Chapter 2
Modulation Schemes Effect on RF Power Amplifier Nonlinearity and RFPA Linearization Techniques

2.1 Introduction

In this chapter, RF modulation schemes effects on RF power amplifier nonlinearities are presented. A review of various power amplifier RF linearization techniques are discussed.

2.2 RF Modulation Scheme in Bandpass Radio Communication Channel

In radio communications, modulation can be described as the process of conveying a message signal by superimposing an information bearing signal onto a carrier signal by varying the signal characteristic [31–33]. Modulation is the process of changing a higher frequency signal in proportion to a lower frequency one or vise versa. The higher frequency signal is referred to as the carrier signal and the lower frequency signal is referred to as the information bearing message signal or modulating signal [31–33]. The characteristics (amplitude, frequency or phase) of the carrier signal are varied in accordance with the information bearing signal. These high-frequency carrier signals can be transmitted over the air, over fiber or coax cable. The use of high frequency signals will make the amplifier and antenna design easier for effective radio design [32, 33].

Figure 2.1 shows the up conversion of the complex-valued baseband signal x'(t) to the passband then the transmission of the real-valued bandpass signal x(t) through the communication channel [31]. After the bandpass signal goes through the channel, a down-conversion of the bandpass output Y(t) into a complex-valued baseband signal Y'(t) occurs. The baseband signal x'(t) is up-converted to the bandpass signal by amplitude, phase or frequency modulation in order to transmit it. The modulated bandpass signal x(t) can be described as

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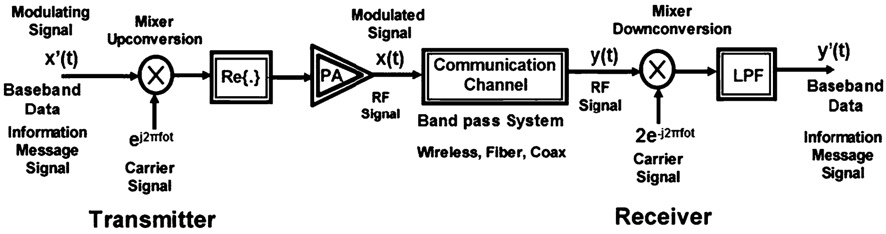

Fig. 2.1 A general universal illustration of a bandpass communication channel system

$$x\,(t) = A\,(t)\cos\left(2\pi f_o t + \phi\,(t)\right) \tag{2.1}$$

where f_o is the carrier frequency, A(t) is the amplitude and ϕ(t) is the phase modulation.

The bandpass signal x(t) has an envelope bandwidth lower then the carrier frequency f_o. Using trigonometric identities, this signal can be re-written as

$$x\,(t) = I\,(t)\cos\left(2\pi f_c t\right) - Q\,(t)\sin\left(2\pi f_c t\right) \tag{2.2}$$

where I(t) is the in-phase component and Q(t) is the quadrature component

$$I\,(t) = A\,(t)\cos\left[\theta\,(t)\right] \tag{2.3}$$

$$Q\,(t) = A\,(t)\sin\left[\theta\,(t)\right] \tag{2.4}$$

Consequently, the bandpass signal x(t) can be re-written in complex form as

$$x\,(t) = A\,(t)\cos\left[\theta\,(t)\right]\cos\left(2\pi f_c t\right) - A\,(t)\sin\left[\theta\,(t)\right]\sin\left(2\pi f_c t\right) \tag{2.5}$$

$$x\,(t) = A\,(t)\cos\left[2\pi f_c t + \theta\,(t)\right] = \mathrm{Re}\left[A\,(t)\,e^{j\theta(t)}e^{j2\pi f_c t}\right] \tag{2.6}$$

$$x\,(t) = \mathrm{Re}\left[x'\,(t)\,e^{j2\pi f_c t}\right] \tag{2.7}$$

where x'(t) is the baseband input signal and can be represented as

$$x'\,(t) = I\,(t) + jQ\,(t) \tag{2.8}$$

$$x'\,(t) = A\,(t)\,e^{j\theta(t)} \tag{2.9}$$

Therefore, the real-valued bandpass input signal x(t) can be obtained from the complex valued baseband input signal x'(t) as [31, 33]

$$x\,(t) = \mathrm{Re}\left\{x'\,(t)\,e^{j2\pi f_o t}\right\} \tag{2.10}$$

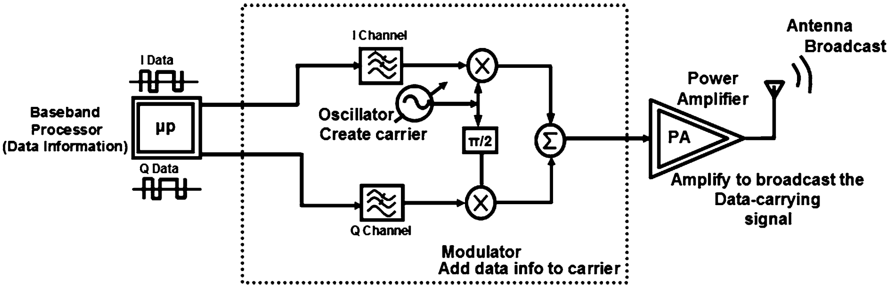

Fig. 2.2 Ideal radio quadrature upconverter transmitter

where f_o is the carrier frequency. Similarly, the baseband output signal y'(t) can be obtained from the bandpass output signal y(t) through demodulation process $2e^{-j2\pi f_o t}$.

The communication channel can be linear or nonlinear. The choice of a modulation scheme depends on the physical characteristics of this channel, required levels of performance and hardware trade-offs [33].

2.2.1 Ideal Radio Transmitter

As shown in Fig. 2.2 the baseband processor converts the information we want to send into data. The data can be either analog (continuously varying) or digital (in discrete states) in format [31, 33, 34].

An ideal radio quadrature upconverter transmitter generates a high-frequency carrier for the data information to ride on. To do this we use a component called an oscillator as shown in Fig. 2.2. Ideal radio quadrature upconverter transmitter as shown in Fig. 2.2 has an oscillator that converts DC bias into a radio-frequency carrier. Then the carrier is combined with the data using a component called a modulator [32–34]. The data adjusts or modulates the characteristics of the carrier (amplitude, frequency or phase) in a controlled manner. The third step is to increase the signal strength with a power amplifier so that it can be detected by the receiver. The output of the power amplifier feeds an antenna which broadcasts the information carrying signal into the air. It also can be transmitted through other communication mediums such as fiber or coax cable [32–34].

2.2.2 RF Power Amplifier Linearity for Non-Modulated Signal

Active MOSFET devices can be modeled by nonlinear current and charge sources that depend on the device voltages [12, 13]. These nonlinear sources will give rise to distortion when driven with a modulated signal. The real MOSFET device output impedance is nonlinear and the mobility μ is not a constant but a function of the vertical and horizontal electric field. We may bias the active MOSFET device where the device behavior is more exponential. And there is also an internal feedback so when the input signal driven into the amplifier is increased, the output is also increased until a point where distortion products can no longer be ignored [12, 14].

No transistor is perfectly linear since the inherent nonlinearity of the diode junctions that comprise many of the active devices found in most amplifiers. The harmonics of the output signal are generated by nonlinearities of the MOSFET devices. The major three nonlinear elements of the MOSFET devices are nonlinear transconductance g_m, the device drain capacitance C_d and gate capacitance C_{gs} [12,15]. The real MOSFET devices generate higher order distortion [12,16]. Models are used to characterize the nonlinear behavior of a semiconductor device in order to predict the resultant signal properties [15, 16].

Power amplifiers can be classified in to two categories, linear and nonlinear. Linear power amplifiers preserve amplitude and phase information where as nonlinear power amplifiers only preserve phase information [32, 33]. Linear power amplifiers employ transistors as current sources with high impedance. Nonlinear power amplifiers employ transistors as switches with low impedance. Linear power amplifiers can drive both broadband and narrowband loads. Nonlinear power amplifiers usually drive a tuned circuit narrowband load. Models are used to characterize the nonlinear behavior of a semiconductor device in order to predict the resultant signal properties. The simple polynomial approximation is a nonlinear transfer function based upon the Taylor series expansion. Typically the first-order (gain), second-order (squaring) and third-order (cubing) terms are considered [15, 16].

Power amplifier device nonlinearity can be modeled by a polynomial [14, 35]

$$v_o(t) = f\,(v_i(t)) = a_1 v_i(t) + a_2 v_i^2(t) + a_3 v_i^3(t) + \cdots a_N v_i^N(t) = \sum_{n=1}^{N} a_N v_i^N(t) \tag{2.11}$$

Applying a single-tone RF signal to the power amplifier transistor

$$v_i(t) = A_1 \cos(\omega_o t + \phi_1) \tag{2.12}$$

$$v_o(t) = a_1 A_1 \cos(\omega_o t + \phi_1) + a_2 A_1^2 \cos^2(\omega_o t + \phi_1) + \cdots + a_n A_1^n \cos^n(\omega_o t + \phi_1) \tag{2.13}$$

Writing out the response $v_o(t)$ by performing trigonometric expansion [36, 37]

$$\begin{aligned} v_o(t) &= a_1 A_1 \cos(\omega_o t + \phi_1) + a_2 \frac{A_1^2}{2} - a_2 \frac{A_1^2}{2} \cos^2(2\omega_o t + 2\phi_1) \\ &\quad + a_3 \frac{A_1^3}{4} \cos^2(3\omega_o t + 3\phi_1) + a_3 \frac{3A_1^3}{4} \cos^2(\omega_o t + \phi_1) \end{aligned} \tag{2.14}$$

Table 2.1 One tone signal generated harmonics

$a_1 A_1 \cos(\omega_o t + \phi_1)$	Linear gain
$a_2 \frac{A_1^2}{2}$	DC offset (self-bias)
$a_2 \frac{A_1^2}{2} \cos^2(2\omega_o t + 2\phi_1)$	Second harmonic distortion
$a_3 \frac{A_1^3}{4} \cos^2(3\omega_o t + 3\phi_1)$	Third harmonic distortion
$a_3 \frac{3A_1^3}{4} \cos^2(\omega_o t + \phi_1)$	(AM AM and AM PM)

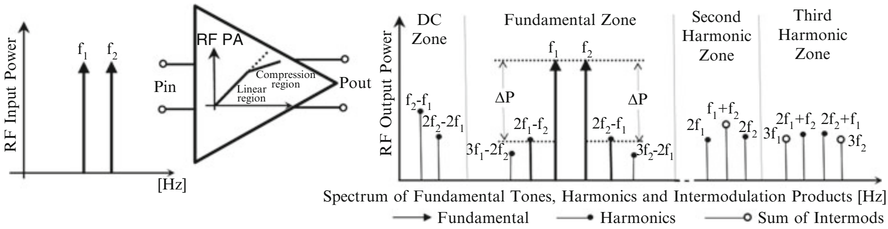

Fig. 2.3 Output spectrum of a power amplifier that includes the desired fundamental signals as well as the spurious products created by intermodulation distortion

Another method of testing power amplifier linearity is the two-tone method with two closely spaced fundamental signals tones applied to the test amplifier (Table 2.1). The amplitude is increased until the third-order cross-product produces a signal above the noise floor [32–34].

As shown in Fig. 2.3 the result of applying two tones to amplifiers that exhibit a degree of nonlinearity is intermodulation distortion (IMD) and third-order harmonics grouped in harmonic zones. As can be depicted from Fig. 2.4 that the third order intermodulation products $(2f_1 - f_2)$ and $(2f_2 - f_1)$ are the main contributor to distortion in that they are very near the fundamental tones and are not filtered out as is the case of the second order intermodulation products $(f_1 - f_2, 2f_1, f_1 + f_2$ and $2f_2)$ [32–34].

Typically the third-order intermodulation distortion product (IM3) are of most concern since distortion products which are far away in frequency from the desired output can be removed by filtering as shown in Fig. 2.4 [32–34].

Applying a two-tone RF signal to the power amplifier

$$v_i(t) = v\cos(\omega_1 t) + v\cos(\omega_2 t) \tag{2.15}$$

The two-tone signal covers the complete dynamic range of the amplifier (Table 2.2). The amplifier output is a power series expansion up to the fifth-order is given by Rogers and Plett [32]

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + a_4 v_i^4 + a_5 v_i^5 \cdots \tag{2.16}$$

The output voltage with two-tone signal

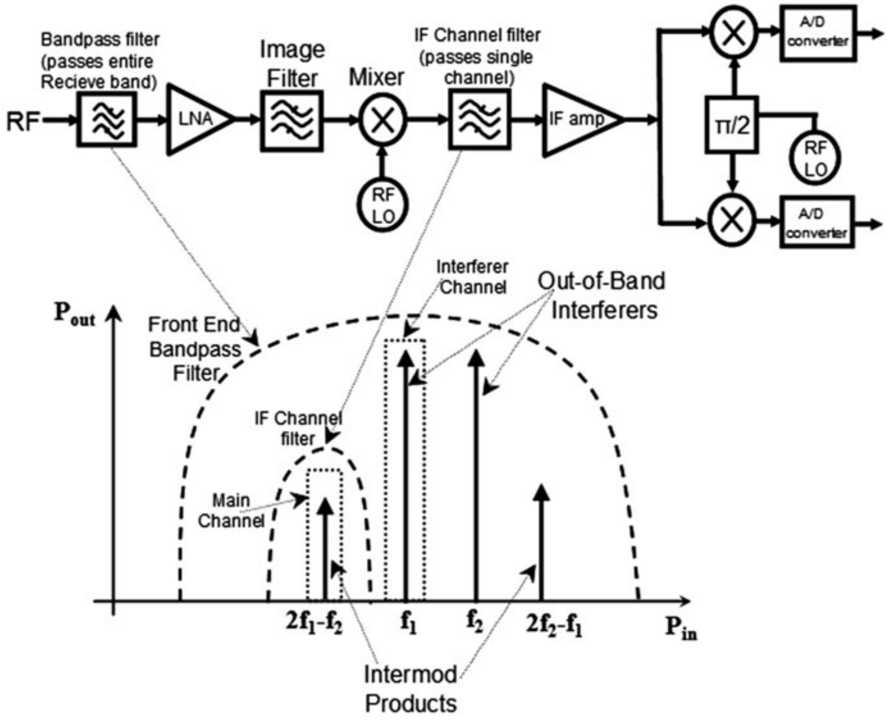

Fig. 2.4 Intermodulation products falling in-band

$$\begin{aligned}v_o(t) = a_1 v\left[\cos(\omega_1 t) + \cos(\omega_2 t)\right] + a_2 v^2\left[\cos(\omega_1 t) + \cos(\omega_2 t)\right]^2 \\ + a_3 v^3\left[\cos(\omega_1 t) + \cos(\omega_2 t)\right]^3 + a_4 v^4\left[\cos(\omega_1 t) + \cos(\omega_2 t)\right]^4 \\ + a_5 v^5\left[\cos(\omega_1 t) + \cos(\omega_2 t)\right]^5\end{aligned} \tag{2.17}$$

Figure 2.5 shows a plot of IM3 versus P_{in} and P_{out} versus P_{in}. If the 1:1 slope line of the fundamental Pout and the 1:3 slope line of the third order intermodulation product are extended, they will intersect at a point called IP3, the third-order intercept point. IP3 is an approximation because the slope assumption is not truly valid outside the linear region. The higher the IP3 point the less distortion at higher power levels. In the linear part of Fig. 2.5, the Pout versus Pin curve has a slope of 1:1. The P1dB point which is the power where the gain drops by 1 dB compared to the linear gain was another way to characterize power amplifiers [32–34].

In the nonlinear region in Fig. 2.5 higher efficiency is gained over 50%, however distortion is increased significantly. Constant amplitude modulation schemes like AMPS or FM radio use saturated power amplifiers that are more efficient than linear ones [32–34].

Table 2.2 Two tone signal generated harmonics coefficients

	a_1v	a_2v^2	a_3v^3	a_4v^4	a_5v^5
DC		1		9/4	
ω_1	1		9/4		25/4
ω_2	1		9/4		25/4
$2\omega_1$		1/2		2	
$2\omega_2$		1/2		2	
$\omega_1 \pm \omega_2$		1		3	
$2\omega_1 \pm \omega_2$			3/4		25/8
$\omega_1 \pm 2\omega_2$			3/4		25/8
$3\omega_1$			1/4		25/16
$3\omega_2$			1/4		25/16
$2\omega_1 \pm 2\omega_2$				3/4	
$\omega_1 \pm 3\omega_2$				1/2	
$3\omega_1 \pm \omega_2$				1/2	

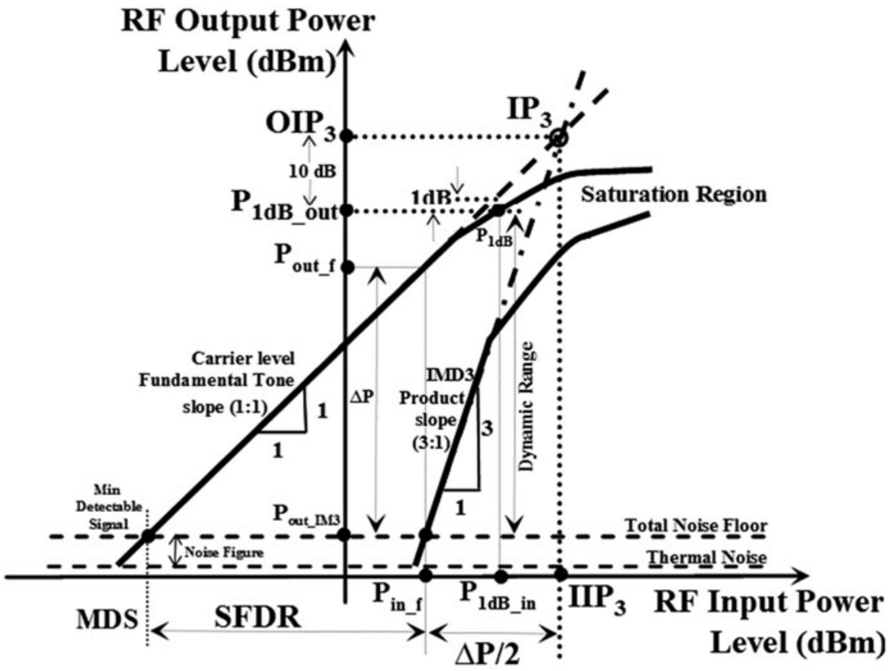

Fig. 2.5 Output power versus input power defining third-order intercept point IP3

$$P_{IM3} = 3 \times P_{IN} - 2 \times IIP3\,(dBm) \tag{2.18}$$

$$OIP_3 = \frac{3 \times P_{out\_f} - P_{out\_IM3}}{2} \tag{2.19}$$

Dynamic range is the signal range in which the signal can still be processed with high quality. It is the signal range whose lower limit is defined by the sensitivity level and whose upper limit is defined by the acceptable maximum level of signal distortion [32–34]. SFDR (spurious free dynamic range) can be found from the two linear equations (2.18) and (2.19) for the harmonic and third-order intermodulation product where MDS is the minimum detectable signal [33].

$$SFDR = {}^{2}\!/_{3}\,(IIP3 - MDS) \tag{2.20}$$

All amplifiers have maximum output power capacity which is called saturation output power. There are a number of ways to specify the nonlinear behavior of a power amplifier. One method of defining amplifier's linearity is third-order intercept point (IP3) [32–34]. This method relies on a figure of merit that is determined by graphical extrapolation of amplifier data taken well below saturation. The IP3 is a theoretical point obtained by extending the two functions until they intersect. If an amplifier was operated at a given level below this third order intercept point then its linear performance was considered adequate. Figure 2.5 is a plot of the output versus input transfer function of the power amplifier whose desired fundamental outputs (f_1 and f_2) describe a function with a slope of one. The third order intermodulation products are also plotted in Fig. 2.5. The output level continues to increase with an increase of input power until a point is reached where output device begins to saturate resulting in a gradual roll-off of output power.

When the actual output power level differs by 1 dB compared to the ideal output value, the P1dB compression point is reached. In other words, P1dB is the output power level point at which the gain is 1 dB compressed. The P1dB is another main power amplifier identification parameter. The higher the intercept point, the better the amplifier is at amplifying large signals [32–34]. However, with variety of new modulation methods, the P1dB compression point is not enough for power amplifier performance prediction [32–34].

IIP3 can be described by

$$IP3_{|dBm} = P_{IN|dBm} + \frac{\Delta P_{|dB}}{2} \tag{2.21}$$

IP5 may be determined using the two-tone test as well. Similar to IP3 equation, IP5 can be described by

$$IP5_{|dBm} = P_{IN|dBm} + \frac{\Delta P_{|dB}}{4} \tag{2.22}$$

2.2.3 RF Power Amplifier Linearity for Modulated Signals

The new generation of mobile communication technologies employ linear modulation (QPSK, QAM) and wide bandwidth for increasing bit rate and spectrum efficiency. Therefore the power amplifier is required to process high data rate

Table 2.3 Different PAR values for different modulated signal types [1, 2]

Modulated signal type	Modulation method	PAR [dB]
CDMA	QPSK	10
TDMA	Π/4-DQPSK	3.5
2-tone	AM	3
1-tone	FM	0

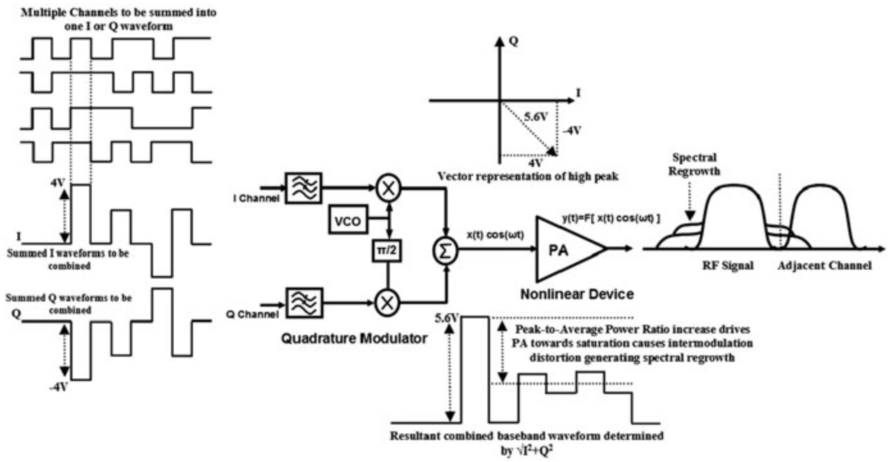

Fig. 2.6 RF power amplifier spectral regrowth

non-constant envelope signals. For achieving good power efficiency, the power amplifier should work around its compression point however making the output signal distorted nonlinearly [38, 39].

Spectrally efficient modulation schemes in wireless systems non-constant envelope signals have high peak to average power ratio. These modulation techniques require a highly linear PA to process high data rate non-constant envelope signals. In general the higher the data rates the higher the peak to average power ratio (PAR) [2]. High peaks can cause the power amplifier to move toward saturation. This causes intermodulation distortion which generates spectral regrowth as shown in Fig. 2.6. Spectral regrowth is a condition that interferes with signals in adjacent frequency bands and can be reduced by using power amplifier linearization techniques [38, 39]. Table 2.3 shows the different PAR values for different modulated signal types [1]. The PAR is a strong function of the type of modulation. For 1 dB of PAR that means operating the power amplifier at 1 dB lower power or power back-off which is not as power efficient [40].

Power peaks develop in wireless digital communication signal such as CDMA waveforms [2, 38, 39]. A wireless digital communication signal is generated from a quadrature modulator as shown in Fig. 2.6. The waveform is composed of an I waveform and a Q waveform and these waveforms are the summation of multiple channels. Whenever the channel waveforms simultaneously contain a bit in the same state a high power peak occurs in the summed waveform as shown in Fig. 2.6.

The I and Q waveforms combine in the quadrature modulator to create an RF waveform [38,39]. The magnitude of the RF envelope is determined by the I squared plus Q squared modulator equation where the squaring of I and Q always results in a positive value. The simultaneous positive peaks in the I and Q waveforms combine to create a greater peak as shown in Fig. 2.6.

Power amplifier nonlinearity effects over modulated signals are out-of-band distortion and in-band distortion effects. The out-of-band distortion effects produces a spectrum widening which results in higher ACPR (Adjacent Channel Power Ratio) value. The in-band distortion effects produces a constellation distortion which results in higher BER (Bit Error Rate).

2.2.4 RF Power Amplifier Spectral Regrowth: Out-of-band Distortion

Adjacent-channel power ratio is the linearity figure-of merit for wireless communication systems employing non-constant envelope modulation techniques such as QAM and Π/4-DQPSK [38, 39]. These linear modulation techniques, although spectrally efficient, produce modulated carriers with envelope fluctuations. This envelope fluctuation results in signal distortion and spectral spreading when the modulated carrier is passed through a saturated RF power amplifier.

RF power amplifier nonlinear effect impacts the CDMA signal's out of band emission levels. A general mathematical model of a CDMA signal's spectrum, s(t) can be described as [38,39,41,42]

$$s\left(t\right) = \sqrt{2}x\left(t\right)\cos\left(2\pi f_o t + \theta\right) \tag{2.23}$$

where x(t) is a base-band white Gaussian process with phase θ.

The input–output relationship can be approximated using Taylor polynomial of the input signal for a weak nonlinearity. A general mathematical model of a RF power amplifier can be described as [41,43]

$$y\left(t\right) = F\left(s\left(t\right)\right) = a_1 s\left(t\right) + a_3 s^3\left(t\right) \tag{2.24}$$

A nonlinear power amplifier transfer function leads to odd-order intermodulation products. These third-order intermodulation products cause distortion. Only the odd-order terms in the Taylor series are considered. The effect of spectra generated by the even-order terms on the passband are negligible since they are at least f_c away from the center of the passband.

Coefficient a_1 describes the linear gain of the amplifier and a_3 is the nonlinear coefficient. For a linear power amplifier the expression for the a_1 and a_3 coefficients can be expressed as [41,43]

$$a_1 = 10^{\frac{G}{20}} \tag{2.25}$$

and

$$a_3 = \frac{2}{3}10^{\left(\frac{-IP3}{10}+3\frac{G}{20}\right)} \tag{2.26}$$

Coefficient a_3 is by far the major contributor to the distortion in a power amplifier since it's product appear around carrier frequency f_c.

The spectrum P_y(f) of the RF power amplifier can be expressed as [41, 43]

$$\begin{aligned} Py\left(f\right) = {} & \frac{1}{2B}\left[Po - 6P_o^2 10^{-\frac{IP3}{10}} + 9P_o^3 10^{-\frac{IP3}{5}}\right] \\ & + \frac{3}{4B^3}P_o^3 10^{-\frac{IP3}{5}}\left[6B^2 - (f - f_c)^2\right], |f - f_c| \leqslant B \end{aligned} \tag{2.27}$$

$$Py\left(f\right) = \frac{3}{8B^3}P_o^3 10^{-\frac{IP3}{5}}\left(3B - |f - f_c|\right)^2, B < |f - f_c| \leqslant 3B \tag{2.28}$$

$$Py\left(f\right) = 0 \tag{2.29}$$

when

$$3B < |f - f_c| \leqslant 3B \tag{2.30}$$

Using the results from P_y(f), the emission power level within the band P_{IM3} can be described as [43, 44]

$$P_{IM3} = \int_{f_1}^{f_2} P_y\left(f\right)df = \frac{1}{8B^3}P_o^3 10^{-\frac{IP3}{5}}\left[(3B - f_1)^3 - (3B - f_2)^3\right] \tag{2.31}$$

IP3 can be expressed in terms of P_{IM3} as [38, 39, 44]

$$IP3 = -5\log\left[\frac{P_{IM3}\left(f_1 - f_2\right)B^3}{P_{IM3}\left[(3B - f_1)^3 - (3B - f_2)^3\right]}\right] + 22.2dBm \tag{2.32}$$

Equation 2.32 describes IP3 in terms of the out-of-band emission power of a CDMA signal power amplifier [43]. Figure 2.7 Effects of PA nonlinearity on adjacent channel power ratio. Figure 2.8 shows the predicted output power spectral density (PSD) spectrum for CDMA signal of an RF power amplifier and its distortion effects. A nonlinear power amplifier transfer function leads to odd-order intermodulation products in which these third-order intermodulation products cause spreading of the distortion. These effects lead to spectral regrowth in adjacent channels [38, 39, 44].

Adjacent Channel Power Ratio (ACPR) is defined as the ratio of the main channel output power to the power in the adjacent channel [38, 42]. ACPR helps in determining the amount of signal energy leaked from the main channel to the adjacent channel and is used in testing of CDMA-based communication systems [45].

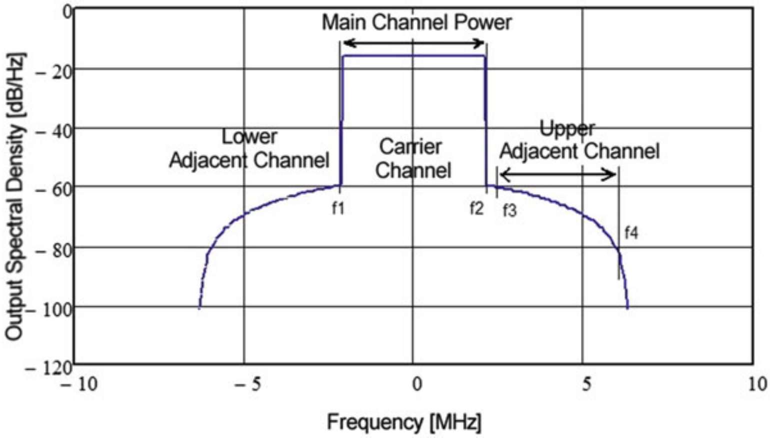

Fig. 2.7 Effects of PA nonlinearity on adjacent channel power ratio

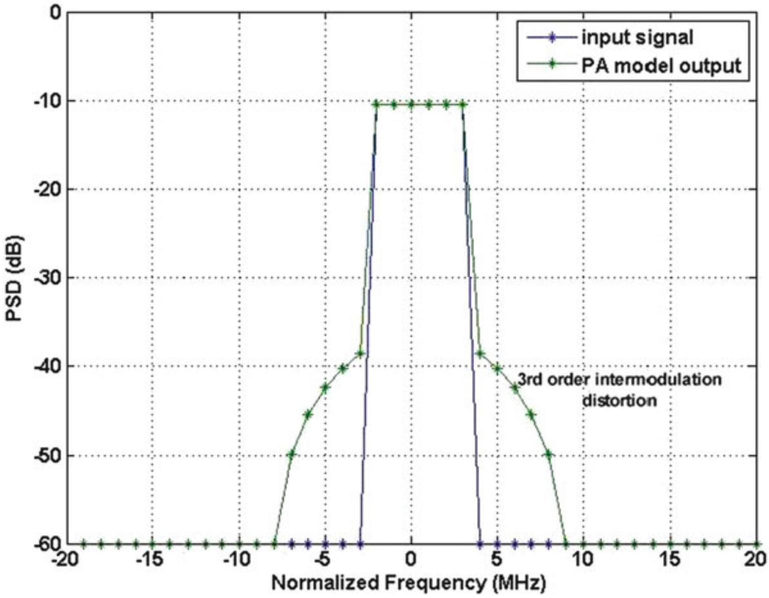

Fig. 2.8 Effects of PA nonlinearity on adjacent channel power ratio with third-order distortion

$$ACPR = \frac{\int\limits_{adjacent\_channel} P_{out}(f).df}{\int\limits_{main\_channel} P_{out}(f).df} \tag{2.33}$$

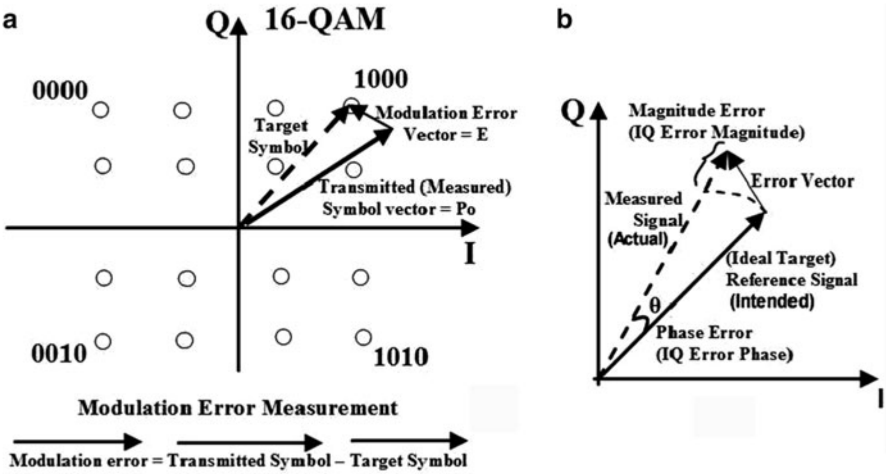

Fig. 2.9 Effects of PA nonlinearity on error vector magnitude

High crest factor can be defined as [38, 39, 44]

$$\xi = 10 \log \left(\frac{P_{peak}}{P_{average}} \right) \tag{2.34}$$

$$ACPR = -20.75dB + 1.6\xi + 2\,(P_{in} - IP3) \tag{2.35}$$

RF power amplifier linearization techniques can enhance the overall system response of non-constant modulated signals by reducing ACPR in the PA output power spectral density.

2.2.5 *Error Vector Magnitude Signal Modulation Quality: In-band Distortion*

For achieving good power efficiency, the power amplifier should work around its compression point which makes the output signal distorted nonlinearly. These nonlinear distortions generate in-band interferences which results in amplitude and phase deviation of the modulated vector signal. In band interference causes errors in the symbol vectors. While ACPR describes the effects of nonlinearity on other channels, the error vector magnitude (EVM) is used to analyze in-band distortion [46]. EVM is the measure between the ideal reference target symbol vector and the transmitted measured symbol vector as shown in Fig. 2.9. Signal and error vectors are defined in the I-Q constellation diagram. EVM is defined as a percentage of peak signal level, it measures the modulation quality of the signal and indicates modulation accuracy.

The ratio of the error vector magnitude to the original symbol magnitude defines the EVM as

$$EVM = \frac{E}{P_o} \tag{2.36}$$

where E is the error vector and P_o is the transmitted measured symbol vector. An unimpaired 16-QAM digitally modulated signal would have all of its symbols land at exactly the same 16 points on the constellation over time. Real-world impairments cause most of the symbol landing points to be spread out somewhat from the ideal symbol landing points as shown in Fig. 2.9a.

2.3 Role of RF Power Amplifier Linearization Techniques

This section will discuss techniques for the cancellation of power amplifier distortion that are also known as linearization. Linearization of power amplifiers for radios, using advanced modulation schemes with large peak-to-average ratios, is important in achieving high efficiency as shown in Fig. 2.10. Many linearization techniques have been developed to improve power amplifier linearity and to decrease adjacent channel interference ACPR [44]. The basic idea is to run the power amplifier as close to saturation as possible to maximize its power efficiency, and then employ some linearization technique to suppress the distortion introduced in this near saturated region [35].

There are many linearization techniques for minimizing power amplifier nonlinear distortion. Linearization can be conducted at either circuit-level or sub-system

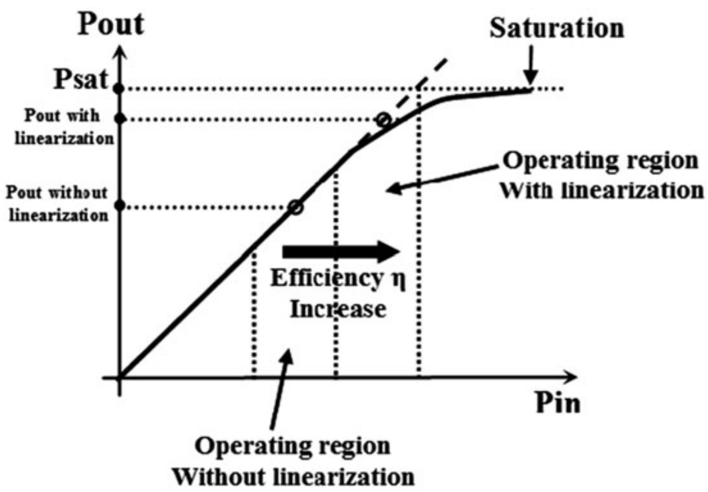

Fig. 2.10 Role of linearization techniques

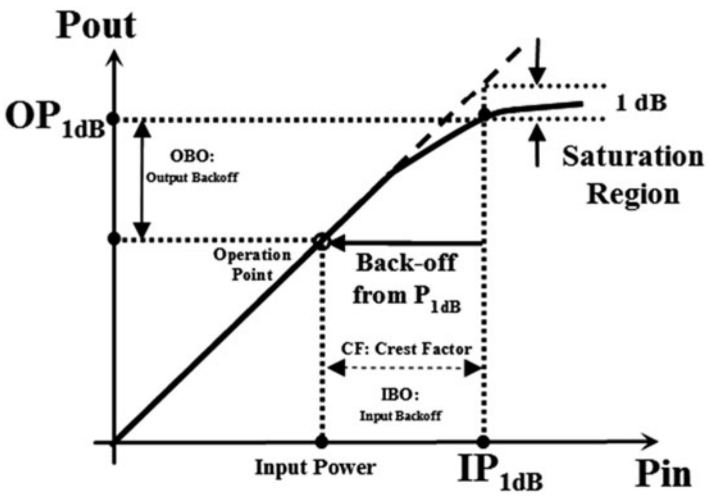

Fig. 2.11 RF power amplifier power back-off

level. Linearization techniques such as RF power amplifier power Back-off, RF predistortion, feedback and feedforward are often used. Here is a brief review of the major techniques for improving power amplifier linearity [35].

2.3.1 RF Power Amplifier Power Back-off

A simple way to improve power amplifier linearity performance is the Back-off operation [35]. To reduce distortion to an acceptable level one must operate the power amplifier at reduced power level (back-off from saturation). The back-off is the distance between the saturated point and the average power level. Increasing the back-off of the power amplifier means that the signal is contained better in the linear range, and thus the effects of nonlinearities are reduced. However, power efficiency is reduced as well. When a power amplifier is driven with decreased input power, the linearity of the power amplifier is improved as shown in Fig. 2.11.

$$Input\ Power = IP_{1dB} - IBO \tag{2.37}$$

The benefits of the Back-off linearization technique is that it is simple. However, output back-off results in poor efficiency of DC-to-RF power conversion. Since efficiency has a high impact on cellular units talk time, allowances for output back-off have significantly been reduced [35]. So a trade off between efficiency and linearity must be made. Linearization techniques prove to be the best solution in order to improve power amplifiers linearity without having negative impact on efficiency as shown in Fig. 2.10.

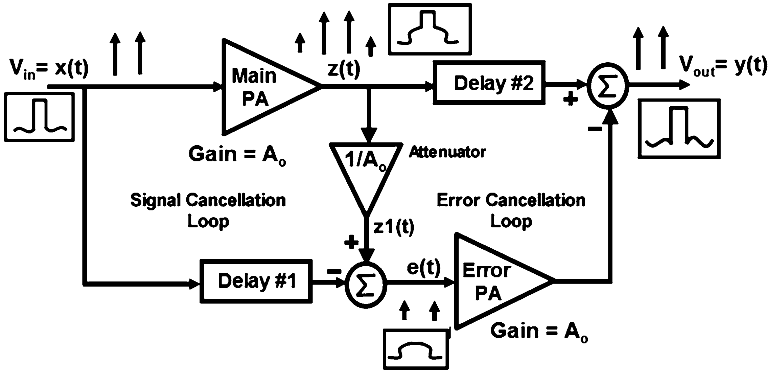

Fig. 2.12 RF power amplifier feedforward linearization

2.3.2 RF Power Amplifier Feedforward Linearization

The feedforward linearization technique was invented by H. S. Black and has since found applications in many communication systems [35] and [47]. The feedforward linearization architecture is shown in Fig. 2.12 and it is based on splitting the input signal x(t) into two branches. In the main branch the input signal x(t) is amplified by the main power amplifier yielding the PA output z(t). In the secondary branch the PA output z(t) is scaled and compared with the original input x(t) [35].

The resulting error signal e(t) goes through a second PA known as the error PA. After the error signal e(t) is obtained it is amplified and subtracted from the delayed output of the main PA. Since the error signal e(t) is the nonlinear distortion, removing it from the PA output linearizes the PA [35].

The following equations describes the feedforward linearization. Once the PA output $z(t)$ is attenuated to the same level of the input signal $x(t)$ by Webster and Parker [35]

$$z1(t) = {}^{z(t)}/_{A_0} \tag{2.38}$$

then obtaining the distortion by comparing $z1(t)$ with the input signal $x(t)$

$$e(t) = x(t) - z1(t) = x(t) - {}^{z(t)}/_{A_0} \tag{2.39}$$

The distortion can be amplified with the auxiliary error PA and subtracted from the original PA output as shown in Fig. 2.12

$$y(t) = z(t) + e(t) \cdot A_0 = z(t) + \left[x(t) - \frac{z(t)}{A_0} \right] \cdot A_0 = A_0 \cdot x(t) \tag{2.40}$$

Feedforward linearization is stable however it suffers from poor efficiency since an auxiliary error PA is needed.

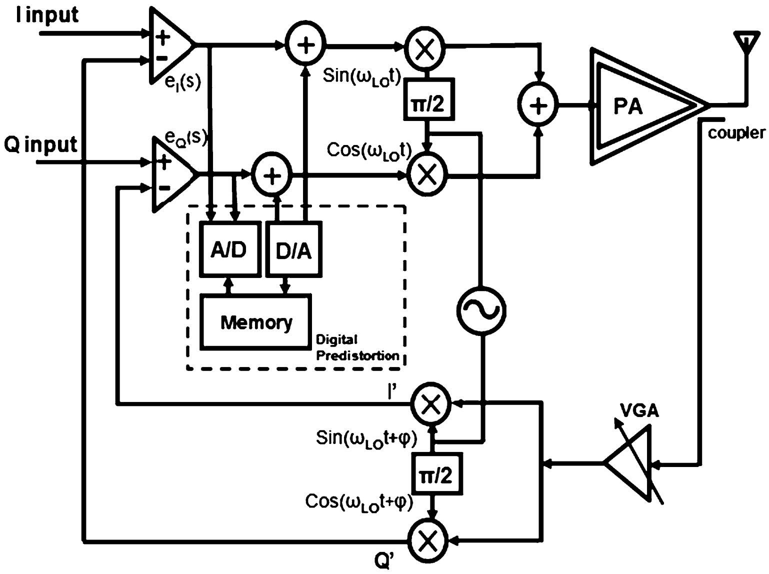

Fig. 2.13 RF power amplifier digitally assisted cartesian feedback linearization

2.3.3 RF Power Amplifier Cartesian Indirect Feedback Linearization

Many types of feedback linearization techniques exist including cartesian feedback and polar feedback [7, 35, 48]. Cartesian feedback linearization technique is based on feedback control system [7].

In cartesian feedback linearization as shown in Fig. 2.13 [2], the distorted PA output is fed back through an I-Q demodulator to build two negative feedback loops [49]. The distorted RF signal from the antenna is split into distorted Cartesian components I' and Q' [35]. The undistorted I and Q signal from the input and the distorted I' and Q' signal from the antenna are fed into differential amplifiers. The differential amplifiers compare two input signals and the amplified error signal e(s) are up-converted to an RF signal using a modulator. Because the feedback technique takes the output of the power amplifier as a reference during the correction process and it overcomes the behavior variation of the power amplifier [35]. The main objective of the cartesian feedback is to keep feedback phase φ aligned with the input signal phase. Cartesian feedback technique is simple and power efficient however it suffers from limited bandwidth [2, 35, 50].

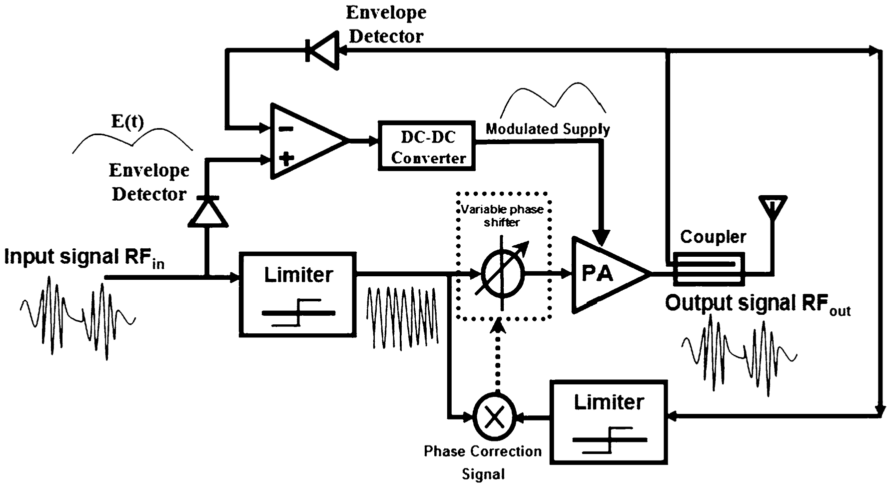

Fig. 2.14 RF power amplifier polar feedback linearization

2.3.4 RF Power Amplifier Polar Feedback Linearization

Like cartesian feedback the polar feedback linearization technique is a baseband feedback scheme [47, 51]. The polar feedback uses the magnitude and the phase of the PA output signal as feedback signals opposed to the cartesian feedback which uses inphase and quadrature signals [35, 52]. It seems more appropriate to use the envelope signal as one of the feedback signals because the distortion (AM/AM and AM/PM) is directly related to this signal [35, 47, 51, 52].

First the output from the PA is down converted to an intermediate frequency as shown in Fig. 2.14. Then the envelope of the signal is extracted. This is carried out by mixing the signal with an amplitude limited version of itself [35]. The amplitude of the input signal and the PA signal is subtracted to calculate the amplitude error. This signal is fed into the power regulator of the PA where the amplitude is adjusted. The phase error is calculated by the phase detector and used to adjust the phase of the VCO. This way the phase distortion of the PA is compensated by a phase change in the VCO. Polar feedback linearization technique provides relatively high efficiency since the power amplifier can operate completely nonlinearly [35].

2.3.5 RF Power Amplifier RF Predistortion Linearization

RF Predistortion is a popular linearization technique [53], it actively tracks and applies an inverse to the amplifier nonlinearity [11]. If the amplifier exhibits a gain compression the predistortion linearizer is designed to have a gain expansion

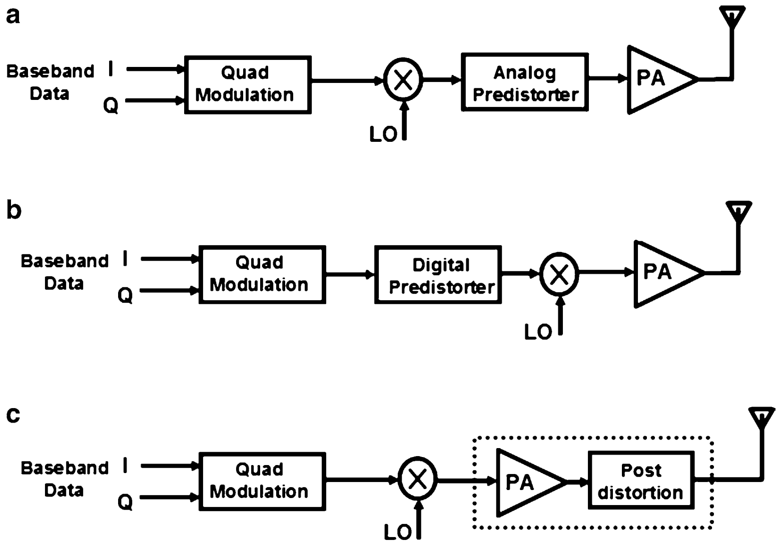

Fig. 2.15 RF power amplifier RF predistortion linearization

characteristic. The linearizer can be either active, passive, shunt or series [35]. As input power is increasing it will absorb less power to compensate the power gain roll-off of the following PA. When the input power is decreasing the effect is reversed. The fundamental principle of these predistortion techniques is to adjust the amount of input power [6].

An RF predistortion system uses an active or passive analog nonlinear element operating at the radio carrier frequency to generate the predistorted signal as shown in Fig. 2.15. IF predistortion implements the predistortion at some intermediate frequency allowing the system to be used at a number of different carrier frequencies [18]. Another implementation of predistortion is baseband predistortion where the inverse transfer function is applied prior to upconversion of the signal.

A possible simplified implementation of adaptive digital predistortion is shown in Fig. 2.16 [2]. Adaptive digital predistortion solves the problem of power amplifier variations in RF predistortion. It maintains a dynamically updated model of the power amplifier. Adaptive digital predistortion has an advantage of not suffering from bandwidth limitations incurred by feedback techniques [35, 54]. A comparison of different RF power amplifier linearization techniques is shown in Table 2.4 [2, 35, 52].

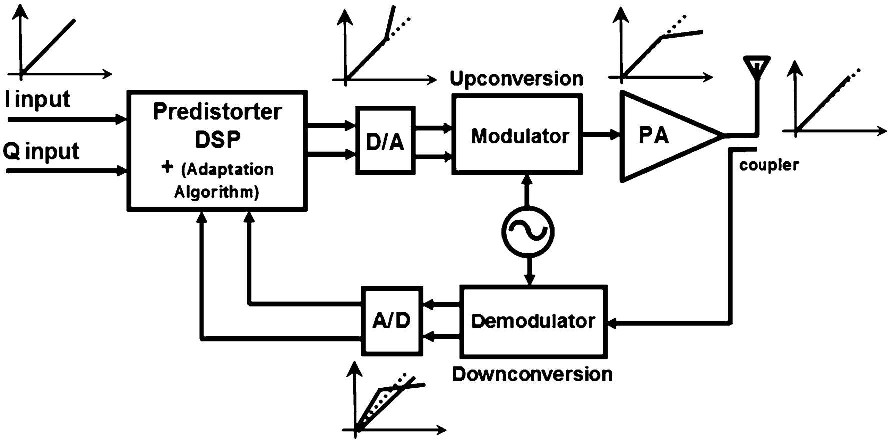

Fig. 2.16 RF power amplifier adaptive digital predistortion linearization

Table 2.4 Comparison of different RF power amplifier linearization techniques

Linearization technique	Linearization performance	Compensation bandwidth	Cost	Issues	Control applied at
Feedforward	Good	Wider	High	Low efficiency	Output
Cartesian indirect feedback	Moderate	Narrow	Moderate	Reduced gain stability	Input
Analog RF predistortion	Low	Wide	Low	Reduced gain	Input
Digital predistortion	Moderate	Wide	Moderate	Easy to control depends on DSP	Input
Polar feedback	Moderate	Wide	Moderate	Reduced gain	Input

2.4 Radio-over-Fiber for Wireless Communication

Radio-over-Fibre (RoF) is a technology that integrates radio and optics [4, 5]. Radio transmission over fiber is used in cable television networks and in satellite base stations. The RoF system generally consists of commonly used components such as light sources, modulators, photo-detectors and optical fibers [3, 6, 7].

In RoF architecture, light is modulated by a data-carrying radio signal and transmitted over an optical fiber link as shown in Fig. 2.17. RF signals are optically distributed to base stations directly at high frequencies and converted to electrical domain at the base stations before being amplified and radiated by an antenna [3–8]. In IF-over-Fiber architecture, an IF (Intermediate Frequency) radio signal with a lower frequency is used for modulating light before being transported over the optical link as shown in Fig. 2.18.

Some of the advantages of RoF system are low attenuation, lower cost and low complexity [3, 4, 6, 7, 55]. In the basic RoF transmitter design, light intensity is modulated by the (modulated) RF signal, either directly modulating the laser current

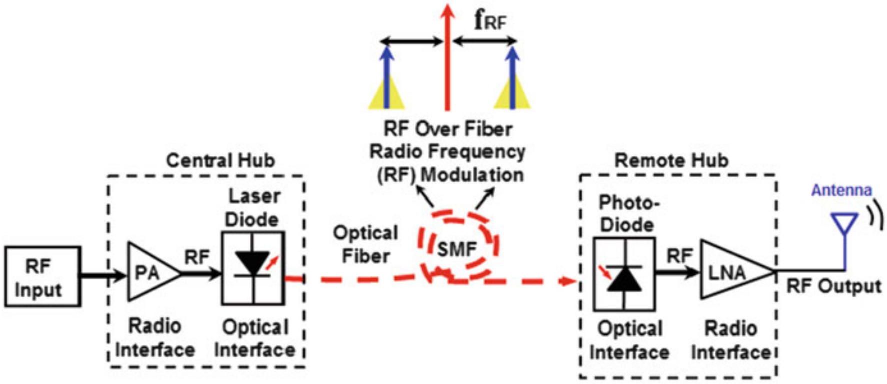

Fig. 2.17 Direct modulation of laser with RF over fiber radio frequency RF modulation

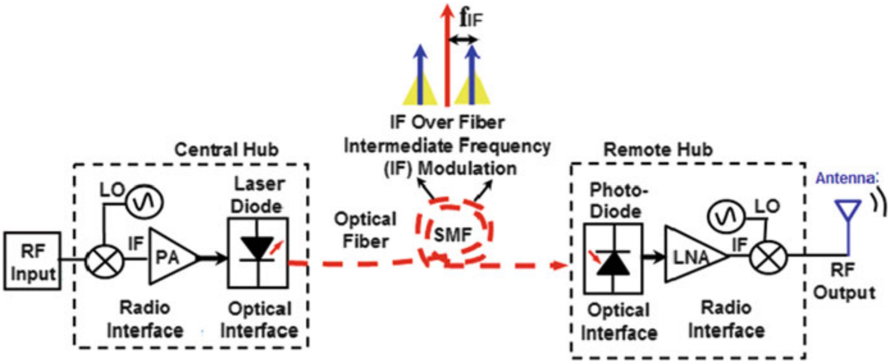

Fig. 2.18 Direct modulation of laser with if over fiber intermediate frequency modulation

or by applying an external modulator. Typically direct modulation is available for frequencies less than 1 GHz. External modulators such as the MachZehnder modulator are used for higher frequencies such as 1 GHz as shown in Fig. 2.19 but at additional cost [3, 5–7]. At the receiver side, the intensity of the transmitted RF signal guided by the optical fibre is detected with the aid of a photodetector and such a process is commonly referred to as intensity-modulation direct-detection (IM/DD) [6–8].

In RoF the optical fiber is used to carry RF signals. Since RoF involves detection of light, it is fundamentally an analog transmission system. Although the RoF transmission system itself is analog, the radio system being distributed does not have to be analog as well. It may be digital using comprehensive multi-level signal modulation formats such as QAM or Orthogonal Frequency Division Multiplexing (OFDM). RF communication systems use advanced forms of modulation to increase the amount of data that can be transmitted in a given amount of frequency spectrum by combining multiple single-carrier into a single transmitter such as OFDM [3, 5].

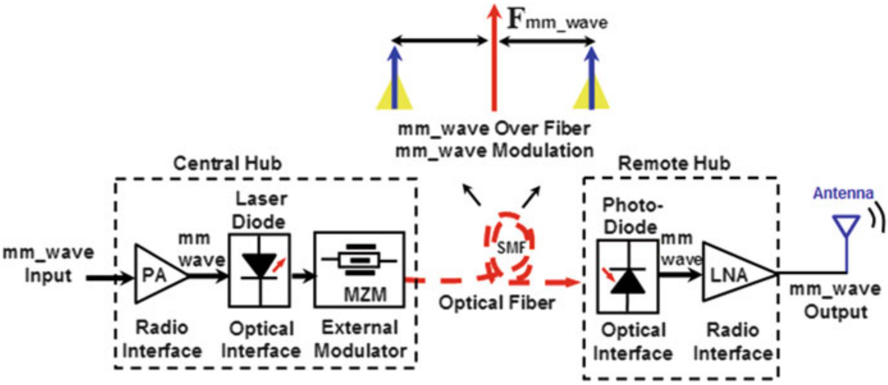

Fig. 2.19 External modulators are used for mm-wave over fiber modulation

Radio technologies such as ultra wideband (UWB) are able to provide high bit-rates. UWB RoF utilize OFDM modulation scheme for high rate networks with data rates reaching up to 480-Mbps [3, 4, 6, 7, 55].

However, combining several carrier signals within the transmitter power amplifier creates large variations in the instantaneous output power, a condition described as high peak-to-average ratio (PAR) [3, 5]. Signal impairments such as distortion, which are important in analogue communication systems, are important in RoF systems as well. Large PAR can generate performance degradation and transmitter power amplifier may exhibit nonlinear behavior as a result of the high PAR. These impairments tend to limit the dynamic range of the RoF links. Dynamic range is an important parameter for wireless communication systems because the power received at the base station varies widely [3–5, 55].

In applications requiring a linear PA due to PAR, back-off from the peak power point must be applied to avoid clipping the waveform. Another way to minimize distortion is to apply power amplifier linearization techniques.

2.5 Summary

In this chapter, RF modulation schemes effect on RF power amplifier nonlinearities was presented. RF power amplifier linearity for non-modulated and modulated signals was presented as well. RF power amplifier spectral regrowth out-of-band distortion and in-band distortion was discussed. A review of various power amplifier RF linearization techniques such as feedforward, cartesian feedback, polar feedback and RF predistortion were discussed.

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