Amplifier Linearization Using Adaptive RF Predistortion

Linearization techniques can improve performance without excessive inefficiency

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Active linearization, a critical technology for modern communications systems, describes the automatic reduction of intermodulation (IM) products generated by high power linear amplifiers. In almost all cases, linearization is more desirable than backing off a Class A amplifier, which can significantly effect efficiency.

This is the second in a series of articles focusing on active linearization. The first installment appeared in the February 2001 issue of Applied Microwave & Wireless.

The first installment of this article series focused on DSP-based digital predistortion, in which the adaptation mechanism is based on assessing the difference between the desired modulation and the power amplifier’s output, and then using this as the basis of a gain and phase adjustment to the signal before the amplifier. This article introduces the concept of adaptive RF predistortion and offers a detailed look at a design example that employs an adaptive work-function-based predistortion technique.

Adaptive RF predistortion, a process that employs an adaptive work function to optimize out-of-band IM performance, is another valuable technique. RF predistorters can handle larger bandwidths than DSP-based digital predistorters and are able to adjust continuously for changes in the power amplifier’s characteristics due to temperature, channel switching, power supply variation or transistor degradation. The RF predistorter functions independently of the modulation scheme, just like digital predistorters.

RF predistortion

Predistortion, the most common linearization technique, inserts a nonlinear module between the input signal and the power amplifier. This module generates IMD products that are precisely anti-phase with the IMD products from the power amplifier, which reduces out-of-band emissions. RF predistortion has two primary advantages. First, as with digital predistorters, correction is applied before the power amplifier, which minimizes the effect of high power insertion loss. Second, unlike digital predistorters that are limited by the performance of the DSP, the correction architecture of an RF predistorter can handle moderate bandwidths.

The RF-based linearizer circuit in Figure 1 creates a predistorted version of the desired modulation. The predistorter consists of a complex gain adjuster that controls the amplitude and phase of the input signal. The amount of predistortion is controlled by two nonlinear...
work functions that interpolate the AM/AM and AM/PM nonlinearities of the power amplifier. The envelope of the input signal is used as an input to the work functions. The feedback path samples a portion of the undesired spectrum and enables the DSP to adjust the work function parameters to minimize the undesired signal, which typically consists of the adjacent channel power.

When we apply a two-tone signal at the input, we observe the spectral response at various nodes in the RF predistorter. The envelope detector on the lower branch senses the amplitude modulation of the input RF signal as seen in Figure 2, while the delay element in the upper branch compensates for the time required for the work function. Once optimized, the complex gain adjuster generates a signal predistorted with the inverse nonlinear characteristics of the power amplifier. The spectral growth from the predistorter at the input node of the power amplifier is shown in Figure 2. Ideally, the IM products will be equal in amplitude, but anti-phase to those created as the two tones pass through the power amplifier. The out-of-band filter on the branch at the power amplifier output samples the adjacent power interference (ACPI), senses its power amplitude and feeds it to the DSP, which adapts the work function parameters so that ACPI is minimized.

A series of patents have been granted for adaptive predistortion, starting around the mid-1980s. These patents describe essentially two methods of adaptation. Some are based on power minimization; others are based on gradient signals.

Power-minimization adaptation is based on fine-tuning the complex gain adjuster so that the measured power of the error signal in the out-of-band frequency is minimized. Once the parameters of the gain adjuster are optimized, the system requires insertion of deliberate perturbations to maintain updated coefficients, which also effectively reduces IMD suppression.

Gradient signal adaptation is based on continuously computing estimates of the gradient of a three-dimensional power surface. The error surface generated by the RF predistorter circuit is the difference between the input signal and the scaled output signal. IM power is minimized when the error signal is completely suppressed. Since the gradient is continuously computed, no deliberate misadjustment is required, as with power-minimization adaptation.

In addition to two fundamental adaptation techniques, there are also three different approaches that can be used for RF-based predistortion. The rectangular work function approach employs a low-order polynomial to fit the AM/AM and AM/PM characteristics of the power amplifier. The second technique uses a look-up table and generally provides a better fit to the characteristics of the power amplifier. However, the look-up table technique requires a more sophisticated adaptation mechanism. The third approach to RF-based predistortion is the analog nonlinearity technique, which

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![Figure 2. Spectral response at various nodes of the RF predistorter using a two-tone input signal.](image)

![Figure 3. Diagram of the rectangular work-function predistortion circuit.](image)

![Figure 4. Diagram of the power-minimization adaptation circuit.](image)
consists of using diodes to generate IMD products that are precisely anti-phase with those generated by the power amplifier.

Rectangular work-function predistortion

The rectangular work-function implementation uses a complex gain adjuster that incorporates in-phase and quadrature controls. The rectangular gain function consists of a simple second-order polynomial that is given in terms of the squared envelope expressed as:

\[ F_1(\rho) = 1 + G_1 \times \rho + G_2 \times \rho^2 \]

\[ F_2(\rho) = 1 + P_1 \times \rho + P_2 \times \rho^2 \]

where \( \rho \) is the squared envelope. Figure 3 shows the circuit representing this work function.

When the gain function is multiplied by the input signal in the complex gain adjuster, a fifth-order polynomial is produced in terms of the signal envelope. Four parameters (two each for gain and phase) must be gradually adapted by a DSP or microprocessor to minimize ACPI.

Power-minimization adaptation

The adaptation controller shown in Figure 4 represents the power minimization approach to adaptation for RF predistortion. The I and Q control voltages are adjusted to minimize the power on port O, which is a sample of the interference created in the adjacent channel. The drawbacks of this method are slow convergence to the minimum and sensitivity to measurement noise near the minimum.

Power measurements are inherently noisy, so lengthy dwell times are required at each step to reduce the variance of the measurement. Two methods have been devised to mitigate this problem. The first uses a tunable receiver that selects a frequency band that includes only distortion. The controller then works to minimize only this quantity. The other approach entails subtracting a phase and gain adjusted replica of the input from the output, ideally leaving only the distortion. The distorted signal is then fed into port O and used in the minimization algorithm.

RF-based predistortion simulation example

Now we simulate a real RF-based predistorter based on the rectangular work function (i.e., fifth-order polynomial) technique just described. The circuit schematic for the RF predistorter is shown in Figure 5. The adaptation technique is based on the power minimization method, and the rectangular implementation is used for the complex gain adjuster. The four coefficients (\( G_1, G_2, P_1, \) and \( P_2 \) from Figure 3) are adjusted using an iterative least mean squared adaptation. In the simulation, the third- and fifth-order coefficients are represented in complex form (\( a_3 \) and \( a_5 \)).

The power amplifier employed in the simulation is a
standard off-the-shelf Motorola device (Figure 6). For the input, a one MHz wide, two-tone modulated signal centered at 850 MHz is used. Also, it is assumed that all passive components are ideal (e.g., power splitters and combiners).

The real third-order coefficient is adapted first (Figure 7), followed by the imaginary third-order coefficient. Note that the coefficients are adapted slowly — a dwell time of 450 microseconds is specified per iteration to achieve stable output power measurements. Instability can occur if the design of the adaptation process is not closely monitored. The fifth order coefficients are similarly adapted.

Now, we will assess the amount of improvement in the third-order IM levels at the output of the RF predistorter. First, the measured improvement in third-order IMD is 13 dB, as shown in Figure 8. Further, the performance of the power amplifier using the RF predistorter is significantly better than a system employing a 5 dB back-off, as seen in Figure 9.

Conclusion

The performance demonstrated by the RF-based predistorter is significant and indicates that this technology is ready for the jump from research to development. System-level simulations provide a solid starting point for actual implementations, which is the next logical stage for this technology.

Author information

Dr. Shawn P. Stapleton has more than 17 years of experience designing RF and microwave circuits and systems. He is currently a professor of electrical engineering at Simon Fraser University and works as a consultant to the EEsof Division of Agilent. He has developed GaAs MMIC components, including mixers, amplifiers, frequency dividers and oscillators, and has recently worked on projects related to digital signal processing, mobile communications and RF/microwave systems.