

## INTRODUCTION

The radiofrequency (RF) power amplifier is one of the most important components of a wireless communication system. It plays a significant part in determining the overall performance, cost, and reliability of the wireless system. In fact, the increasing use of modulation schemes with amplitude modulation of the carrier signal, to achieve higher spectral efficiency, is only expected to enhance this significance. The RF power amplifier is also one of the most challenging components of the wireless system front end to design, analyze, and model for, as it generally operates at the limits of the capability of the semiconductor device technology. This situation is exacerbated by the current trend toward migration of the radio front-end to silicon-based technologies, which are considerably less suitable for RF power amplifier design than are the traditional III–V-based technologies. RF power amplifier design encompasses, and is impacted by, several areas: semiconductor technology, which provides the active and passive devices used in power amplifier design and determines the performance and reliability of the power amplifier to a large extent; transistor device modeling, which makes it possible to design and predict the behavior of the power amplifier; RF measurement and characterization techniques; integrated circuit (IC) design; architectural techniques, which help improve the performance of the power amplifier; behavioral “blackbox” modeling, which enables analysis of the impact of the characteristics of the power amplifier on the performance of the wireless system; and IC packaging and thermal management technology.

## 1.1 SEMICONDUCTOR TECHNOLOGY AND RF POWER AMPLIFIER DESIGN

A wide variety of semiconductor technologies have been used for RF power amplifier design: gallium arsenide (GaAs)-based heterojunction bipolar transistors (HBTs), metal semiconductor field effect transistors (MESFETs), high-electron-mobility transistors (HEMTs), and pseudomorphic HEMTs (or pHEMTs), silicon bipolar junction transistors (Si BJTs), silicon metal oxide semiconductor field effect transistors (Si MOSFETs), silicon laterally diffused metal oxide semiconductor (LDMOS) FETs, silicon germanium (SiGe) HBTs, and gallium nitride (GaN)-based HEMTs. The choice of technology is dictated by the suitability of the properties of the semiconductor device for a particular application. For instance, Si LDMOS technology is widely used to build power amplifiers for base-station transmitters in cellular networks. This is because it is a mature device technology; offers a good combination of gain, linearity, reliability, and cost; and is capable of delivering tens or hundreds of watts of output power from tens of volts of power supply. It is worth emphasizing the role of cost in the choice of semiconductor technology. For example, in the case of base-station power amplifiers, high-power GaAs pHEMTs and MESFETs have been shown to exhibit superior performance compared to Si LDMOS FETs. However, the higher cost of these devices has meant that LDMOS technology continues to dominate this application, especially at frequencies below 2 GHz.

The quest for new materials and technologies, improvement of the characteristics of existing semiconductor devices, and better processing techniques, to reduce the cost of a technology, is a constant pursuit, and the subject of active research and development. Good examples of emerging technology are the wide-bandgap semiconductors, silicon carbide (SiC) and gallium nitride (GaN). Their excellent material properties, such as high breakdown voltage (their breakdown electric field is over 5 times higher than that of Si or GaAs), high saturated electron drift velocity, and high thermal conductivity (especially that of SiC), have generated an enormous amount of interest in their potential for high-power applications.

GaAs HBTs and GaAs MESFETs have been the mainstays of RF power amplifier design for mobile handsets for many years. In handset applications, the maximum power is of the order of 1 W. Device area is a critical concern, since compactness is an essential feature. GaAs HBTs in particular, enjoy an advantage in this respect, because of their high-power density, which originates from their high-current-handling capability. The area of the power transistor for a given output power requirement is, therefore, typically smaller than that of most other devices for the GaAs HBT (even other GaAs devices such as GaAs FETs), despite the GaAs HBT requiring additional circuitry such as ballast resistors. GaAs HBTs possess other advantages over GaAs MESFETs, such as requiring only a single positive supply voltage, low leakage current requiring no extra DC switch to turn off the power supply in standby mode, and breakdown voltage being independent of input voltage. As a result, they have come to dominate the handset power amplifier market. However, GaAs HBTs

suffer from thermal issues, such as self-heating and current gain collapse, which have to be carefully managed. Self-heating can lead to a significant power difference between continuous and pulsed modes of operation in a GaAs HBT, unlike a GaAs MESFET.

GaAs HBTs usually use the AlGaAs/GaAs configuration. Here, a bandgap difference is introduced by using two different materials for the emitter and the base (i.e., AlGaAs and GaAs, respectively). The idea of improving device performance by introducing a bandgap difference was conceived by Shockley in 1948, but fabrication technology was not sufficiently developed to accomplish this until the development of molecular beam epitaxy (MBE) in the mid-1970s [1]. This bandgap difference increases the current gain of the device, which can be achieved while simultaneously increasing base doping to reduce its resistance. The reduced base resistance enables a higher frequency of operation. The current flow is vertical, so surface defects do not have a big effect on performance. More recently, HBTs based on the structure InGaP/GaAs have found use in RF power amplifier design. One advantage of InGaP/GaAs HBTs is that they do not suffer from early current gain collapse as do the AlGaAs/GaAs HBTs. The variation in current gain over operating temperature range for an InGaP/GaAs HBT is much smaller than that for an AlGaAs/GaAs HBT.

In recent times, there has been a great interest in building RF power amplifiers in silicon-based technologies. A silicon implementation of the RF power amplifier would go a long way toward achieving the holy grail of “system on a chip,” where the whole radio system would be integrated on a single die, enabling large cost savings. SiGe HBT technology has been the pioneering technology in the effort to build the RF power amplifier in silicon, with commercial power amplifier products now available. Building power amplifiers in Si CMOS, on the other hand, is more challenging, and considerable effort is currently being expended in this area. The considerations and challenges in designing RF power amplifiers in silicon, and advanced techniques to overcome these challenges, are discussed in Chapter 6.

## 1.2 DEVICE MODELING

Transistor device models are indispensable in modern IC design, most of which is computer-aided. In the early days of the use of transistors in electronic circuits, the design of these circuits relied heavily on empirical methods. The designer actually built the conceived circuit on a circuit board with discrete elements, and tested its electrical performance. The elements were consequently changed in value and configuration, until the desired specifications were met. However, this “breadboarding” methodology became infeasible with the advent of the integrated circuit (IC), because the complexity of circuits that could be designed increased enormously, and because parasitic effects and coupling between various devices on the same substrate became significant. As a result, it became essential to develop “equivalent circuit” models for the quantitative terminal description of the transistor (and other electrical elements), which could be used to “simulate” the performance of the proposed circuit configuration. The

emergence of device models enhanced flexibility in IC design, allowed for components that were difficult to breadboard, and shortened the circuit design-cycle. Transistor models used for circuit simulation are usually called “compact” models, as distinct from the more elaborate numerical device simulation models based on fundamental device physics, which are used for device design. RF power amplifier design, like any other circuit block in the radio front end, relies on accurate transistor models to predict the performance of the power amplifier, and hence enable it to be designed efficiently. Over the years, several different models have been developed for both bipolar and FET devices. However, many of the traditionally used models are not very suitable for RF power amplifier design. This is because many effects that are important from in terms of power amplifier design, such as self-heating effects in bipolar transistors, especially those in GaAs-based processes, distributed effects in the gate and substrate of Si MOSFETs, and scaling of transistor model parameters with power cell size, are not adequately modeled. Chapters 2, 3, and 4 provide a description of various device models for bipolar devices and MOSFETs, and discuss advanced modeling techniques.

### 1.3 POWER AMPLIFIER IC DESIGN

The design of RF power amplifiers is often regarded as being as much an art as a science. Traditionally, power amplifiers are designed as much by experimental iteration and tweaking, as by computer-aided design (CAD) techniques and simulation. The large-signal behavior of the RF power transistor has often been a source of controversy and debate. The optimum output power match impedance was regarded as something that could be measured only experimentally, by “load-pull” measurements, an indispensable, albeit expensive tool, in power amplifier design. However, the constant power contours obtained in load-pull measurements are not as mysterious as they are made out to be, and it is possible to reconcile them with simple load-line principles [2]. Another reason for the confusion surrounding power amplifier design is the multitude of classes of power amplifier operation. The behavior of the RF power transistor can be quite complex; it can act either as a high-resistance current source, or as a low-resistance switch, or, in some amplifiers, as a high-resistance current source during one part of the cycle, and low-resistance switch during another part of the cycle (mixed-mode operation). Further, the same circuit topology can operate in different modes, depending on how the transistor is biased and on specific inductance-resistance-capacitance ( $L-R-C$ ) values in the load network. In fact, the power amplifier often operates in modes unbeknownst to, and unintended by, the designer, because of insufficient analysis of the design, occasionally even resulting in better performance than anticipated. Indeed, the understanding of the nuances of power amplifier operation is far from complete, and is still a subject of research. Chapter 5 provides an introduction to the various concepts and considerations in RF power amplifier IC design. A discussion of the main power amplifier classes is included, as is a summary of various power amplifier performance metrics. Chapter 6 discusses silicon-based power amplifier design,

a topic of great interest today. Chapter 7 focuses on efficiency enhancement techniques for linear power amplifier design. This is also a topic of much importance, in view of the increasing use of nonconstant-envelope modulation schemes in modern wireless communication systems.

## 1.4 POWER AMPLIFIER LINEARITY

A fundamental concern when transmitting an RF signal is that it must not interfere with transceivers operating in adjacent channels. However, nonlinearity in the wireless transmitter (especially the power amplifier) causes distortion of the signal, which results in the bandwidth of the signal spreading out into adjacent channels. In general, two types of distortion occur when a signal passes through a nonlinear circuit. One is harmonic distortion, which causes the signal to be replicated at harmonic frequencies of the carrier, and the other is intermodulation distortion, which adds a “skirt” to the signal, and causes its bandwidth to spread. Harmonic distortion is the easier of the two to deal with, as it can be removed using a bandpass filter. However, the intermodulation distortion products overlap (and add skirts to) the original signal bandwidth, and cannot be removed by filtering. Thus, some amount of the transmitted power will leak into adjacent channels. This spreading of the signal bandwidth due to intermodulation distortion is called *spectral regrowth*. To allow the operation of many different communication channels in the available wireless spectrum, there are specified limits to the allowed level of spectral regrowth or adjacent-channel interference. Thus, the linearity of a power amplifier is a critical consideration in its design. For a given power amplifier design, the degradation it produces in the spectral regrowth depends on the nature of the envelope of the modulated RF signal. A constant envelope results in lesser degradation than a variable envelope. In other words, if the modulated RF signal has a nonconstant envelope, it will require a highly linear power amplifier to satisfy the adjacent-channel interference requirements. The linearity of the power amplifier, in addition to affecting signals in neighboring channels, also affects the achievable bit error rate of the wireless communication system. Linearity metrics for RF power amplifiers are discussed in greater detail in Chapter 5.

## 1.5 MODULATION SCHEMES

The constant or variable nature of the envelope of the RF carrier is the consequence of the modulation scheme used in the wireless communication system. Modulation is the method by which the information desired to be transmitted is encoded onto the RF carrier. In analog modulation, some parameter of the transmitted signal (the carrier) is varied as a linear function of the amplitude of the original audio or video signal (the modulating signal) to be transmitted. The parameters of the carrier that can be modulated are its amplitude, phase, and frequency. Frequency and phase modulation are less sensitive to nonlinearities in the amplitude response of RF circuits, noise, and

time-varying fading in the channel, than amplitude modulation, but this improvement in performance is at the expense of increased transmission bandwidth. The purpose of digital modulation is to convert an information-bearing discrete-time symbol sequence into a continuous-time waveform. In digital modulation, the signal to be transmitted is typically binary data, which may, interestingly, be a quantized and digitized analog signal. A simple form of digital modulation is on-off keying (OOK), in which a carrier is turned on and off, depending on the value of each bit. The generalized version of this is amplitude-shift keying (ASK), where the amplitude of the carrier is varied in discrete steps, with each level representing one or more bits. ASK demonstrates poor performance, as it is heavily affected by noise and interference. Frequency-shift keying (FSK) uses discrete frequencies as the symbols. For example, to transmit binary data, two different frequencies slightly offset from the carrier frequency are usually used. Phase-shift keying (PSK) uses a carrier of constant nominal frequency, with different phase shifts in the phase of the carrier signal relative to a reference phase used to represent different symbols. For example, in binary phase-shift keying (BPSK), a phase shift of  $\pi$  may be introduced when the transmitted symbol changes from 0 to 1, and the same would happen when it changes from 1 to 0. BPSK demonstrates better performance than ASK and FSK, and filtering can be employed to limit spectral spreading. However, the transmitter and receiver are also more complex. Quadrature phase shift keying (QPSK) is an improvement over basic BPSK. The phasor representation of BPSK and QPSK, shown in Figure 1.1, illustrates the difference between the two. In QPSK, a higher bit rate is achieved for the same bandwidth by coding two bits into one phase shift. QPSK is effectively two independent BPSK systems (called in-phase  $I$ , and quadrature  $Q$ ), and therefore exhibits the same performance at twice the bandwidth efficiency. In PSK systems, instead of using phase shifts relative to a reference signal of the same frequency, a phase shift relative to the previously transmitted signal can be used; this is differential phase shift keying. Such a scheme is preferable in mobile systems, since the phase of the received signal changes rapidly and it is difficult to maintain a constant phase reference. An important issue in wireless communication is the spectral occupancy, or bandwidth, of the transmitted signal. It is desirable to limit the bandwidth of the signal, to improve spectral efficiency, and reduce interference with adjacent channels. Filtering is used for this purpose; root raised-cosine filters are popular because they offer an approximation to the minimum required bandwidth (the Nyquist bandwidth). For instance, in QPSK, raised-cosine filters are used to achieve good out-of-band suppression. Filtered QPSK exhibits a nonconstant envelope, and therefore a linear power amplifier is required in the transmitter. Conventional QPSK is also not very spectrally efficient, due to the instantaneous  $\pi$  phase shift. In offset QPSK, the  $I$  and  $Q$  channels are staggered, and phase transitions are therefore limited to  $\pi/2$ . In  $\pi/4$ -QPSK, the set of constellation points are toggled each symbol, so transitions through zero cannot occur. These schemes produce smaller envelope variations compared to conventional QPSK. QPSK-based modulation formats are used in NADC (North American Digital Cellular), Japanese PHS (personal handy-phone system), and code-division

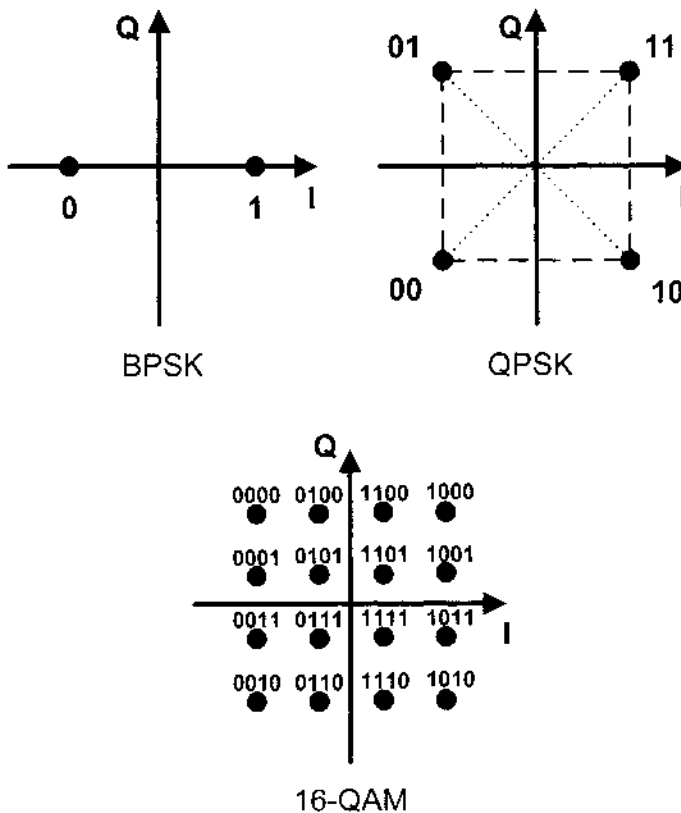
multiple-access (CDMA) systems. Minimum-shift keying (MSK) is a form of continuous-time FSK, where the phase is changed between symbols so as to provide a constant envelope. In MSK, phase ramps up by  $\pi/2$  for, say, a binary 1, and down by  $\pi/2$  for 0. Adding a Gaussian lowpass filter to the MSK scheme results in the so-called Gaussian MSK (GMSK), which is a popular constant-envelope modulation format, and is used in GSM (global system for mobile communications) systems. However it is spectrally less efficient than filtered QPSK modulation. Also, if the bandwidth-bit period product (or  $BT$ ) is too low, significant intersymbol interference (ISI) is created.

Amplitude and phase shift keying can be combined to transmit several bits per symbol. Such modulation schemes require linear power amplifiers. Higher linearity in power amplifiers is achieved at the expense of efficiency. Thus, there is a fundamental tradeoff between spectral efficiency and power efficiency in wireless transmission. Quadrature amplitude modulation (QAM) is an example of a modulation format which uses symbols that vary in both amplitude and phase. An example of this type of modulation, 16-QAM, is shown in Figure 1.1. Such multilevel (or  $M$ -ary) modulation formats are, in general, more bandwidth-efficient, but are also more susceptible to noise.

Orthogonal frequency-division multiplexing (OFDM) is a multicarrier modulation technique, where the source symbols are transmitted in parallel using many orthogonal subcarriers. IEEE 802.11a/g wireless LAN (local area network) systems use OFDM. Multicarrier modulation exhibits good ISI mitigation. Also, frequency-selective fading may influence only some subcarriers, and not the whole signal. However, multicarrier modulation techniques result in a more stringent linearity requirement on the power amplifier, because they exhibit a large peak-to-average power ratio (PAPR). Ultra-wideband (UWB) is another, relatively new technique, used in wireless transmission. Pulses with a high bandwidth (1 GHz or more) are used for transmission in a UWB system. Pulse position modulation, where the value of a transmitted symbol is given by the precise timing of the pulse, is a modulation format suitable for UWB systems.

Spread-spectrum techniques are a category of techniques used to combat narrowband interference, or cochannel interference, between modulated signals, by spreading each signal over a wider bandwidth using a code that is known to both the transmitter and the receiver. In frequency-hopping spread spectrum (FHSS) systems, the total available bandwidth is split into many channels of smaller bandwidth. The transmitter transmits on one of these channels for a certain period of time, and then hops to another channel. Thus FHSS implements both frequency- and time-division multiplexing. The hopping may be slow, where the transmitter uses one frequency for several bit periods, or fast, where the transmitter may change the frequency several times during a bit period. Fast hopping systems offer greater tolerance to narrowband interference and frequency-selective fading, at the cost of increased complexity. An example of an FHSS system is Bluetooth. In direct-sequence spread-spectrum (DSSS) systems, the bit sequence is multiplied by a binary pseudonoise (PN) sequence. The PN sequence rate that is higher than the bit rate, and each data bit is broken into several chips, where each chip is the product of the data bit and a digit of

the PN sequence. This process spreads the signal power over a wider bandwidth. The bit stream is recovered by correlating the received signal with an identical PN sequence. If the transmitter and receiver are perfectly synchronized and the signal is not too distorted by noise or multipath fading, it is easy to recover the transmitted data using a correlator. In a real-world situation, where effects such as multipath fading exist, recovery is complex. A rake receiver, which uses  $n$  correlators for the  $n$  strongest paths, is used in such a case. Each correlator is synchronized to the transmitter plus the delay on that specific path. As soon as the receiver detects a new path that is stronger, it assigns this path to the correlator with currently the weakest path. DSSS can be used as a form of multiple access, by assigning different PN sequences that have low cross-correlation, to several users. The users can then share the same frequency spectrum because only the desired transmitter will have a high correlation with the PN code used at each receiver.



**Figure 1.1.** Phasor representation, or constellation diagrams, for BPSK, QPSK, and 16-QAM modulation schemes.

## 1.6 CIRCUIT SIMULATION

Simulation tools play a vital role in the design of the RF power amplifier IC. They enable computer-aided design by utilizing transistor and passive device models to solve for the various voltages and currents in the electric circuit being designed, making it possible to predict its characteristics. SPICE (simulation program with integrated circuit emphasis) is an example of a circuit simulator. In fact, it has (in its various versions) for long been the most popular circuit simulation tool. However, RF circuits present a unique problem for traditional transient analysis using SPICE. This is because, in wireless communication, the signal comprises a high-frequency carrier, modulated by a low-frequency modulation signal. The high-frequency carrier requires a small time step in such a transient analysis, while the low-frequency modulation necessitates a long simulation interval. Thus, modulated RF signals represent a worst-case scenario for the efficiency of SPICE transient analysis. Techniques more suitable for RF IC design have been developed, and in general, these can be classified into two groups: harmonic balance-based methods and shooting methods [3]. Harmonic balance and shooting methods have been incorporated in commercially available and widely used RF circuit simulators. These techniques compute the periodic steady-state solution for a circuit, which is the steady-state response of a circuit driven with periodic waveforms. The steady-state response of a circuit driven by one or more large periodic signals can also be computed using quasiperiodic analysis techniques. The solution of such an analysis is used as a periodic or quasiperiodic operating point for further simulations. Harmonic balance techniques formulate the circuit equations in the frequency domain. Shooting methods are designed to solve boundary-value problems, using iterative techniques in addition to transient analysis. Newton methods figure prominently in shooting-method-based simulators, and such an algorithm is called the *shooting-Newton algorithm*. Harmonic balance is very efficient for circuits that are not very nonlinear, that is, if the distortion levels are low. It is also very accurate if the stimuli are sinusoidal. However, harmonic balance poses problems with circuits that are highly nonlinear, because, a large number of frequencies are needed to accurately represent the signals, which considerably slows down the analysis. The harmonic balance method also encounters convergence issues with strongly nonlinear circuits. However, techniques have been developed to improve the convergence of harmonic balance under such conditions. This involves initially reducing the amplitude of the input signal to achieve convergence, and subsequently increasing the amplitude in steps, using the result computed at one step as the starting point for the next one. Such techniques, called *continuation* or *homotopy methods*, improve convergence of harmonic balance, but at the expense of speed. Shooting methods, on the other hand, are intrinsically better at handling strongly nonlinear circuits, since they use nonuniform time steps. Also, since they use Newton's method to iteratively arrive at a solution, their convergence under nonlinear conditions is very good. It is worth noting that many wireless communication applications use nonconstant-envelope modulation and require a high level of linearity in the power amplifier. In such a situation, harmonic balance is quite a suitable and

efficient tool for circuit simulation. Harmonic balance is also very adept at handling transmission lines, and table-based interpolated  $S$ -parameter models. Shooting methods, on the other hand struggle to handle distributed components, such as transmission lines. This is why harmonic-balance-based simulators have been more popular in microwave design, in which such components are often used. System-level simulation tools, which allow cosimulation with embedded circuit components, have also successfully used harmonic balance for the analysis of these circuit blocks.

Spectral regrowth is very difficult to predict with traditional SPICE transient analysis. This is because the high carrier frequency, and the fact that a large number of bit transmissions (hundreds or a few thousand) must be simulated to obtain a reasonably representative spectrum, makes the use of traditional transient analysis impractical. The stimulus signal, generated by the digital modulation format in use in the wireless communication system, has to be accurately represented. Transient envelope analysis may be used to simulate modulated carrier systems. In such an analysis, a series of linked large-signal pseudoperiodic analyses, which are periodic analyses that have been modified to account for slow variations in the envelope as a result of modulation, are performed [3]. The pseudoperiodic analyses are performed often enough to adequately capture the changes in the envelope. Harmonic-balance based envelope simulation techniques, where the amplitude of the frequency components can vary as a function of time, have also been developed to simulate modulated RF signals and analyze spectral regrowth. However, because of the large number of simulation points usually required to simulate digitally modulated signals accurately, it is computationally quite expensive to use transient envelope techniques based on harmonic balance or shooting methods. An alternative is to use a behavioral model of the power amplifier, which is usually extracted from AM-AM and AM-PM measurements. Spectral regrowth can then be quickly and efficiently computed using this behavioral model and an appropriate mathematical characterization of the stimulus signal.

## 1.7 LOAD-PULL MEASUREMENTS

Load-pull measurements are widely used in RF power amplifier design and characterization. In a load-pull measurement, a whole range of output impedances are presented to the power transistor or power amplifier, and the characteristics of the device, like output power, power-added efficiency, intermodulation distortion, or adjacent-channel rejection, may be measured for each output impedance condition. The results are usually plotted on a Smith chart, to generate the so-called load-pull contours. Similar to load-pull, the source impedance may also be varied, and such a measurement is called *source-pull*. The output or input impedances are varied using tuners, which may be passive or active. A typical passive tuner system is shown in Figure 1.2. The two tuners may be used to simultaneously tune the source and load impedances at the fundamental frequency. Load-pull measurements are often used to optimize the match impedance, to extract the best possible performance from the

power amplifier. Figure 1.3 shows typical load-pull contours for output power and power-added efficiency (PAE). Each of the contours represents the set of terminations corresponding to a particular output power level or value of PAE.

The termination impedance for which the output power (or PAE) is maximum is the center of the concentric set of contours. The optimum output impedance for maximum output power, for a power amplifier, is generally close to the periphery of the Smith chart. This means that the magnitude of the optimum impedance is small, which is expected since the output stages are large transistors carrying large current. This leads to practical difficulties in performing load-pull measurements, since losses in the RF signal path in the measurement setup reduces the effective area of the Smith chart that can be covered by the system. Prematching tuners may be used to shift the impedance of the device under test (DUT) to a range that can be easily achieved with the tuner setup, if the optimum impedance lies outside its range. The shape of the load-pull contour can be explained to consist of two arcs of constant power on the Smith chart [2]. For a given output power level, the set of output impedances corresponding to this power level consist of arcs of constant resistance (say  $R_{opt}$ ) and constant conductance ( $G_{opt} = 1/R_{opt}$ ) on the Smith chart, which intersect to give the load-pull contour.

In the system shown in Figure 1.2, the impedances at the harmonics of the fundamental frequency are not controlled. Harmonic terminations can be important in optimizing the performance of an RF power amplifier. Harmonic load- and source-pull measurements may be performed to characterize the effect of, and optimize, harmonic impedances. In a measurement where the second-harmonic impedances are being investigated, diplexers are used at the input and output of the DUT, to separate the signal paths at the fundamental and second-harmonic frequencies. Separate tuners are connected to each diplexer output, so that the terminations at the two frequencies can be tuned independently. Similarly, triplexers are used in a measurement involving third-harmonic terminations in addition to the fundamental and second-harmonic.

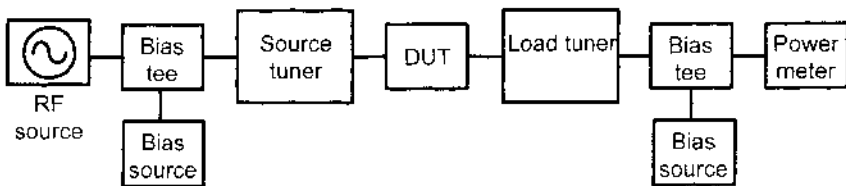
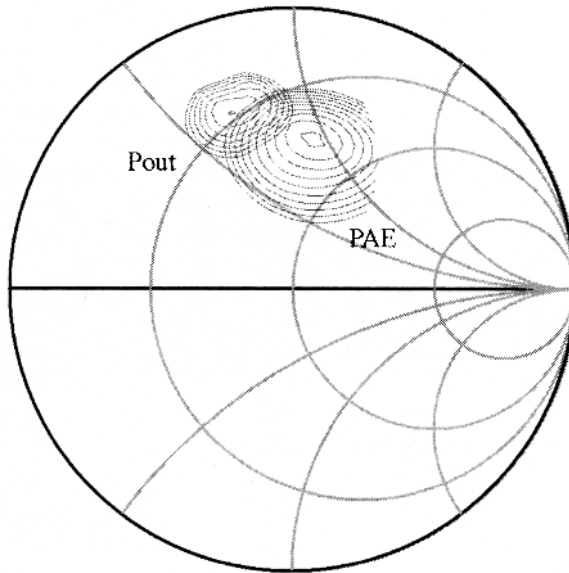


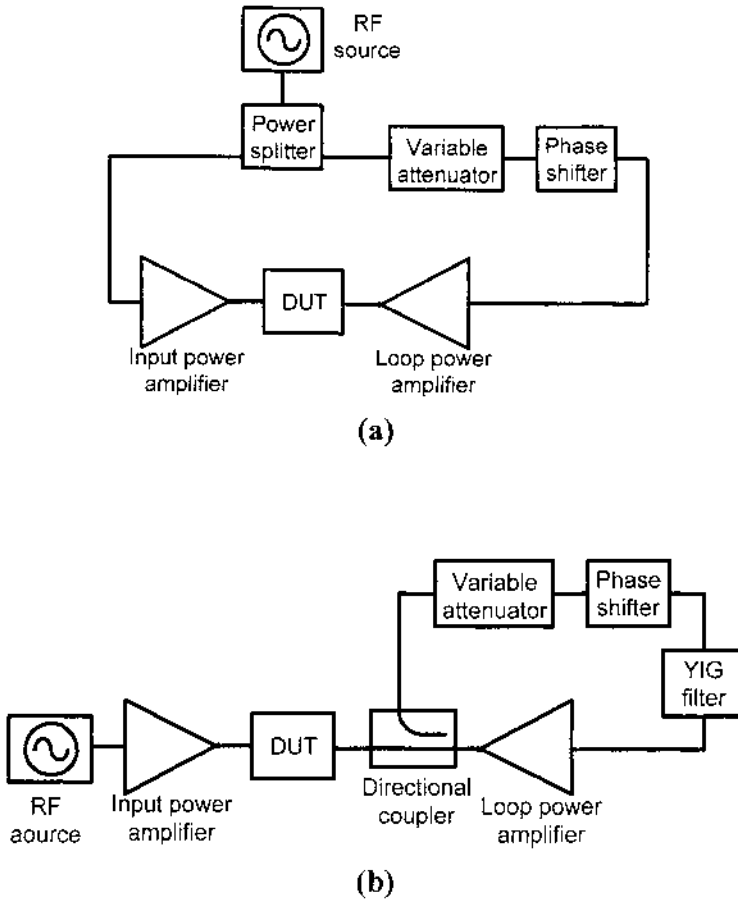
Figure 1.2. Load-pull system using passive tuners.



**Figure 1.3.** Typical load-pull contours for output power and PAE.

Active load-pull systems use active tuners, and are generally categorized into two types: the two-signal-paths type, and the feedback type [4]. In the two-signal paths type active load-pull system, shown in Figure 1.4a, a power divider splits the source RF signal into two parts. One drives the input port of the DUT, while the other is properly amplified, phase-shifted and injected into its output port. In the feedback type (see Figure 1.4b), a portion of the output signal of the DUT is drawn using a direction coupler and is fed back to the DUT output after proper amplification and phase shift. A high-selectivity filter has to be introduced in the loop, as shown in Figure 1.4b, to avoid oscillations, which this type of load-pull system is susceptible to, due to the broadband nature of the loop components. The two-signal-paths system is not susceptible to oscillations because of the high isolation of the power amplifiers. However, it suffers from the drawback that the load impedance also depends on the input power level and the DUT characteristics. Hence, a complicated sequence of attenuator and phase shifter adjustments is needed at each power level to keep the load impedance constant, during a power-sweep measurement.

Load/source-pull measurements find widespread application in designing and optimizing RF power amplifiers, and in characterizing, developing, and validating large-signal transistor models for use in power amplifier simulations.



**Figure 1.4.** Active load-pull system configurations: (a) the two-signal-paths system; and (b) the feedback loop system.

## REFERENCES

1. H. Kroemer, Heterojunction devices. *IEEE Trans. Electron Devices*, **39**(11): 2635–2636 (Nov. 1992).
2. S. Cripps, A method for prediction of load-pull power contours in GaAs MESFETs. *IEEE MTT-S Int. Microwave Symp. Digest*, 1983, pp. 221–223.
3. K. S. Kundert, Introduction to RF simulation and its applications. *IEEE J. Solid-State Circuits*, **34**(9): 1298–1319 (Sept. 1999).
4. J. E. Müller and B. Gyselinckx, Comparison of active versus passive on-wafer load-pull characterization of microwave and mm-wave power devices. *IEEE MTT-S Int. Microwave Symp. Digest*, 1994, pp. 1077–1080.

