop configuration (although the actual predistortion operation is performed in open-loop) the proposed algorithm can also be used to compensate for memory effects.

References

1. J. Yi, Y. Yang, M. Park, W. Kang, and B. Kim, "Analog predistortion linearizer for high-power RF amplifiers," *IEEE Trans. Microwave. Theory Tech.,* vol. 48, no. 12, Dec. 2000, pp. 2709-2713.

2. Chan-Wang Park, F. Beauregard, G. Carangelo and F.M. Ghannouchi, "An independently controllable AM/AM and AM/PM predistortion linearizer for cdma2000 multicarrier applications," Radio and Wireless Conference, 2001. 19-22 Aug. 2001, pp. 53-56.

3. Karam, G and Sari, H, "A data predistortion technique with memory for QAM radio systems," *IEEE Transactions on Communications,* Vol. 39, no. 2, Feb. 1991, pp. 336-344.

4. Shawn Stapleton, "Adaptive FeedForward Linearization for RF Power Amplifiers," November 2000.

5. Jim Cavers and Thomas Johnson, "Wideband Linearization: Feedforward plus DSP," 2005.

6. Lloyd Butler, "Intermodulation Performance and Measurement of Intermodulation Components," August 1997.

Author Information

Rahul Gupta is a senior at Worcester Polytechnic Institute, where he is majoring in Electrical and Computer Engineering. His interests are in the field of PA linearization, analog integrated circuit design and embedded systems.

Saad Ahmad is a senior at WPI, where he is double majoring in ECE and System Dynamics. His research interests are PA predistortion and distributed electric generation.

Reinhold Ludwig is a Professor in the ECE department of WPI where he teaches courses on RF circuit design and conducts research in high frequency coils for magnetic resonance imaging.

John McNeill is an Associate Professor in the ECE department of WPI where he teaches courses and conducts research in the area of analog and mixed signal integrated circuit design.