Linearization: Reducing Distortion in Power Amplifiers

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Our society's need to exchange greater and greater amounts of information has created an unprecedented demand for highly linear power amplifiers (PAs). High linearity is required for the spectrally efficient transmission of information.

This article discusses techniques for the cancellation of distortion (linearization). Different methods of linearization are introduced and compared. The linearization of solid-state power amplifiers (SSPAs), traveling-wave-tube amplifiers (TWTAs) and klystron-power amplifiers (KPAs) are considered. Although the focus of this article is on power amplifiers, many of the techniques are applicable to other components as mixers, low-noise amplifiers, and even photonic components, such as lasers and optical modulators.

Amplifier Linearity

Technological developments are rapidly changing the communication business. In the past, the bulk of satellite transmissions was single-carrier video signals. Digital compression now allows many television signals to be transmitted in the frequency space previously occupied by a single signal. Nonvideo, broadband very small aperture terminals (VSATs) and mobile telephone/Internet services are altering traditional satellite loading. New terrestrial microwave services for the transmission of video, data, cellular telephone, and personal communications are appearing daily. Bandwidth-efficient modulation (BEM) schemes are becoming common. Virtually all of these services involve the transmission of multiple signals and/or large quantities of information at high data rates. For such signals,

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whether transmitted by frequency-division multiple access (FDMA), code-division multiple access (CDMA), or time-division multiple access (TDMA), amplifier linearity is a major consideration.

At high power levels (>100 W) TWTAs and KPAs offer the best microwave performance in terms of size, cost, and efficiency but lag behind SSPAs in linearity. The use of linearization can yield TWTA and KPA performance comparable or superior to conventional SSPAs. At lower powers, the advantage switches to SSPAs. As a result of new stringent linearity requirements, even relatively linear SSPAs can benefit from linearization.

Nonlinear Distortion

Nonlinear distortion can be thought of as the creation of undesired signal energy at frequencies not contained in the original signal. Distortion is produced by a loss of linearity. Amplitude linearity can be considered a measure of how closely the input-output transfer response of an amplifier resembles a straight line. When an amplifier's input level increases by a certain percent, its output level should increase by the same percent. A deviation from a straight line can be represented by a power series

$$V_{out} = K_1 V_{in} + K_2 V_{in}^2 + K_3 V_{in}^3 \cdots + K_n V_{in}^n. \quad (1)$$

When a single-carrier input signal, represented by a sine wave, is substituted into this expression, the output waveform will contain the original sine wave and harmonic distortion products. The harmonics can be eliminated by filtering and do not pose a problem except for wideband-communications applications of an octave or greater bandwidth. However, when more than one carrier is present, beat products are produced in the vicinity of the input signals. These new signals are known as intermodulation-distortion (IMD) products. They are located at frequencies above and below the input carriers and at frequency intervals equal to the separations of the input carriers (Figure 1). Filtering cannot easily eliminate IMD products since they are located on the same frequency or near to the desired input signals.

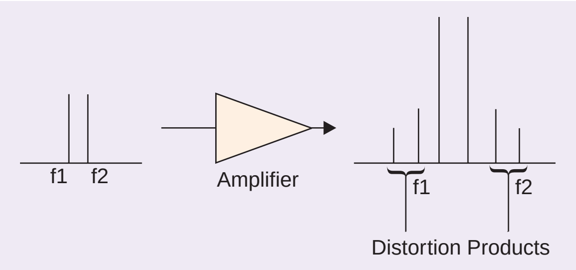

Figure 1. *When ≥ 2 signals are amplified, distortion products appear in the vicinity of the desired signals.*

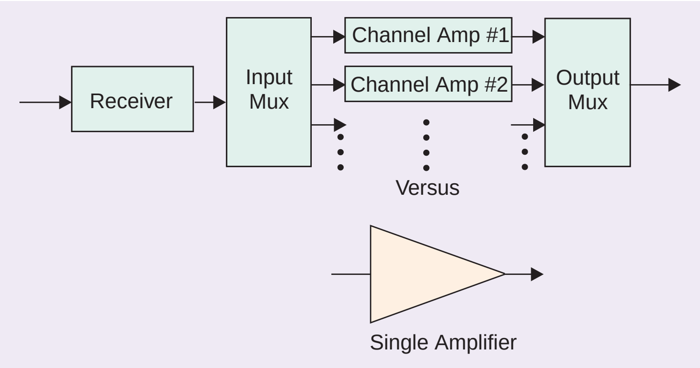

Figure 2. *In cellular telephony, sending several carriers through one amplifier is more cost effective.*

Distortion is also produced by phase nonlinearity. The shift in phase angle that a signal encounters in passing through an amplifier is a measure of the time delay. Ideally, this phase shift, or time delay, should be constant for all power levels. A change in time delay with frequency, known as phase delay, envelope delay, or group delay, causes linear distortion and can be corrected with a phase equalizer

$$\theta(P_{in}) = \text{constant}, \quad (2)$$

where P_{in} is the instantaneous-input power level. In practical amplifiers, there can be a substantial change in phase with power level

$$\theta = f(P_{in}). \quad (3)$$

This change in phase with amplitude converts variations in signal level to phase modulation (PM). For a sinusoidal signal envelope

$$P_{in}(t) = k\left(A\cos[\omega_m t]\right)^2,$$

the resulting spectrum resembles that of a sinusoidal modulated PM signal

$$A_c \cos\left(\omega_c t + M\cos[\omega_m t]\right) = A_c \sum_{n=-\infty}^{n=\infty} J_n(M)\cos\left([\omega_c + n\omega_m]t\right), \quad (4)$$

where ω_c is the carrier frequency, ω_m is the modulation frequency (frequency of the envelope), and M is the modulation index (proportional to A). The PM sidebands are the IMD. Thus, phase nonlinearity produces IMD products in a similar fashion to amplitude nonlinearity. In some systems, phase nonlinearity is the principal cause of distortion.

When multiple signals are sent through a communications system, an amplifier must be operated at a reduced power level (backed off) in order to keep distortion at an acceptable level. Distortion is often measured as the ratio of the carrier-to-IMD power level. This ratio is known as C/I. An acceptable level of IMD or C/I usually depends on the carrier-to-noise ratio (CNR) required at the receiver. IMD products can be considered to add to a receiver's noise level on power basis. For a carrier to IMD ratio,

- If C/I = CNR, the resultant CNR degrades by approximately 3 dB.
- If C/I = CNR + 6 dB, the resultant CNR degrades by approximately 1 dB.
- If C/I = CNR + 10 dB, the resultant CNR degrades by approximately 0.05 dB.

Thus, if the IMD products are to have a negligible affect on system performance, they should be at least 10 dB smaller than the carrier level.

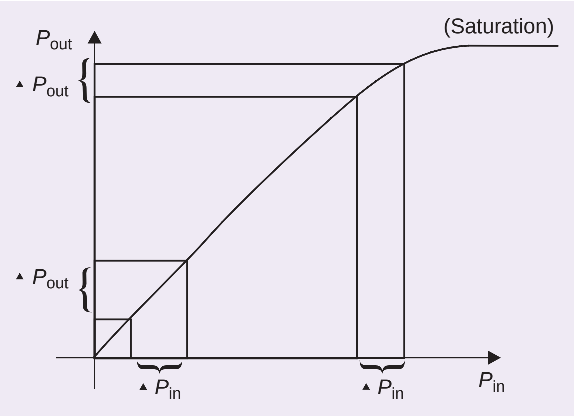

Figure 3. *As an amplifier is driven closer to SAT, its output level will increase by a smaller amount.*

In the case of cellular telephony, it is often more convenient and cost effective to transmit several carriers through a common amplifier rather than to use multiple amplifiers and a lossy multiplexer (Figure 2). To avoid unacceptably high IMD, the common amplifier must be highly linear.

For the transmission of a single carrier, IMD is usually not a limitation. However, with digitally modulated signals, spectral regrowth (SR) can be a serious problem. SR manifests itself in a form equivalent to IMD. It is not unique to digital signals but an aspect of angle modulation (FM and PM). Angle-modulated signals have a theoretically infinite bandwidth; for example, the spectrum of a sinusoidal modulated-PM signal of (3) contains an infinite number of sidebands. In practice, the bandwidth is limited to a finite frequency band beyond which sideband amplitude drops off rapidly. Analog PM has an approximate bandwidth given by Carson's rule

$$BW = 2(\Delta f + f_m), \tag{5}$$

where Δf is the peak frequency deviation and f_m is the modulation frequency. The effective bandwidth of angle-modulated digital signals can be much greater than predicted by (5) due to the high-frequency components of the modulating waveform. To reduce their bandwidth to a more acceptable value, digital waveforms are normally low-pass filtered before modulation. Because of the mechanics of most digital modulators, which are not true angle modulators, the amplitude of the carrier is also modulated by this process. In addition, any "band-limiting" filtering of an angle-modulated signal will introduce amplitude modulation. It is primarily this incidental amplitude modulation that causes the SR when a digital signal is passed through a nonlinear amplifier. The distortion of the induced-amplitude waveform produces IMD products that increase the signal's spectrum.

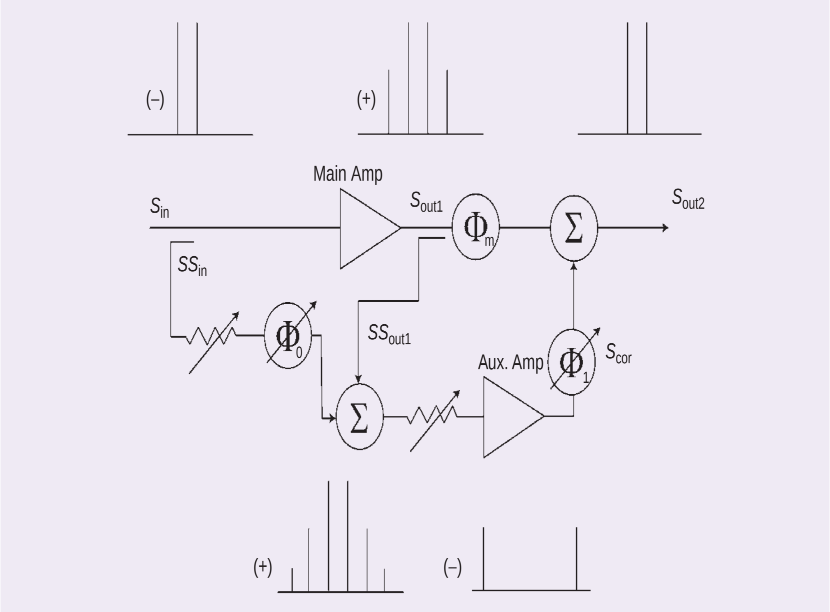

Figure 4. *Feedforward linearization employs two loops for the cancellation of IMD.*

The change in phase with amplitude (3) converts the variations in signal level to angle-modulation sidebands. These new sidebands further broaden the signal bandwidth. Amplitude and phase-induced spectral products add as vectors and are classified, in general, as IMD.

The summation of the IMD terms in an adjacent channel is referred to as the adjacent-channel power level (ACPL),

$$\text{ACPL} = \Sigma\text{IMDs}\,\big|\text{ in an adjacent channel.}$$

The ratio of the adjacent-channel power to the carrier power is known as the adjacent-channel power ratio (ACPR).

ACPL is a major concern in personal-communications systems (PCS) since transmission often occurs on a channel adjacent to one in which reception of a much weaker distant signal may be taking place. To ensure freedom from interference, transmitter IMD products must be below the C/I by anywhere from 35 to >65 dB, depending on the application. These levels of linearity are considerably higher than had been required of communications amplifiers in the past, except for some special applications.

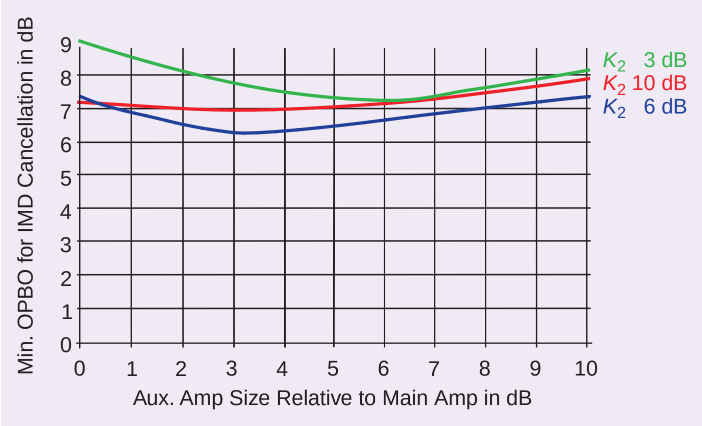

Figure 5. *The minimum OPBO for cancellation of IMD by a FF amplifier depends on the aux-amplifier size and output coupler coefficient.*

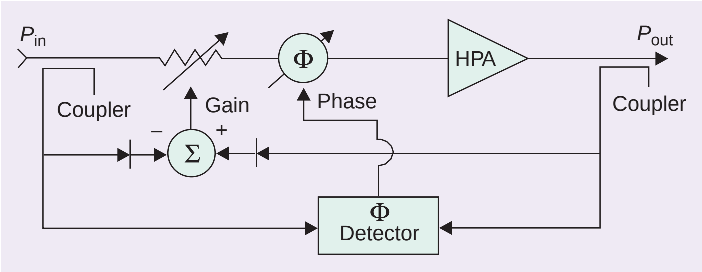

Figure 6. *IFB compares an amplifier's output and input and uses the detected difference to minimize distortion.*

Saturated Power

All amplifiers have some maximum output-power capacity, referred to as *saturated power* or simply *saturation* (SAT) (Figure 3). Driving an amplifier with a greater input signal will not produce an output above this level. As an amplifier is driven closer to SAT, its deviation from a straight-line response will increase. Its output level will increase by a smaller amount for a fixed increase in input signal, as shown in Figure 3. Thus, the closer an amplifier is driven to SAT, the greater the amount of distortion it normally produces.

The SAT point of TWTAs and KPAs is clearly defined as the output power normally decreases beyond SAT. Many SSPAs are sensitive to overdrive and can be easily damaged by operation at or beyond SAT. In addition, SSPAs tend to approach SAT exponentially. These factors make engineers reluctant to measure and use SAT as a reference for comparison of SSPA performance. They prefer to use the power at which an amplifier's gain compresses by 1 dB as the reference (REF) for amplifier comparison.

$$\text{REF} = \text{1-db CP} = \text{SAT} - D. \tag{6}$$

For SSPAs with reasonable linearity, the difference (D) in output level between SAT and the 1 dB compression point (CP) is

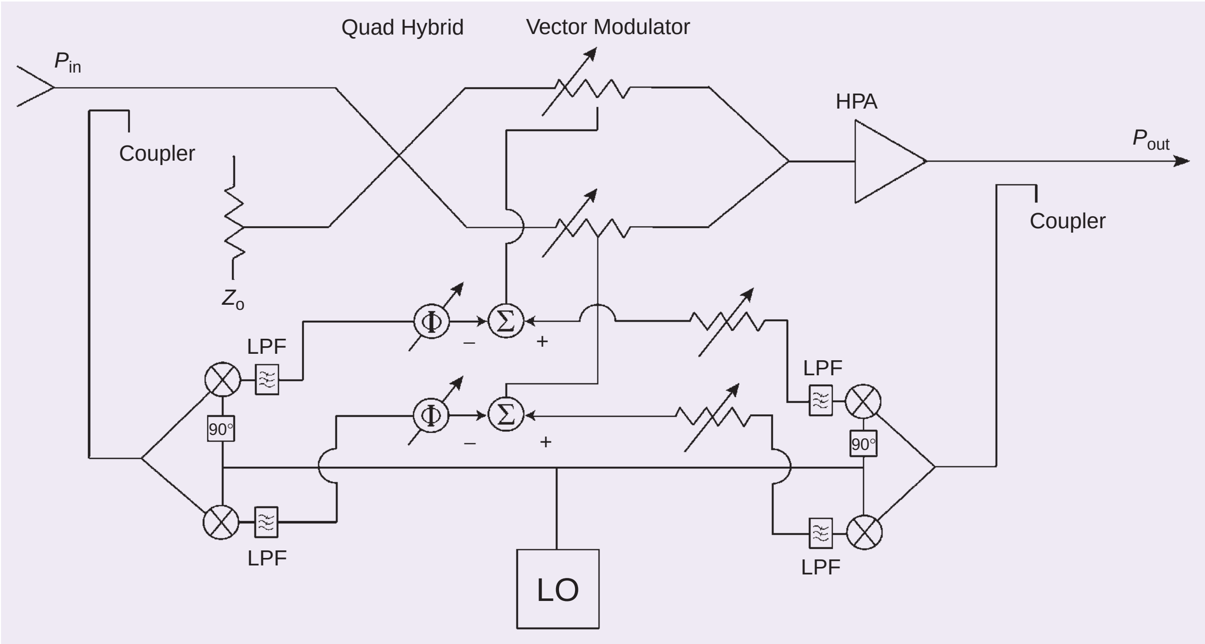

Figure 7. *Cartesian feedback eliminates the need for phase correction components by using the difference between in-phase and quadrature signals to control attenuators in a vector modulator.*

about 1 dB. Unfortunately, *D* varies from amplifier to amplifier. Generally, amplifiers with high linearity will have a smaller difference ($D < .25$ dB), while amplifiers with poor linearity can have a difference of several dB ($D > 2$ dB).

For this reason, in this article the relative amplifier performance will be referenced to (single-carrier) SAT. Output-power backoff (OPBO) will be relative to an amplifier's single-carrier SAT. (For most SSPAs, SAT can be safely determined using a network analyzer in a rapid power-sweep mode. For amplifiers that are especially thermally sensitive, pulsed power-sweep techniques may be used.) When comparing the data presented here with that of SSPAs based on a 1-db CP REF, an appropriate correction factor should be assumed.

Generally the greatest efficiency of a high power amplifier (HPA) will occur at or near SAT. Similarly, the closer to SAT a linear amplifier (class-A and, to a large extent, class-AB) is driven, the greater the amount of distortion it produces. For a satellite system, if a CNR of 16 dB (10 dB FM threshold + 6 dB for rain fading) is required and the IMD products are to have a negligible effect, then a C/I ≥ 26 dB is needed. To satisfy this requirement, a TWTA would typically have to be backed off 5-7 dB and sometimes more. This is about a 4-to-1 reduction in usable power. For TDMA applications, the backoff is less, usually 2-4 dB, to keep distortion in the form of SR from interfering with adjacent-channel communications. To satisfy cellular/PCS adjacent-channel IMD requirements, a (class-A) SSPA would have to be backed off about 6.5 dB for a C/I = 35 dB and by more than 15 dB for a C/I = 65 dB. These are huge reductions in usable output power. Therefore, it is desirable to look at various linearization techniques.

Linearization Techniques

Linearization is a systematic procedure for reducing an amplifier's distortion. There are many different ways of linearizing an amplifier. Usually, extra components are added to the design of a conventional amplifier. These extra components can often be configured into a subassembly or box that is referred to as a linearizer. Linearization allows an amplifier to produce more output power and operate at a higher level of efficiency for a given level of distortion. Feedforward, feedback, and predistortion are the most common forms of linearization. Besides these, there are a variety of other approaches that are being investigated. Most of these approaches use special techniques to obtain a linear output signal from highly nonlinear amplifiers. None of these alternate methods have been widely applied in wireless or microwave applications.

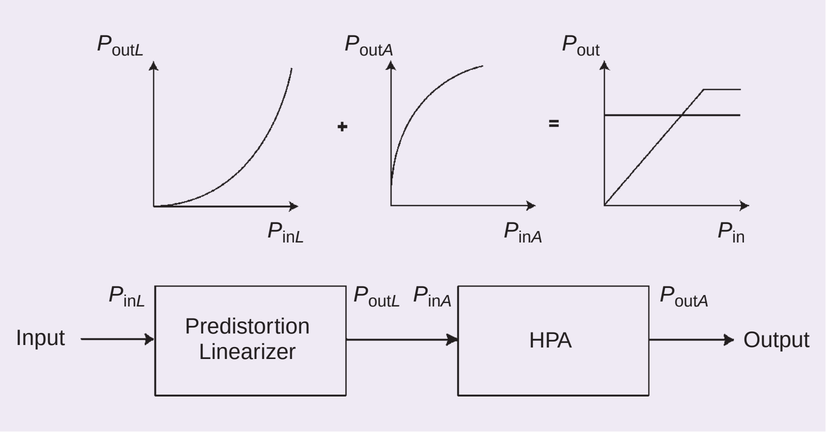

Figure 8. *PD linearizers generate a response opposite to an HPA's response in magnitude and phase.*

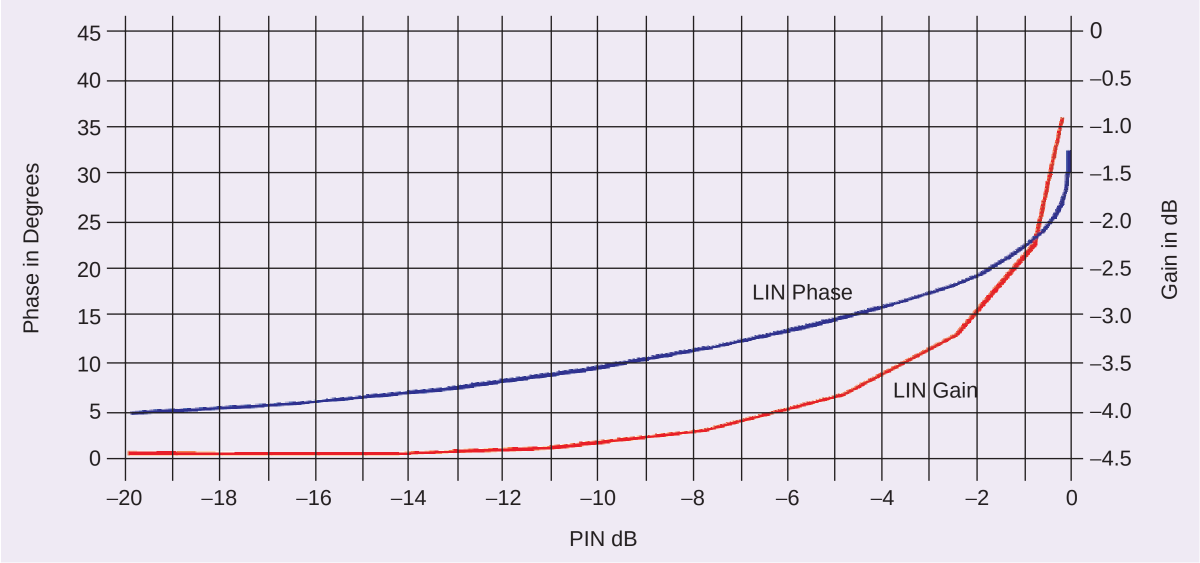

Figure 9. *An ideal PD-linearizer response requires the gain-and-phase slope to become infinite as SAT is approached.*

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