BASE STATIONS AND HANDSETS NEED RF AMPLIFIERS WITH HIGH LINEARITY AND EFFICIENCY. WITH SOME CLEVER TECHNIQUES, DESIGNERS CAN ALIGN THESE MUTUALLY EXCLUSIVE GOALS.

Heads and ~~or~~ tails

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DESIGN RF AMPLIFIERS FOR LINEARITY AND EFFICIENCY

Cell phones use modern modulation schemes that require linear amplification of the RF signal. A typical way to achieve this linearity is to burn more power in the output stage. This approach reduces efficiency, even though efficiency is one of the most important operating parameters in a phone, a base station, or any other electronic system.

Important efficiency requirements exist on both the handset and the base-station sides of the telecom world. In handsets, efficiency directly translates into battery life. By increasing cell-phone efficiency, you can also increase talk time—a fundamental figure of merit for a handset. On the base-station side, efficiency results in lower electric bills and, just as important, less heat. Reducing heat and power consumption creates a cascading set of results that provide lower initial costs, lower operation costs, and lower total cost of ownership.

In older cell-phone-modulation designs, the linearity of the output stage was unimportant because the demodulation did not depend on linearity. CW (continuous-wave), FM (frequency-modulation), and GMSK (gaussian minimum-shift keying) for GSM (global-system-for-mobile) communication technologies have a constant envelope and require no linear amplification. To work properly, new modulation schemes, such as EDGE (enhanced data for GSM evolution), require linear amplifiers. You can achieve this linearity by underdriving the RF amplifier and leaving head room between the output signal and the power-supply voltage. The problem with this approach is that it directly decreases the amplifier's efficiency.

Efficiency in single-transistor output stages improves as the output swing approaches the power-supply rails. To improve efficiency, select power-supply voltages and load impedances so that the output stage swings close to the rails. This approach dissipates less average power in the output transistors because the output transistor always has less voltage across it as the output signal nears the power rail.

Unfortunately, driving the output signal closer to the supply rail also reduces the amplifier's linearity. This reduction occurs just as frequently at RF frequencies as it does at audio frequencies. Any amplifier whose circuit design causes it to swing to values near the power-supply rails has less linearity. The ultimate expression of linearity problems in an amplifier is amplifier clipping, and the power-supply voltage is insufficient to allow the signal excursion to properly represent the amplified input signal (**Figure 1**).

THE NEED FOR LINEARITY

It may not be immediately apparent, but linearity is not a primary concern in designing many RF systems. The fact that designers use Class C amplifiers should suggest that a perfect representation of the input sine wave might not be critical to the communications requirements of some types of signals. Imagine the RF signal from an FM-radio station. In FM transmissions, the zero crossings of the waveform contain all the information in the signal. Even if the peaks of the waveform become distorted, the fidelity of the demodulated signal do not. Overdriven FM-radio signals create frequency harmonics of the carrier frequency, and those harmonics may be objectionable from an interference standpoint, but a receiver tuned to an overdriven-FM-radio signal still operates successfully (**Figure 2**).

AT A GLANCE

- New cell-phone standards require linear RF amplifiers.
- Improving linearity often hinders efficiency.
- Digital predistortion is one method of achieving linearity and efficiency.
- The Doherty amplifier implements a hardware method for improving efficiency.
- Modeling and simulating nonlinear systems are challenges.

Over the past decade, the acquisition costs and revenue demands of cell-phone-radio bands have encouraged the design of advanced modulation schemes that allow for more information in a narrower frequency band. A figure of merit for these schemes is bandwidth efficiency, which you express in megabits per megahertz or bits per second per hertz. Modern and proposed cell-phone standards, such as EDGE, contain information in far more than the zero crossings of the signal. The new cell-phone-modulation schemes, such as QAM (quadrature-amplitude modulation), carry information in both the phase and the amplitude of the envelope signal on the RF-carrier frequency. Examine the classic 64-QAM (64-state-QAM)-vector constellation (**Figure 3**). The phase and amplitude of the signal use a series of symbol vectors to create the envelope of the RF signal. Because there are 64 vectors, the information that any vector carries can represent 6 bits of digital information, providing the bandwidth efficiency of 64-QAM schemes, which approach 6 Mbps/MHz.

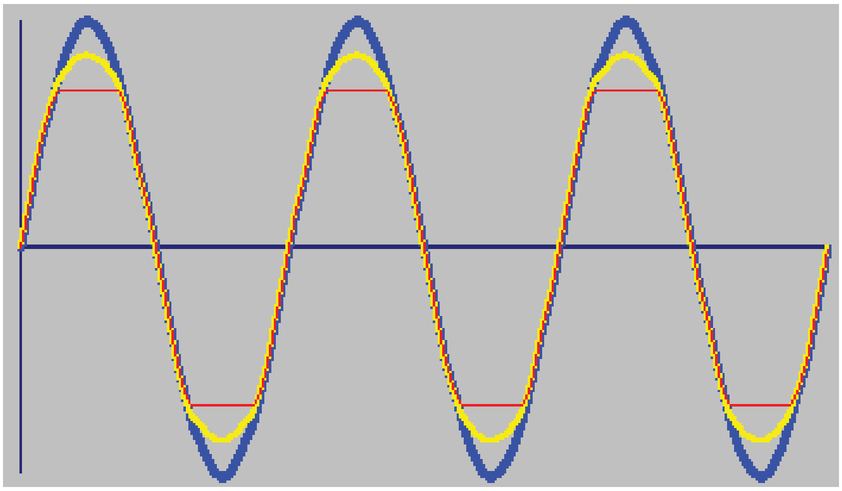

Figure 1 Clipping distortion is apparent when comparing the blue input with the yellow, moderately clipped output waveform or the red, heavily clipped output waveform. Symmetrical clipping such as this one appears as odd harmonics in the frequency domain. Amplifier nonlinearity creates intermodulation distortion that is harmonically unrelated to the two input tones.

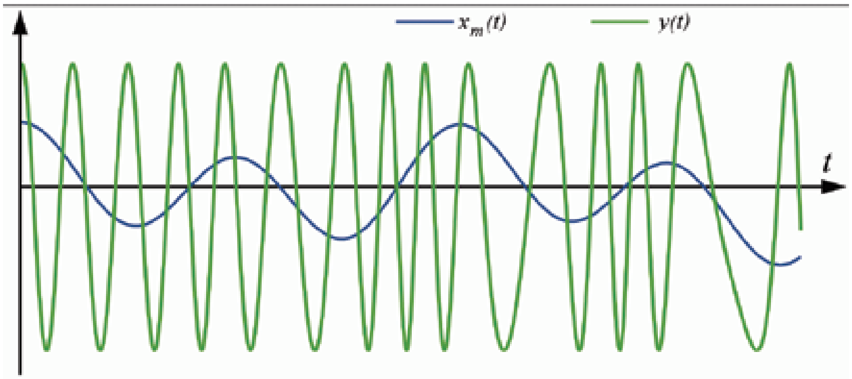

Figure 2 The frequency-modulated signal, y(t), is immune to amplifier nonlinearity. The zero crossings, rather than the amplitude, contain the information, so amplitude distortion in the amplifier causes no problems.

Poor linearity causes problems in such an advanced modulation scheme. Because the demodulator needs an accurate depiction of both the amplitude and the phase of the signal, the instantaneous accuracy of the signal is important, unlike with FM transmissions, in which only the zero crossings matter. If the operating signals drive the RF-power amplifier close to the output rail, the transistor approaches saturation, compounding its inherent logarithmic nonlinearity. Thus, the symbol vector that the amplifier encodes loses the correct amplitude and phase. When the nonlinearity is severe enough, the symbols overlap and lose the information.

A demodulation scheme might account for the inherent nonlinearity of a transistor, but the biasing of that transistor establishes at which point on the logarithmic-transfer function the transistor operates. Thus, coming up with such a demodulation scheme would be difficult. Further, the saturation of the transistor as it approaches the power rails would be difficult to factor into to any demodulation scheme because each RF source has a somewhat arbitrary power-supply voltage. The only approach to correcting poor symbol accuracy is improving the accuracy of the RF-power amplifier.

Class A output stages have inherent nonlinearity due to the transistor's curve, making the positive and the negative excursions of the output signal asymmetrical. At lower frequencies, feedback overcomes this nonlinearity. Transistor amplifiers soon evolved into operational amplifiers that have forward gain that can exceed 120 dB, enabling designers to improve linearity by using a large amount of negative feedback. This feedback combines with Class A-B output stages to produce linearity such as that of the National Semiconductor LME49710, which specifies a linearity of 0.00003%. Note, however, that this linearity spec is for operation at relatively low frequencies. All amplifiers exhibit a roll-off of gain with frequency. Current-feedback-amplifier architectures have less gain loss at high frequencies, but they still roll off at high frequencies.

Remember that the linearity improvement you achieve with large feedback involves also having a large forward gain. Because amplifiers have less forward gain at higher frequencies, they also have less feedback at high frequencies. As a result, RF amplifiers, especially RF power amplifiers, cannot use conventional feedback at the 1-GHz and higher frequencies at which they operate.

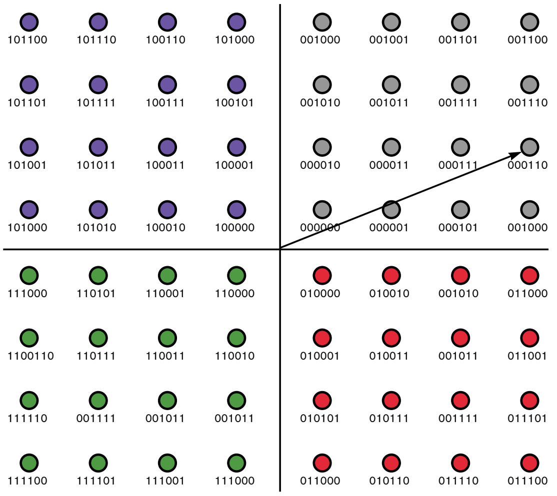

Figure 3 A 64-QAM constellation can encode 6 bits per symbol vector. Some vectors are subject to phase errors, and some vectors are sensitive to amplitude errors. In either case, the accuracy of the waveform envelope is critical, which makes amplifier linearity so important.

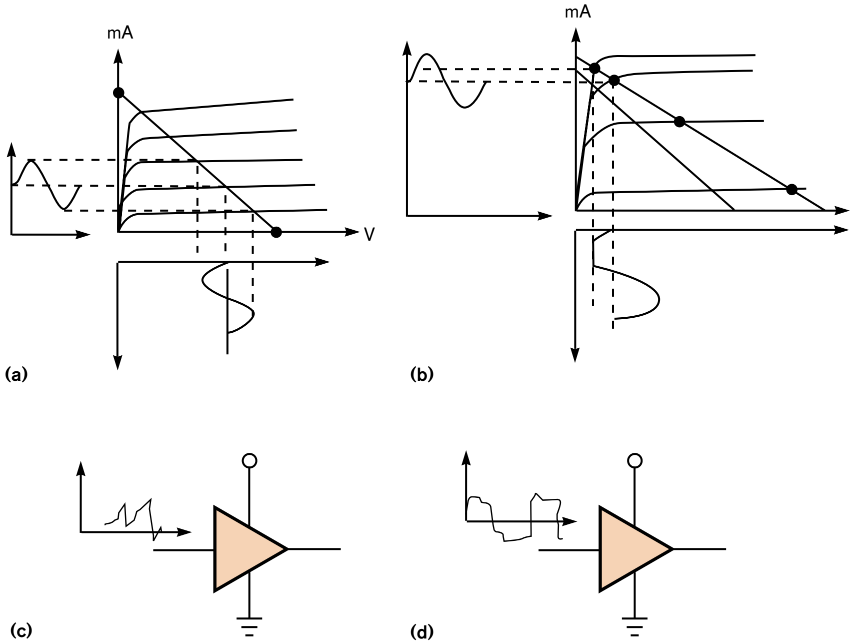

Figure 4 RF-power-amplifier nonlinearity occurs because of the inherent nonlinearity of a transistor amplifier (a), clipping distortion (b), and both electrical-memory (c) and thermal-memory (d) effects.

Just as daunting, the open-loop nature of most RF amplifiers means that they are subject to power-supply-rejection and output-saturation problems. Because RF amps operate near the frequency limits of the transistors themselves, you cannot practically make them into high-gain operational amplifiers. In this regard, RF-amplifier design still incurs all the difficulties that designers of tube equipment faced decades ago.

In addition to the linearity problems facing all amplifier designers, other linearity impediments make RF amplifiers even more challenging. For example, the electrical and thermal operation of the amplifier can cause memory effects that in turn introduce time- or data-dependent nonlinearity. Electrical-memory effects are analogous to the memory effects that you can observe in old tube-guitar amplifiers. These amps had cheap power-supply systems—often, open-loop linear supplies comprising a capacitor hanging across a tube-rectified line voltage. A loud power chord would heavily drive the output stage and pull down the power-supply voltage as the capacitor drained. The line voltage restores the capacitor after the heavy load, but it takes 10s of milliseconds to do so. The sag in the power-supply voltage changes the biasing of the output transistors in the guitar amplifier, creating distinct "data-dependent" nonlinearity. The degree of nonlinearity depends on the previous signal. RF-power amplifiers are subject to the same phenomenon. The sequence of data may require symbols that cause the heavy driving of the amplifier. This situation affects the power supply and biasing of the amplifier and creates time-dependent nonlinearity that changes with the modulation of the RF carrier.

Besides these electrical-memory effects, amplifier designers must also handle thermal-memory effects. Hot and cold transistors have different transfer functions, introducing a time-dependent nonlinearity into the system. If the environment is hot or the data stream heats up the output stage, then the transistor exhibits different nonlinearity from what it would exhibit at a cool temperature. As more CMOS chips are integrating RF-power amplifiers, even more thermal problems emerge.

Figure 4 shows the nonlinearity of RF-power stages. At the core of transistor nonlinearity is the fact that the current-to-voltage transfer function of a

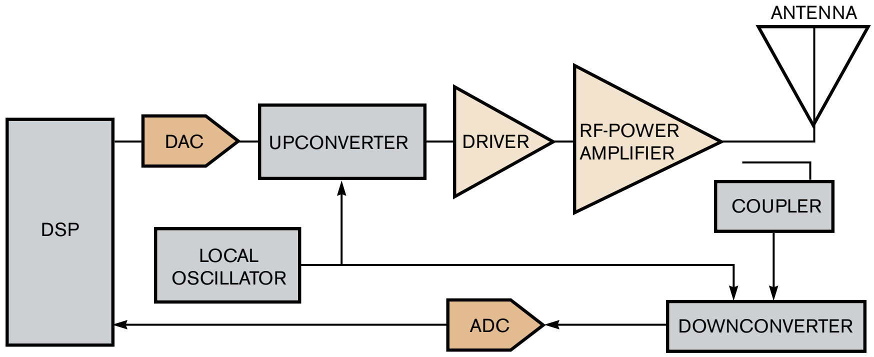

Figure 5 A cell-phone base station uses digital predistortion depending on the components the base station uses. Cartesian feedback also allows dynamic algorithms that can help compensate for memory effects and other nonlinearity.

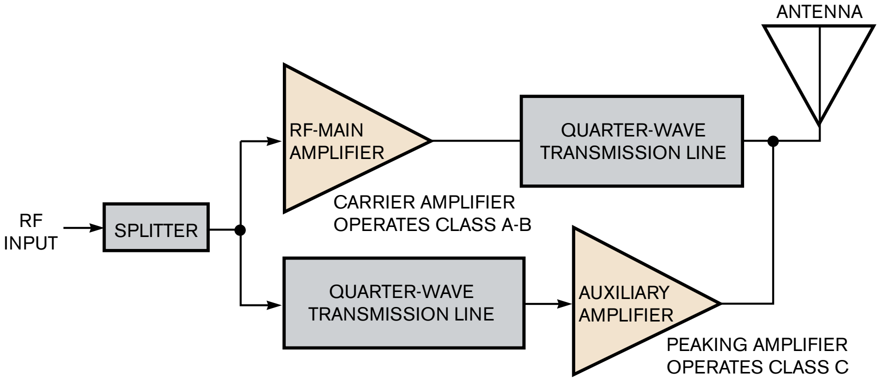

Figure 6 The Doherty RF amplifier achieves better efficiency by using an auxiliary amplifier to vary the load impedance on the primary amplifier. This approach allows the primary amplifier to continue to swing a large signal, dissipating less power in the amplifier. If the auxiliary amp lowers the load impedance on the primary amplifier, the primary amplifier delivers more power.

transistor is a logarithmic curve, not a straight line. The next issue is the saturation of the transistor as it approaches the power-supply rail.

APPROACHES TO LINEARITY

RF designers cannot just swing the output of the amplifier across a smaller range and suffer with the efficiency hit. They can use feedback, feedforward, or predistortion approaches to preserve efficiency for battery life and power savings. The feedback approach suits designs requiring high linearity, narrow bandwidth, and medium efficiency. The feedforward technique also works for designs requiring high linearity but with wide bandwidth and a low-efficiency requirement. Predistortion allows for medium linearity and bandwidth but yields high efficiency. Because RF-power amplifiers operate at such high frequencies, the use of conventional feedback techniques is impractical. In this context, the term “feedback” often refers to Cartesian feedback, in which circuitry converts the RF output back down to baseband, deriving the I (in-phase) and Q (quadrature) signals and feeding those signals back to the input stages. This system can achieve high linearity but only if you don’t overdrive the output stage. The efficiency is lower than you might think. Because feedback amplifiers are subject to oscillation, you cannot use this technique on wideband amplifiers.

To get both acceptable linearity and high bandwidth, RF designers have resorted to predistortion techniques: The I and the Q signals that perform the modulation can compensate for the deterministic nonlinearity of a system. Because a digital system can also use complex algorithms to predict the thermal- and electrical-memory effects, these setups also preserve linearity in the face of these problems. Note that the inherent linearity of the components in the RF-signal path is still relevant. There is a limit to the corrections that you can apply in the digital domain. The closer the signal path is to ideal, the easier job a digital-system designer will have providing an accurate predistorted signal.

Designers are always cognizant of the inherent linearity of system components, according to James Wong, high-frequency-product-marketing manger at Linear Technology. "An active upconverter with built-in amplification, noise, linearity, and superior isolation results in a superior dynamic range … compared with a passive upconverter followed by an amplifier," he says. "This [approach] greatly reduces the challenge [for] digital designers … providing predistortion to the signals." He points out that modern base stations also use Cartesian feedback. Circuitry downconverts and extracts the I and Q components of the output and then feeds them back to the DSP core. This approach allows the system to use sophisticated algorithms that use real-time Cartesian feedback as well as predistortion based on the components the signal chain uses (**Figure 5**).

Hardware designers need not resort to using digital predistortion to improve linearity, however. Hardware can also improve linearity and efficiency; the better the inherent linearity, the less digital systems must correct. Designers may want to consider the use of a Doherty amplifier, which William H Doherty of Bell Laboratories invented in 1936 (**Figure 6** and **Reference 1**). This amplifier has two RF paths. The RF does not just shuttle between a low-power stage and a high-power stage. The output-voltage swing in an RF amplifier should be close to the power-supply-rail voltage. The Doherty amplifier uses the second amplifier to change the apparent output impedance on the main amplifier. An amplifier feeding a transmission line faces an infinite output impedance if the second amplifier produces an identical signal on the other end of the line (**Figure 7**). Because both ends of the transmission line are equipotential, no current flows, and the line delivers no power. If you don't drive the secondary amplifier at all, then the output impedance that the first amplifier "sees" is the characteristic impedance of the transmission line. By extension of this principle, if you drive the secondary amplifier 180° out of phase from the first, then you are differentially driving the right side of the transmission line, and the apparent output impedance that the first amplifier sees is half the characteristic line impedance, increasing the delivered power. The main amplifier always swings near the output rails. If the design requires low-power transmission, the secondary amplifier increases the ap-

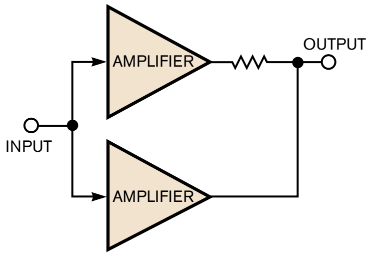

Figure 7 In this circuit, the same signal passes to both sides of a resistor, and the upper amplifier sees an infinite load. The amplifiers drive both sides of the resistor at the same amplitude, so neither amplifier sources any current or delivers power to the resistor. If the signal to each amplifier is 180° out of phase, the load that each amplifier perceives would be twice the resistor value. A Doherty amplifier uses this principle to vary output power and maintain efficiency.

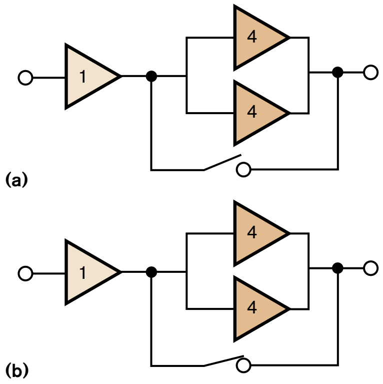

Figure 8 The low cost of handsets encourages the use of straightforward methods to improve efficiency. Avago makes amplifier modules that switch between high-power mode with output power greater than 16 dBM (a) and low-power mode with output power less than 16 dBm (b). The improvement in efficiency can add an hour of talk time.

parent output impedance that the main amplifier sees, and, for a given voltage swing near the rail, the amplifier delivers less current and, hence, less power.

The sophistication of the Doherty amplifier makes it a good fit for use in the base-station side of the cell-phone world. On the handset side, space and cost constraints are far more severe. In this case, you can use RF switches to switch gain blocks as necessary, providing substantial power savings. For example, Avago's CoolPAM (power-amplifier-module) RF devices provide cell-phone designers a way to maintain efficiency over wide output-power levels (**Figure 8**). You can use this straightforward technique instead of feeding the output stage with a dc/dc converter. Using the converters allows the RF-output stage to always operate near saturation and, hence, improve efficiency. However, dc/dc converters consume more space and have efficiency limitations of their own. Using the CoolPAM technology, Avago claims, can increase talk time to more than an hour, a compelling opportunity for cell-phone designers.

THE TROUBLE WITH MODELING

The quest for linearity with efficiency in RF-power amplifiers also affects the EDA tools for developing RF systems. Because these RF systems are inherently nonlinear, they share all the mathematical problems of other nonlinear systems. Using Spice and other circuit-simulation techniques may not apply and may be time-consuming because RF designs often require steady-state operation, a condition that may take billions of signal excursions to achieve. RF designers have typically resorted to black-box-modeling techniques, such as the use of S (scattering) parameters, to design systems. S parameters do not account for nonlinearity and do not model the bias points of the amplifier, however. To solve this problem, Agilent, which popularized S-parameter design, recently introduced X parameters, or polyharmonic-distortion modeling (**Reference 2**). These parameters combine the response of a linear system with the response due to the nonlinear factors. Agilent has provided several papers detailing this technique, and the inclusion of X-parameter simulation in Agilent's RF-design tools and the development of Agilent's test equipment that can characterize X parameters are sure to follow.

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The design of RF-power amplifiers is becoming increasingly difficult due to the design requirements for new cell-phone-modulation schemes. The RF domain has long been the realm of intuitive design and experienced engineers. The demands on linearity and efficiency in these new designs only further accentuate the need for expertise when creating designs that work properly. The design effort is also spreading across disciplines. RF-, analog-, and digital-system designers all contribute to the performance of the signal chain. With experienced designers now getting access to sophisticated tools and instruments from EDA and test-equipment manufacturers, you can all look forward to even more amazing performance gains, all at significantly lower costs.EDN

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