9

Linearization and Efficiency Improvements of RF Power Amplifiers

9.1 Introduction

High efficiency and high linearity of power amplifiers [1–85] are of primary importance in wireless communication systems. Wireless communication systems transmit voice, video, and data with high data rates. High efficiency is required for low energy consumption, a longer battery lifetime, and thermal management. Linearity is required for achieving low distortion of the amplified signals. The radio-frequency (RF) power amplifier specifications call for intermodulation (IM) levels of −60 dBc. Linearity and efficiency enhancement techniques of RF power amplifiers, which are used in transmitters, are studied in this chapter.

Signals used in modern digital wireless communications systems have a time-varying envelope (amplitude modulation; AM) and time-varying angle (phase modulation; PM)

$$v_{AM/PM} = V_m(t)\cos[\cos\omega_c t + \phi(t)] \tag{9.1}$$

A nonconstant envelope signal requires linear power amplifiers in the transmitters. The output power in CDMA2000 and WCDMA transmitters may vary in a wide dynamic range of 80 dB. The average output power is usually lower than the peak power by 15–25 dB. The transmitters must be designed for the maximum output power. A high peak-to-average ratio (PAR) drives many power amplifiers into saturation, causing signal distortion and generating out-band interference. The maximum efficiency of linear power amplifiers such as Class A, AB, and B amplifiers occurs at the maximum output power. In a linear Class A power amplifier, the average power is usually set at a back-off (BO) of 10–12 dB, resulting in a very low average efficiency. In this case, the maximum amplitude of the drain-to-source voltage V_m is nearly equal to the supply voltage V_I. This corresponds to the AM index equal to 1. However, the average AM index is in the range of 0.2–0.3, when the amplitude of the drain-to-source voltage V_m is much lower than

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RF Power Amplifiers, Second Edition. Marian K. Kazimierczuk.
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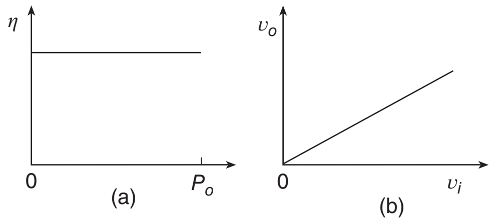

Figure 9.1 Ideal characteristics of a power amplifier. (a) Efficiency η as a function of the output power. (b) Output voltage v_o as a function of the input voltage v_i.

the supply voltage V_I. Therefore, the statistical average efficiency of linear power amplifiers with AM is much lower than their maximum efficiency. In wireless communication systems, there are two types of transmitters: base-station transmitters and handset transmitters.

Ideal characteristics of a power amplifier are depicted in Fig. 9.1. The efficiency η should be very high over a wide range of the output power, as shown in Fig. 9.1(a). The output voltage v_o should be a linear function of the input voltage v_i, as shown in Fig. 9.1(b). In this case, the voltage gain of the amplifier $A_v = v_o/v_i$ is constant over a wide range of the input voltage.

Power control of RF transmitters is required in modern digital wireless communications. In CDMA, power control is used in both the base-station transmitters and handset transmitters. In base-station transmitters, a higher power is required to transmit the signal to the edges of a cell. In handset transmitters, the output power should be transmitted at variable levels so that the power levels of the signals received at the base station are similar to all users.

This chapter presents an overview of basic linearization and efficiency- enhancement techniques of power amplifiers invented over the years. The purpose of some of these techniques is to improve either the linearity or the efficiency only, while some other techniques address both the linearization and efficiency enhancement together.

9.2 Predistortion

Nonlinear distortion in the output signal of a power amplifier is caused by changes in the slope of the transfer function $v_o = f(v_i)$. These changes are caused by the nonlinear properties of transistors (MOSFETs or BJTs) used in the power amplifier. The changes in the slope of the transfer function cause changes in the gain at different values of the input voltage or power. There are several techniques for reduction of nonlinear distortion.

Predistortion is a technique that seeks to linearize a power amplifier by making suitable modifications to the amplitude and phase of the power amplifier input signal v_i [1–3]. This technique includes analog predistortion and digital predistortion. A block diagram of a power amplifier with predistortion is depicted in Fig. 9.2. A nonlinear block is connected in the signal path to compensate for the nonlinearity of the power amplifier. This block is called a *predistorter* or a *predistortion linearizer*. Predistortion can be performed either at RF or baseband frequencies. Predistortion at baseband frequencies is favorable because of digital signal processing

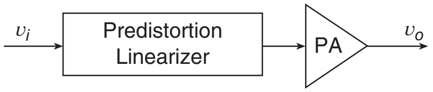

Figure 9.2 Block diagram of power amplifier with a predistortion system.

(DSP) capabilities. This is called “digital predistortion.” DSP ICs can be used to perform digital predistortion. It is an open-loop system, which is inherently stable. The disadvantage of the system is the difficulty in generating the transfer function of the predistorter such that the transfer function of the overall system is linear.

Example 9.1

A power amplifier voltage transfer function has the gain $A_1 = 100$ for small signals and the gain $A_2 = 50$ for large signals, as depicted in Fig. 9.3(a). Find the transfer function of the predistorter to achieve a linear transfer function of the overall system.

Solution. Let us assume the gain of the predistorter for small signals to be $A_3 = 1$. The ratio of the two gains of the power amplifiers is

$$\frac{A_1}{A_2} = \frac{100}{50} = 2 \tag{9.2}$$

Hence, the gain of the predistorter for large signals is

$$A_4 = 2 \tag{9.3}$$

The gain of the overall system for low signals is

$$A_5 = A_1 A_3 = 100 \times 1 = 100 \tag{9.4}$$

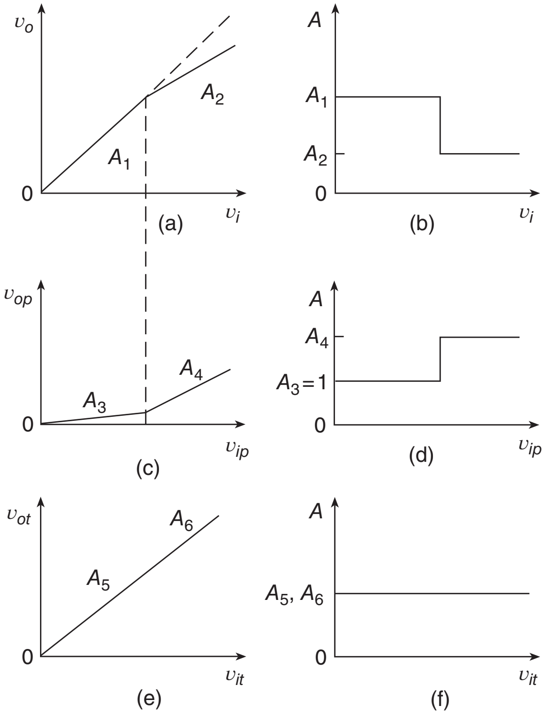

Figure 9.3 Transfer functions of a power amplifier using predistortion. (a) Nonlinear transfer function of a power amplifier $v_o = f(v_i)$. (b) Transfer function of the predistorter A. (c) Transfer function of the predistorter $v_{op} = f(v_{ip})$. (d) Transfer function of a predistortion amplifier A_p. (e) Transfer function of the total amplifier $v_{ot} = f(v_{it})$. (f) Linearized transfer function of the overall system A.

and for large signals is

$$A_6 = A_2 A_4 = 50 \times 2 = 100. \tag{9.5}$$

Thus, $A_6 = A_5$, resulting in a linear transfer function over a wide range of the input signal. Figure 9.3 illustrates the linearization of a power amplifier using the predistortion technique.

9.3 Feedforward Linearization Technique

A block diagram of a basic power amplifier system with feedforward linearization technique [4–9] is shown in Fig. 9.4(a). The feedforward linearization technique relies on the cancellation of the distortion signal. This is done by generating a proper error voltage and subtracting it from the distorted output voltage of a nonlinear power amplifier. The input voltage v_i is applied to two channels. The voltage in one channel is applied to the input of the main power amplifier with the voltage gain A_v and it is amplified. The other channel uses the original input voltage v_i as a reference signal for future comparison. The output voltage of the main power amplifier contains the undistorted and amplified input voltage $A_v v_i$ and the distortion voltage v_d produced by the amplifier nonlinearity

$$v_p = A_v v_i + v_d \tag{9.6}$$

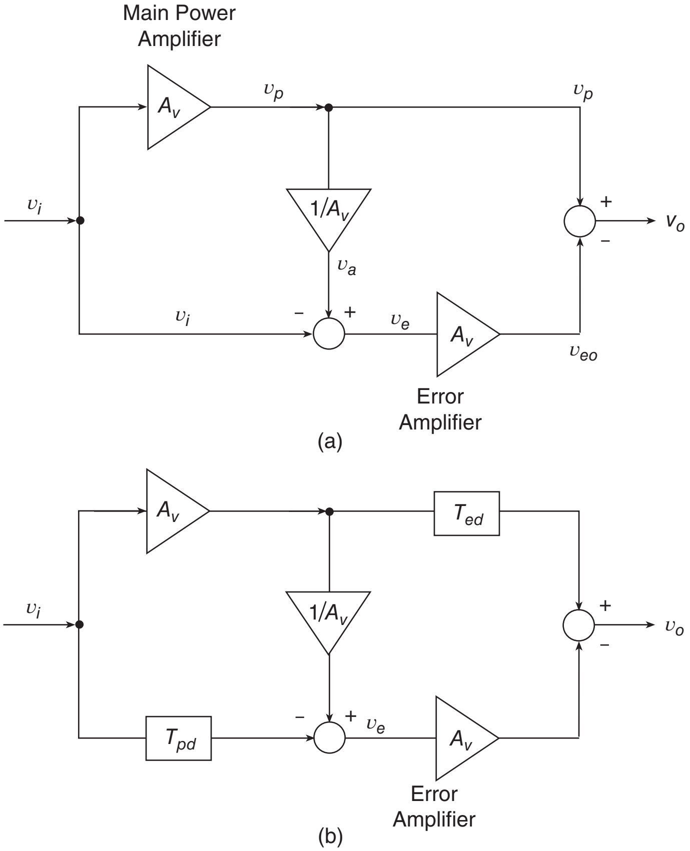

Figure 9.4 Block diagram of a power amplifier system with feedforward linearization. (a) Basic feedforward system. (b) Feedforward system with delay blocks.

The total output voltage of the main power amplifier is attenuated by a circuit with the transfer function equal to $1/A_v$

$$v_a = \frac{v_p}{A_v} = v_i + \frac{v_d}{A_v} \tag{9.7}$$

The attenuated voltage is compared with the original voltage v_i in the subtractor to produce an error voltage v_e

$$v_e = v_a - v_i = v_i + \frac{v_d}{A_v} - v_i = \frac{v_d}{A_v} \tag{9.8}$$

The error voltage v_e is amplified by the error amplifier with the voltage gain A_v, yielding

$$v_{eo} = A_v v_e = A_v \frac{v_d}{A_v} = v_d \tag{9.9}$$

Next, the output voltage of the main power amplifier v_p is compared with the error amplifier output voltage v_{eo} by a subtractor, producing the output voltage of the entire system

$$v_o = v_p - v_{eo} = A_v v_i + v_d - v_d = A_v v_i \tag{9.10}$$

It can be seen that the distortion signal v_d is cancelled out for perfect amplitude and phase matching at each subtractor. In addition to the cancellation of the nonlinear component, the system suppresses the noise added to the signal in the main power amplifier. The first loop is called the signal cancellation loop and the second loop is called the error cancellation loop.

The feedforward linearization system offers a wide bandwidth, reduced noise level, and is stable in spite of large phase shifts at RF because the output signal is not applied to the input. Wideband operation is useful in multicarrier wireless communications such as wireless base stations.

The main disadvantage of the feedforward linearization system is the gain mismatch and the phase (delay) mismatch in the signal channels. The amount of linearization depends on the amplitude and phase matching at each subtractor. If the first loop from the input voltage v_i to the first subtractor has a relative gain mismatch $\Delta A/A$ and the phase mismatch $\Delta\phi$, the attenuation of the magnitude of the IM terms in the output voltage is [5, 7]

$$A_{IM} = \sqrt{1 - 2\left(1 + \frac{\Delta A}{A}\right)\cos\Delta\phi + \left(1 + \frac{\Delta A}{A}\right)^2} \tag{9.11}$$

To improve the signal quality, delay blocks can be added as shown in Fig. 9.4(b). A delay block T_{pd} is added in the bottom path to compensate for the delay introduced by the main power amplifier and the attenuator. The other delay block T_{ed} is added in the upper path to compensate for the delay introduced by the error amplifier. The delay blocks can be implemented using passive lumped-element networks or transmission lines. However, these blocks dissipate power and reduce the amplifier efficiency. In addition, the design of wideband delay blocks is difficult.

9.4 Negative Feedback Linearization Technique

In general, negative feedback reduces nonlinearity [12, 13]. A block diagram of a power amplifier with a negative feedback is depicted in Fig. 9.5. The transfer function $v_o = f(v_s)$ of a power amplifier can be considerably linearized through the application of negative feedback, reducing nonlinear distortion. Large changes in the open-loop gain cause much smaller changes in the closed-loop gain.

Let us assume that the output voltage of a power amplifier without negative feedback contains a distortion component (an IM term of a harmonic) given by

$$v_d = V_d \sin\omega_d t \tag{9.12}$$

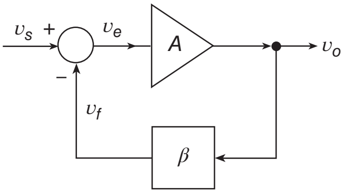

Figure 9.5 Block diagram of a power amplifier system with negative feedback.

The distortion component of the output voltage of the power amplifier with negative feedback is

$$v_{df} = V_{df} \sin \omega_d t \tag{9.13}$$

We wish to find the relationship between v_d and v_{df}. The feedback voltage is

$$v_f = \beta v_{df} \tag{9.14}$$

The reference voltage for the distortion component is zero. Hence, the input voltage of the power amplifier is

$$v_e = -v_f = -\beta v_{df} \tag{9.15}$$

The distortion component at the power amplifier output is

$$v_{od} = Av_e = -Av_f = -\beta A v_{df} \tag{9.16}$$

Thus, the output voltage contains two terms: the original distortion component generated by the power amplifier v_d and the component v_{od}, which represents the effect of negative feedback. Hence, the overall output voltage is

$$v_{df} = v_d - v_{od} = v_d - \beta A v_{df} \tag{9.17}$$

yielding

$$v_{df} = \frac{v_d}{1 + \beta A} = \frac{v_d}{1 + T} \tag{9.18}$$

Since A is generally a function of frequency, the amplitude of the distortion component must be evaluated at the frequency of the distortion component $f_d = \omega_d/(2\pi)$.

It follows from (9.18) that the reduction of nonlinear distortion is large when the loop gain $T = \beta A$ is high. However, the voltage gain of RF power amplifiers is low, and therefore the loop gain T is also low at RF. In addition, stability of the loop is of great concern due to a large number of poles introduced by various parasitic components. A high-order power amplifier may have an excessive phase shift, causing oscillations. For a large loop gain $T = \beta A$,

$$A_f \approx \frac{1}{\beta} \tag{9.19}$$

This equation indicates that the gain depends only on the linear feedback network β. The output voltage of a power amplifier is given by

$$v_o = A_f v_s \approx \frac{v_i}{\beta} \tag{9.20}$$

Thus, the transfer function is nearly linear. However, the feedback amplifier requires a larger input voltage in order to produce the same output as the amplifier without feedback.

Figure 9.6 shows a block diagram of a power amplifier with negative feedback and frequency translation. The forward path consists of a low-frequency high-gain error amplifier, an upconversion mixer, and a power amplifier. The mixer converts the frequency of the input signal f_i to an RF frequency $f_{RF} = f_i + f_{LO}$, where f_{LO} is the frequency of the local oscillator. The feedback