# Learn The Meaning Of Amplifier Linearity

*Microwaves and RF*

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Linearity is an important performance parameter when evaluating a power amplifier for use in certain communications applications, especially systems with advanced modulation formats.

Linearity in an RF/microwave amplifier is a term synonymous with "fidelity" in an audio amplifier. In both cases, the term refers to the essential job of an amplifier, to increase the power level of an input signal without otherwise altering the content of the signal. The term linearity derives from an amplifier's linear relationship of input power to output power which, in an ideal amplifier, would be precisely related by the gain of the amplifier. Of course, this implies an amplifier with a gain response of X 0.0 dB across the frequency range of the amplifier. Even approaching such gain flatness over a narrow band of operation involves complex matching circuits to make a transition from the low impedance of a solid-state transistor to the higher 50-Ohm characteristic impedance of microwave systems. And still, because the tendency of most power transistors is to lose gain with increasing frequency, most amplifiers inevitably suffer a gain rolloff at higher frequencies.

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One of the classic trade offs in poweramplifier transistors is between output power and bandwidth. Active devices are inherently limited in bandwidth by internal parasitic capacitance. Eventually, every transistor reaches a frequency at which signal gain drops below unit and where the device is no longer useful as an amplifier. Smaller transistor geometries can achieve higher operating frequencies, but the smaller dimensions result in reduced current (and power) capacity.

Bandwidth is a limited commodity in modern communications systems, and high spectral efficiency is needed to transfer large amounts of data over finite communications channels. Amplifier linearity is essential to preserving the integrity of the complex modulation formats used to achieve high data rates, which may rely on accurate amplitude and or phase control of a signal.

In communications formats based on traditional modulation schemes, such as frequency modulation (FM), amplifier linearity is not particularly critical. An FM demodulator works at the zero crossings of received signals to extract the modulated information. But in modern communications systems (especially digital communications systems operating at high data rates), such as in quadrature-amplitudemodulation (QAM) schemes, information is carried in the form of the phase and amplitude of the envelope signal. Thus, the instantaneous accuracy of the signal is vital to effectively extracting the carried data upon demodulation. Even time- and/or temperature-related nonlinearities in a power amplifier can result in a loss of transmitted data in systems that rely on vector modulation.

In a plot of input power (x-axis) versus output power (y-axis), theoretical linear performance would be a straight line. In reality, amplifier output power is described in terms of the output power characterized by some gain compression, such as the output power at 1-dB compression, or at 3-dB compression, or the saturated output power. In linear operation, the slope of the line is equal to the gain of the amplifier.

High amplifier linearity is possible, but at the expense of efficiency. Over the years, a number of different biasing schemes have been developed for amplifiers, from extremely linear Class A operation, in which the active devices essentially remain powered on through the full sinewave cycle of an input signal, to more power-efficient schemes, such as Class D, in which multiple transistors are switched on and off to conduct different portions of an input waveform.

What deprives an amplifier of its linearity? Amplifiers are not ideal in their transfer characteristics, and can generate harmonic signals at multiples of the applied fundamental input signals as well as intermodulation distortion, both of which are amplified along with the desired tones. Intermodulation distortion (IMD) is the result of transistors acting as mixers and generating sumand- difference products of applied input signals, again robbing power from the desired fundamental-frequency signals. Intermodulation distortion is usually specified in terms of the output power at a given intercept point, such as the third-order intercept point. In comparing amplifier intermodulation distortion, test conditions must be considered, including the number of tones, their power levels, their frequencies, and the separation between the tones.

In RF/microwave power amplifiers, time-dependent nonlinearities can occur due to memory effects. For example, when input signal dynamics drive a power amplifier close to its output limits and place stress on the power-supply voltage, the resulting sag in the powersupply voltage can change the biasing of the output-stage transistors and create input-signal-dependent nonlinearities or memory effects. A modulation format with varying amplitude characteristics can also drive an RF/microwave power amplifier into nonlinear behavior.

Thermal management in RF/microwave power amplifiers is important not only for extended transistor lifetime, but for maintaining good linearity. The linearity of an RF transistor is dependent upon temperature, with cold and hot transistors exhibiting different transfer functions. As a result, transistor amplifiers operated in hot environments, or driven to higher junction temperatures, will exhibit different linearity behavior than the same transistor amplifier at colder operating temperatures.

## CHARACTERIZING LINEARITY

Amplifier linearity is usually characterized by a number of different parameters, depending upon the type of signal to be amplified and the application. Linearity can be described by such parameters as the carrier-to-intermodulation (C/I) ratio, the noise power ratio (NPR), the adjacent-channel power ratio (ACPR), and the error vector magnitude (EVM). As with other forms of intermodulation distortion, the C/I ratio is determined by testing with multiple input tones and comparing the IMD products to the level of the carrier outputs for the ratio. A linear power amplifier will usually exhibit a C/I ratio of 30 dB or higher. NPR is usually measured with Gaussian noise signals to determine the amount of noise created by amplification as a ratio of the desired output noise level. ACPR is a measure of how much energy is produced outside of a desired band, which could result in interference in multichannel communications systems. EVM is an evaluation of the amount of distortion in signal vectors, usually shown on a constellation diagram, typically specified in terms of peak and root-mean-square (RMS) errors.

Although power transistors are not ideal in their electrical characteristics, high-linearity amplifiers can be achieved by means of a variety of circuit approaches, including the use of feedback, feed forward, and digital predistortion (DPD). In fact, linearity performance approaching 0.0 percent has been achieved at very low frequencies in some negative-feedback designs. These techniques typically trade off excess gain to make corrections in an amplifier's input/output transfer curve, with additional trade offs in efficiency and bandwidth. For signals that are part of complex modulation schemes, for example, feedback may involve the use of Cartesian approaches in which inphase (I) and quadrature (Q) signal components are derived as correction signals. The approach can deliver improvements in linearity, but at the expense of efficiency and, at times, amplifier stability, especially in broadband designs which may be prone to oscillations.

In some amplifiers, improved linearity is achieved by following a practice of "backing off" the output power. Rather than operating the amplifier at conditions close to device saturation, the bias and input signal levels are decreased to maintain the amplifier within the linear portion of its input/output transfer curve. Of course, this approach to linearity results in significantly reduced output power compared to operation close to saturation, while also sacrificing the average efficiency of the amplifier.

When comparing the linearity of different amplifier products for various applications, it is important to normalize the values presented on different data sheets. As with other amplifier figures of merit, such as gain or noise figure, linearity should be compared at similar frequencies and power levels. The type of signals should also be considered, such as continuous-wave (CW), pulsed, or modulated signals, and the types of modulation that are being compared. For portable applications, it may also be useful to include the associated efficiency while also noting the bias (current and voltage) requirements. Because amplifiers with linearization schemes such as feedback and DPD may sacrifice some amount of efficiency to achieve higher linearity. And even in this comparison, the operating frequencies and power levels should be the same.

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