Amplifier Linearization Using Adaptive Digital Predistortion

The need for greater linearity can be addressed at the digital coding level

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The emphasis on higher data rates and spectral efficiency has driven the wireless industry towards linear modulation techniques, such as quadrature phase shift keying (QPSK), quadrature amplitude modulation (64 QAM) and multicarrier configurations. Although these linear modulation techniques provide good spectral efficiency, they produce a signal with a fluctuating envelope that generates intermodulation distortion (IMD) at the system's power amplifiers. Most of the IM power appears as interference between adjacent channels, which requires the use of highly linear power amplifiers.

One way to compensate for these nonlinear distortions is linearization of the power amplifier via predistortion. In most applications, linearization is a more desirable approach than backing off a Class A amplifier, which lowers power efficiency and increases heat dissipation. Recently, active linearization has emerged as a critical technology in modern wireless communications systems that addresses this problem.

Adaptive digital predistortion, in which the adaptation mechanism is based on the difference between the desired modulation and the power amplifier's output, is one linearization technique that is well-suited to baseband applications that employ digital signal processors (DSPs). A digital predistorter provides significant IMD reduction over low to moderate bandwidths, while continuously adjusting for component drift and power variations. This predistortion technique operates independently of the chosen modulation scheme.

This article introduces the concepts of power amplifier linearization and digital predistortion, looking in detail at the complex gain-based look-up table technique of digital predistortion. An actual simulated example of this approach is also demonstrated.

Linearization overview

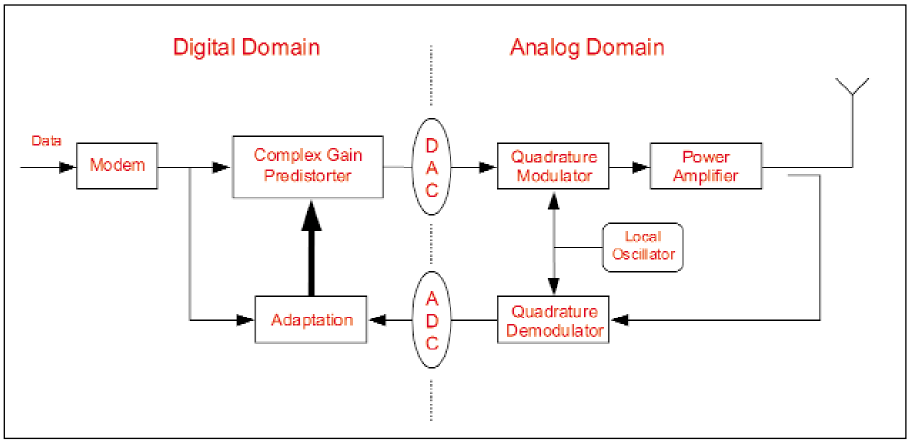
Over the years, a number of linearization technologies have been developed. Predistortion has been the most common approach deployed in new systems today. With predistortion, a nonlinear module is inserted between the modulated input signal and the primary power amplifier stage. The nonlinear module generates IMD products precisely in anti-phase with the IMD products produced by the power amplifier, theoretically removing any out-of-band emissions caused by the power amplifier.

Another common approach is feed-forward linearization, which is the only strategy that simultaneously offers wide bandwidth and good IMD suppression. The price for this performance is high complexity. In addition, automatic adaptation mechanisms are essential for maintaining performance regardless of variables such as temperature and component drift.

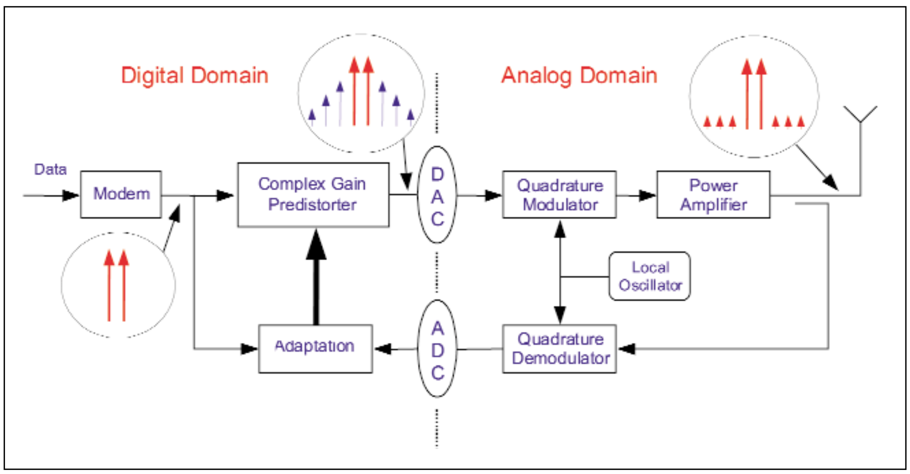
Of the two alternatives, RF predistortion is a better choice for many applications. It offers minimal complexity with reasonable IMD reduction over moderate bandwidths. The primary limitation of this method is the difficulty in acquiring accurate RF functional models.

Cartesian feedback, a relatively low complexity approach, also offers reasonable IMD suppression, but stability problems with this line of attack limit bandwidth to a few hundred kilohertz, as well as restrict accuracy.

Linear amplification using non-linear components (LINC) techniques convert the input signal into two constant envelope signals, which



▲ **Figure 1. Design of the digital predistorter.**



▲ **Figure 2. Spectral response of the digital predistorter at various nodes, using a two-tone input signal.**

are amplified by Class C amplifiers and then combined before transmission. In addition to being complex, LINC designs are particularly sensitive to component drift.

Dynamic biasing is similar to predistortion except that the work function is based on the power amplifier's operating bias. Dynamic biasing is notably limited in its ability to suppress adjacent channel interference.

Digital predistortion

Digital predistortion possesses two advantages. First, the correction from the nonlinear module is applied before the power amplifier where high power insertion loss is less critical. Second, significant IMD reductions can be achieved. The primary disadvantages of digital predistortion are its relative complexity and bandwidth limitations tied to the accuracy and computational rate of the specific DSP used in the system.

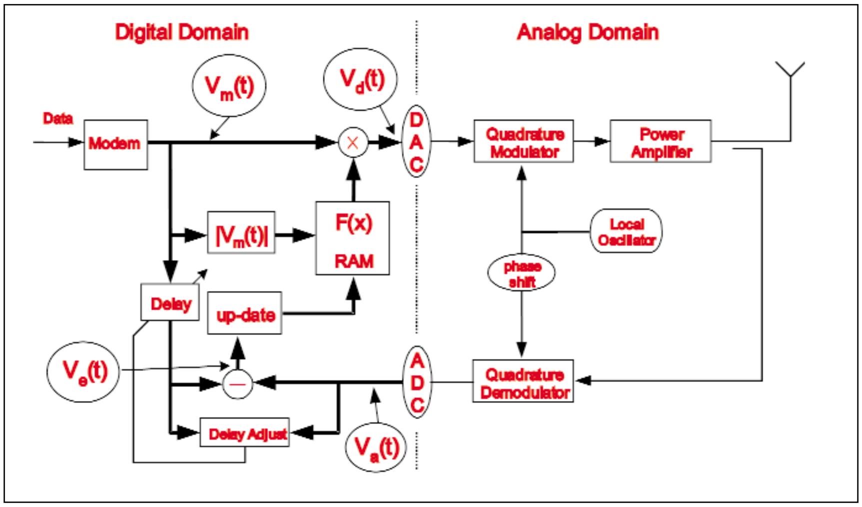
The linearizer circuit in Figure 1 creates a predistorted version of the desired modulation. The predistorter includes a complex gain adjuster that directs the amplitude and phase of the input signal. The amount of predistortion applied is controlled by updating values in a look-up table with the interpolated amplitude modulation to amplitude modulation (AM/AM) and amplitude modulation to phase modulation (AM/PM) nonlinearities of the power amplifier. Note that the inputs to the adaptation function include a delayed version of the output and input signals. The input is delayed and then subtracted from the power amplifier's output signal. Theoretically, the result is only the distortion (that is, the IMD components) added by the power amplifier.

The spectral response of the digital predistorter can be observed at various nodes using two-tone input signal, as shown in Figure 2. Once optimized, the complex gain adjuster (predistorter) should exhibit nonlinear characteristics that are exactly the inverse of the power amplifier. This can be confirmed by observing the spectral growth characteristics of the predistorter at the input node to the power amplifier. Ideally, the IMD products detected at this node will have the same amplitude as the distortion generated when the two tones are passed through the power amplifier, but in anti-phase. The adaptation process quickly adjusts the look-up table entries to minimize distortion.

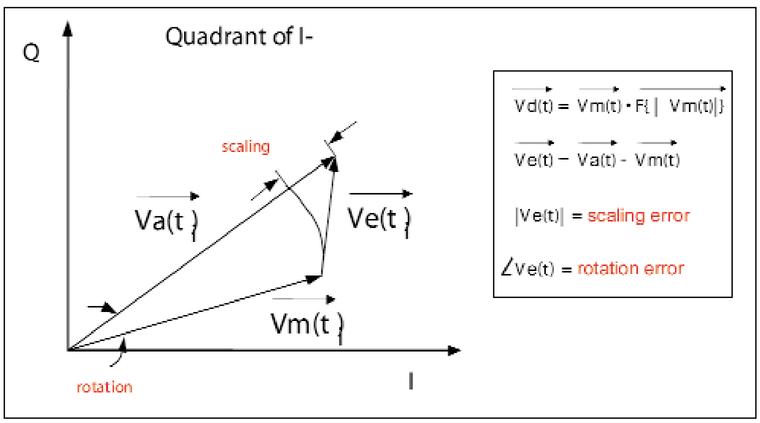
Design techniques

There are three generic approaches to digital predistortion: complex vector mapping lookup, complex gain lookup and Cartesian feedback. The complex vector mapping technique uses interpolated input vectors that are maintained in a look-up table generated by adding an error vector to compensate for AM/AM and AM/PM distortions. The complex gain approach multiplies the input signal by an optimized complex gain vector stored in a look-up table, which is indexed by the envelope of the input signal. Finally, Cartesian feedback is a less complicated approach that does not require a look-up table, but tends to be less stable.

Conventional adaptation techniques for the digital predistorter use a gradient signal that is based on continually computing the gradient of a three-dimensional power surface that represents the difference (i.e., the error signal) between the input signal and the scaled output signal. Adjacent channel interference power is



▲ **Figure 3. The complex gain look-up table.**



▲ **Figure 4. The complex gain function stored in the look-up table is the scaling and rotating error applied to the input vector by the power amplifier.**

minimized when this error signal is completely suppressed. Since the gradient is continuously being computed, no amount of constant misadjustment is required.

Two different gradient estimation methods are commonly used. Linear convergence is a technique that uses a first order feedback loop, while the alternate secant method estimates the gradient using a process based on Newton's classical method.

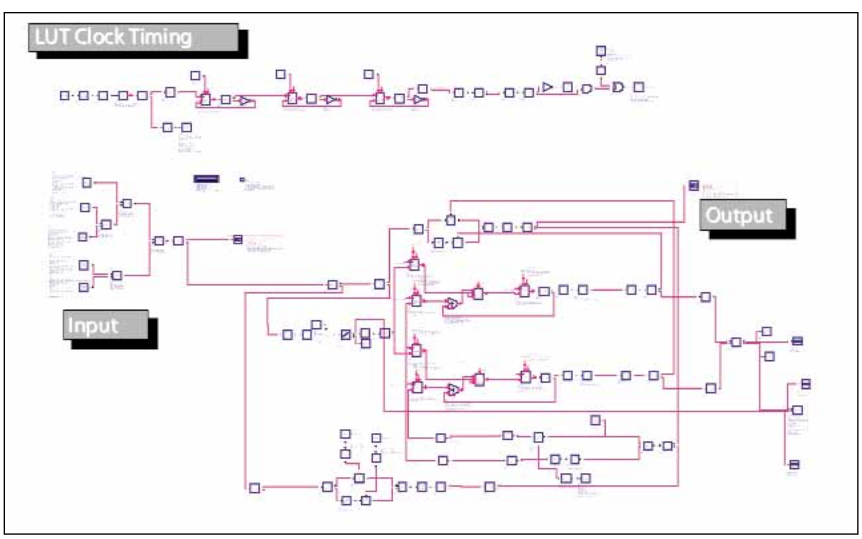
Complex gain look-up predistorter

An example of the complex gain look-up technique is illustrated by the circuit in Figure 3. The input signal is multiplied by a gain signal stored in RAM. This gain value is dependent on the input signal envelope, which is quantized to a finite number of entries. (64 in this example). These entries are optimized by computing the difference between the input signal and the output of the power amplifier. Provided that feedback delay has been accounted for, the resulting difference will contain only the distortion component. A number of techniques are available to adaptively compensate for the feedback delay, operating in the time or frequency domains. Updating the RAM look-up table is accomplished using either linear convergence or the secant method.

The gain function multiplied with the modulated input signal is a complex quantity that is based on the envelope of the input signal, which is required to compensate for the AM/AM and AM/PM distortion generated by the power amplifier. The look-up table entries are derived from the error vector that remains after subtracting the input signal from the power amplifier output, and can be stored in either polar or rectangular format. The power amplifier's distortion can be expressed as a scaling and rotation of the input vector, as seen in Figure 4. This function may be stored in either polar or rectangular format.

Digital predistorter simulation example

Now we will simulate a real digital predistorter based on the complex gain look-up table technique. Figure 5 presents an example of just such as circuit.



▲ **Figure 5. Circuit schematic for the example digital predistorter simulated in the Agilent Advanced Design System.**

The linear convergence technique is used to adjust the look-up table entries to minimize ACPI (adjacent channel power interference), and an adaptation coefficient value of –0.1 is selected to enable rapid optimization. A 64-entry look-up table is chosen to quantize the input envelope. A rectangular format is used for table entries. Timing clocks are used to read and write to the look-up table RAM. For our input, a 25 MHz wide, 10-tone modulated signal centered at 800 MHz is used. Finally, it is assumed that all passive components, such as power splitters and combiners, are ideal.

The error signal derived from the difference between the input and output signals is scaled by the adaptation constant and the result is latched in data registers (Figure 6). The index for the RAM is established by passing the input envelope through an A/D converter. The in-phase and quadrature signals are stored in their respective look-up tables. The fixed-point summation provides the update for the new table entry based on the previous value at the corresponding index.

The plots in Figure 7 compare the envelope of the input signal with the corresponding look-up table for gain magnitude. Thus, only a nominal amount of gain is required to compensate for the AM/AM compression that occurs due to the power amplifier.

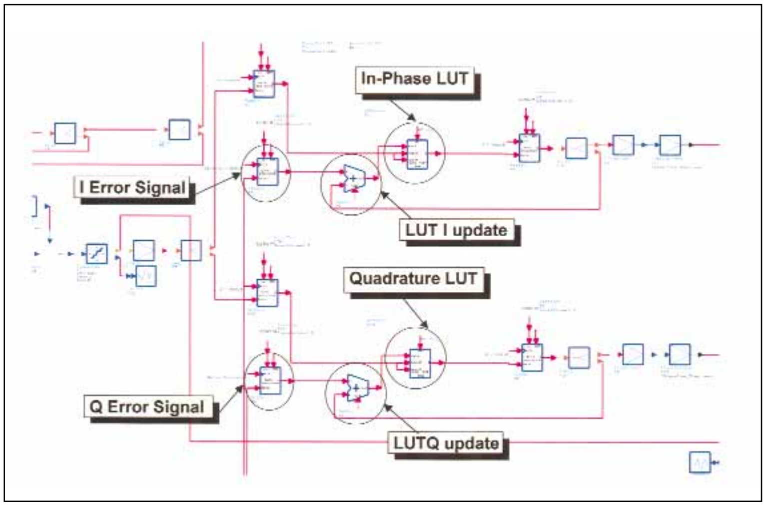
Finally, we can assess the performance of our digital predistortion circuit, as shown in the plots in Figure 8. Observe the spectral growth that occurs using a digital predistorter. Adjacent channel power is spread over a wider bandwidth, but mask requirements can be met more readily.

Conclusion

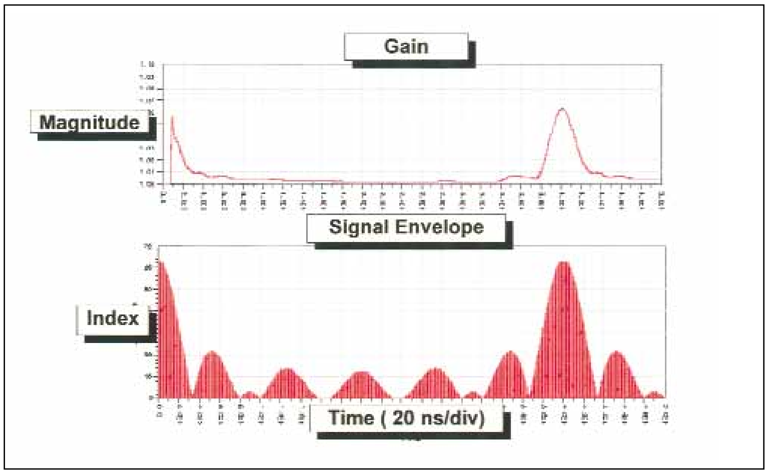
Adaptive digital predistortion is a maturing technology, now making the jump from the realm of research to system development. The digital predistorter example we have discussed in this article exhibits the expected level of performance that can be achieved using linearization. The next stage consists of system-level simulations, which would provide a solid starting point for an actual implementation, where designed components can then be integrated into a system. ■

Author information

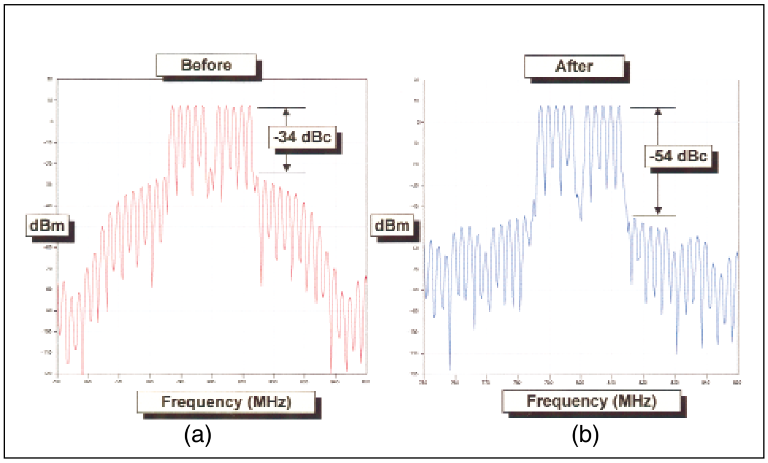
Dr. Shawn P. Stapleton has more than 17 years of experience designing RF and microwave circuits and systems. He is currently a professor of electrical engineering at Simon Fraser University and works as a consultant to the EEsof Division of Agilent. Stapleton has developed GaAs MMIC components, including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



▲ **Figure 6. Look-up table detail for the digital predistorter.**



▲ **Figure 7. Optimized look-up table gain for the digital predistorter.**



▲ **Figure 8. (a) The driving power amplifier with a 5 dB back-off generates high levels of intermodulation power as well as high levels of harmonics. (b) The output resulting from a circuit using the digital predistorter after the look-up tables are optimized.**