CHAPTER 1

INTRODUCTION

1.1 THE MARKET FOR CELLULAR PHONES AND WIRELESS DATA TRANSMISSION EQUIPMENT

The market for cellular phones and wireless data transmission equipment has changed dramatically since the late 1970s when cellular phones were first introduced and the late 1980s when wireless data equipment became available. As would be expected, during this time RF test requirements and RF test equipment has changed dramatically.

The original cellular phones, which were introduced in North America in the 1970s, were FM analog voice phones with a limited data capability of less than 10 kbps. These analog phones are now called first generation (1G). Cellular phones were digitized in the early 1980s to provide for an increased number of user channels in a given RF frequency band. These digital phones are now called second generation (2G).

During the 1990s the use of 2G cell phones increased dramatically throughout the world, growing to over 2 billion handsets worldwide by 2005. Eighty percent of 2G phones are Global System for Mobile Communications (GSM), using digital FM modulation. The reasons for the expansive growth of GSM phones was (1) the excellent voice quality of the digital signal, which could accurately digitize any language, and (2) an effective worldwide management and billing system for all of its customers.

During the growth of GSM phone capacity worldwide, the North American cellular industry was divided between proponents of using a Time Division Multiple Access (TDMA) system similar to GSM, but carefully designed to be backward

RF Measurements for Cellular Phones and Wireless Data Systems. By A. W. Scott and R. Frobenius

compatible with the RF part of the original analog system, and a new Code Division Multiple Access (CDMA) concept advocated by Qualcomm, which provided greater user capacity in a given RF bandwidth. After extensive field trials conducted throughout the United States in the late 1980s, the CDMA system demonstrated an approximate doubling of voice capacity compared to TDMA.

As digital voice cell phone usage grew in the 1980s, equipment manufacturers began the development of third generation (3G) phones that, in addition to providing high-quality wireless voice service, could also provide a wide range of data related services including the following:

- Data rate transfer exceeding 1 Mbps at any location within the cell where voice phones worked
- Wireless connected photographic cameras
- Wireless connected video cameras
- GPS information
- Windows operating system with Word, Excel, and PowerPoint
- Internet access

In order to accomplish this high data rate capacity, the greater bit rate transfer capability of CDMA systems is required. It is predicted that all cellular phone systems will be converted to CDMA by 2012.

The 20% of system operators who had originally opted for CDMA voice phones are already providing data transfer capability up to 1 Mbps, even though voice service still accounted for 90% of their business in 2005.

The GSM service providers, who provide 80% of worldwide cellular voice service, face an economic problem because of the vast amount of installed GSM base station equipment. However, the GSM community now has a worldwide evolution plan to grow from the limited 100 kbps data capability of GSM phones to a data capability of several gigabits per second using Wideband Code Division Multiple Access (WCDMA)/High-Speed Downlink Packet Access (HSDPA). However, the implementation of this high data rate equipment by the GSM community will lag that of the current CDMA carriers by about 3 years.

The importance of these facts is that the measurement equipment needs for cellular phone equipment are stabilized for the next 5 years, until fourth generation (4G) phones replace the 3G phones.

In a similar way, the requirements for short-range, high data rate equipment like Wi-Fi (802.11a, b, g, and n) are stabilized. These systems achieve data rates up to 200 Mbps because their ranges are short. Consequently, the received power is high and complex modulation schemes like 64-quadrature amplitude modulation (64QAM), which transmits 6 digital bits in every Hertz of bandwidth, can be used.

A significant change in RF test equipment occurred in the early 2000s in order to meet the needs of testing the evolving cell phone and wireless local area network (LAN) equipment. Extensive digital processing was added to conventional RF signal generators, vector network analyzers (VNAs), and spectrum analyzers to improve their measurement uncertainty and increase their capability.

For example, many of the newest VNAs now use a Windows operating system instead of a proprietary operating system. This change gives increased capacity for data processing and allows measurements to be easily transferred to laptops or other computers for further analysis and archiving. Electronic calibration of the VNAs is now available to reduce the uncertainty of their measurements that is due to handling damage of the calibration standards and operator error. Measurement of absolute power in decibels relative to 1 mW (dBm) in a VNA is about ±1 dBm. Provision is now available to calibrate the VNA with a power meter and achieve power measurements within an uncertainty of only ±0.2 dBm.

Hardware and software options can now be added to the latest generation of spectrum analyzers to permit them to make the specialized signal analysis measurements required for cell phone and wireless LAN. These upgrades to the spectrum analyzers include the following:

- Measurement of phase noise and noise figure
- Measurement of the spectral regrowth of digitally modulated RF carriers
- Ability to function as a vector signal analyzer (VSA)
- Measurement of the key specifications for any cell phone or wireless LAN system

The life cycle of RF measurement equipment (with hardware and software upgrades) is about 15 years, so the latest versions of RF measurement equipment will cover RF measurement needs throughout the lifetime of the current cell phone and wireless LAN evolutions.

1.2 ORGANIZATION OF THE BOOK

RF Measurements for Cellular Phone and Wireless Data Equipment is organized as follows:

Part I (Chapters 2–4) provides a review of basic RF principles. Many of the users of this book already have knowledge of basic RF terminology, but many do not. For those users who do not, Part I will provide this knowledge and should be studied first. For those users who have this knowledge already, Part I will provide a good review.

Part II (Chapters 5–14) describes RF measurement equipment, including signal generators, power meters, frequency meters, VNAs, spectrum analyzers, VSAs, and other equipment.

Part III (Chapters 15–28) describes the RF devices that are used in cellular phones and wireless data transmission equipment: how they work, what their critical performance parameters are, how they are tested, and what typical test results are.

Part IV (Chapters 29–36) describes the testing of RF devices and systems that use digitally modulated signals to represent the voice, video, or data that the RF wave is carrying. The same RF device will have different performance, depending on the data modulation being used.

1.3 PART I: RF PRINCIPLES

Chapters 2–4 in Part I describe RF principles.

1.4 SUMMARY OF CHAPTER 2: CHARACTERISTICS OF RF SIGNALS

Chapter 2 describes the characteristics of RF signals, which include frequency and wavelength, power (dB and dB relative to 1 mW), and phase.

The range of RF power that must be measured in cellular phones and wireless data transmission equipment varies from hundreds of watts in base station transmitters to picowatts in receivers.

For calculations to be made, all powers must be expressed in the same power units, which is usually milliwatts. A transmitter power of 100 W is therefore expressed as 100,000 mW. A received power level of 1 pW is therefore expressed as 0.000000001 mW. Making power calculations using decimal arithmetic is therefore complicated. To solve this problem, the dBm system is used, which is fully explained in Chapter 2. Figure 1.1 shows the range of RF power and its value in watts and dBm.

1.5 SUMMARY OF CHAPTER 3: MISMATCHES

Chapter 3 describes mismatches, including definition of mismatches: return loss, standing wave ratio (SWR), and reflection coefficient; conversion between units; matching; and use of the Smith Chart for matching design.

Figure 1.2 illustrates the mismatch problem. Figure 1.3 shows how to minimize the mismatch by adding a matching component using a Smith Chart design.

1.6 SUMMARY OF CHAPTER 4: DIGITAL MODULATION

The purpose of a wireless communication system is to transmit voice, video, or data signals wirelessly from one location to another using the least amount of RF bandwidth. The various types of digital modulation [frequency shift keying (FSK), phase shift keying (PSK), and QAM] are explained in this chapter. Trade-offs between capacity and complexity of modulation are presented.

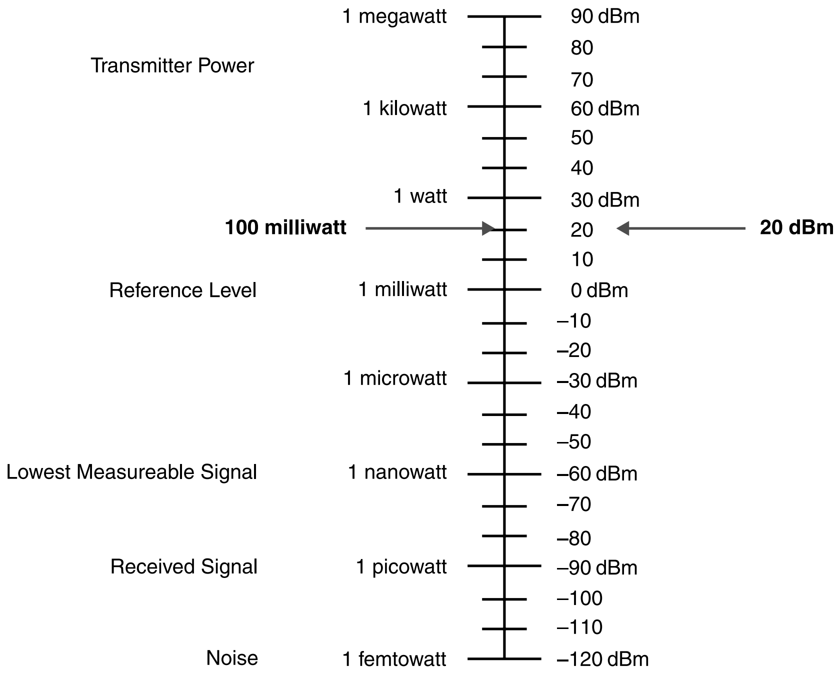


Figure 1.1 Range of RF power in watts and dBm.

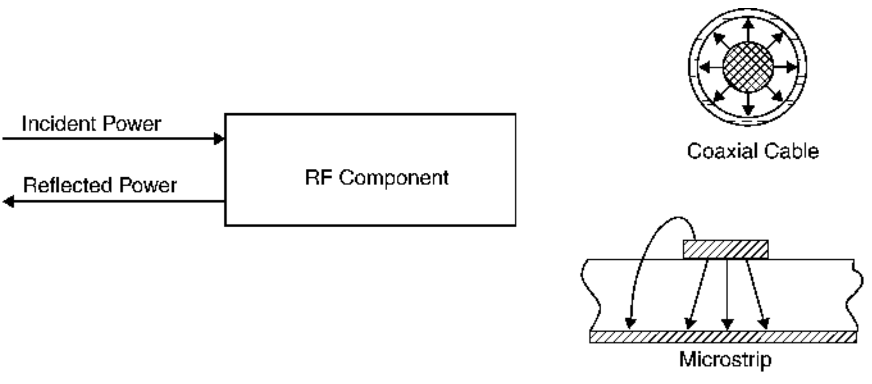


Figure 1.2 Mismatches. Some RF power is reflected as it tries to enter a component because the RF fields do not match. The mismatch is expressed as the percentage of reflected power, return loss, SWR, and reflection coefficient.

Figure 1.4 shows types of digital modulations on an RF wave. The RF wave is called the carrier, because it is carrying digital information by its modulation. The upper curve shows a bipolar digital data stream that is to be transmitted. In a wired communications system, this digital signal is simply transmitted as a voltage

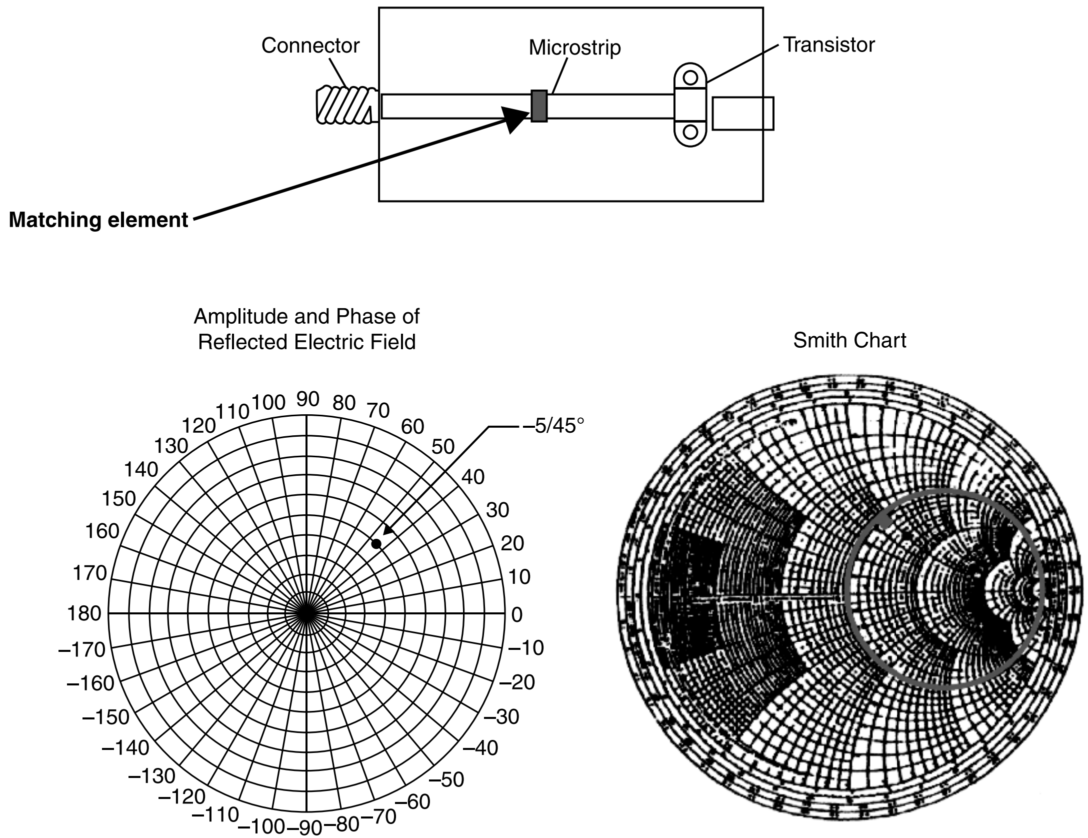


Figure 1.3 Matching with the Smith Chart.

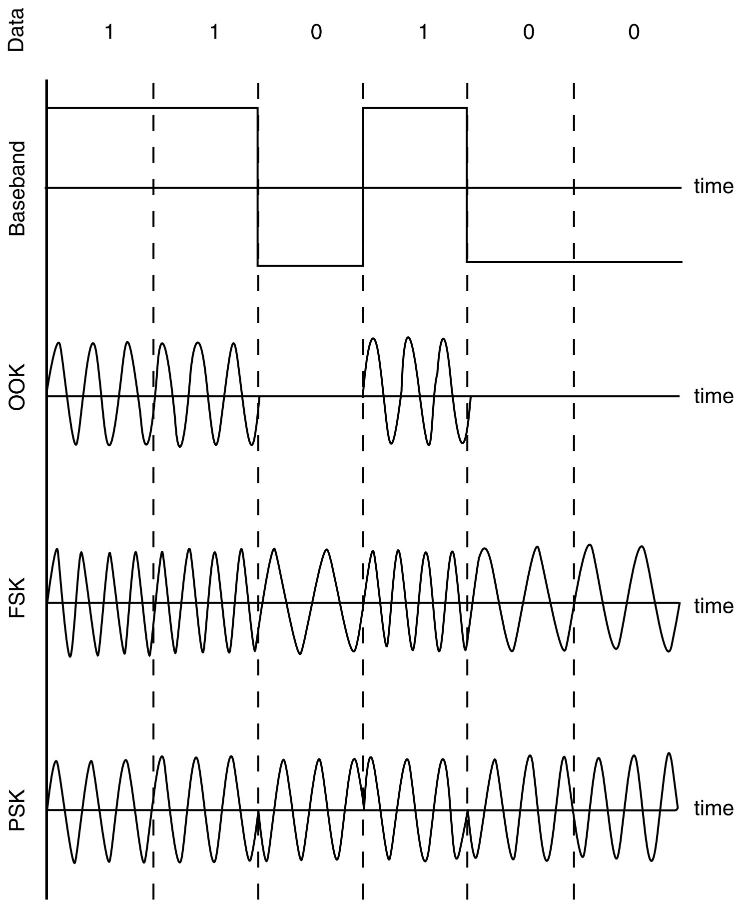


Figure 1.4 Digital modulation.

through wire, coaxial cable, or optical fiber. The data stream in this example is 110100.

The second curve in Figure 1.4 shows the amplitude modulation of a wireless carrier. There are various types of amplitude modulation. The simplest type shown here is on–off keying (OOK). When the RF signal is on, the data is a 1; when the RF signal is off, the data is a 0.

The third curve shows digital FSK. The amplitude (or power level) of the FSK modulated wave is constant, but the frequency is changed to represent the digital information. When the frequency is low, the data is a 0. When the frequency is high, the data is a 1.

The fourth curve shows phase modulation. The amplitude and the frequency of the wave are constant, but the phase is changed to represent information. When the phase is 0º, the data is a 0. When the phase is 180º, the data is a 1. Actually there is no way of telling from the RF wave whether the phase is 0º or 180º. The change can be detected, but not the absolute value. Therefore, a second phase reference signal must be transmitted along with the phase modulated wave. Alternately, a special technique called "differential" PSK (DPSK) can be used, where a change in phase represents a digital 1 and no change in phase represents a digital 0.

Note that the amplitude of the RF wavelets is constant when phase modulation is used. However, the RF amplitude varies during the phase transition between data pulses, and this amplitude change creates difficult design problems for the power amplifier that amplifies the digitally modulated RF signal before transmission.

Each time the amplitude, frequency, or phase of the RF carrier is changed, approximately 1 Hz of bandwidth is used. Therefore, if the data rate is 1 Mbps, the required RF bandwidth to transmit the information is about 1 MHz.

To reduce the RF bandwidth requirements for transmission of a given data rate signal, multiple levels of amplitude, frequency, or phase are used and sometimes two types are modulation are used simultaneously. The number of bits that can then be transmitted in a 1 Hz bandwidth is increased, and this increase is called the "spectral efficiency" of the modulation system.

Constellation diagrams of various multiple level modulation systems are provided in Figure 1.5. These diagrams show the phase of the RF signal in the angular direction and the amplitude of the signal in the radial direction.

The upper left-hand drawing in Figure 1.5 shows the simplest modulation scheme, binary (two level) PSK (BPSK), which transmits 1 bit for every 180º of phase change of the carrier.

The upper center drawing in Figure 1.5 shows QPSK modulation with four phase positions of 45º, 135º, 225º, and 315º, which represent bits 00, 01, 10, 11, respectively. As stated earlier, note that with any phase shift modulation, either a second

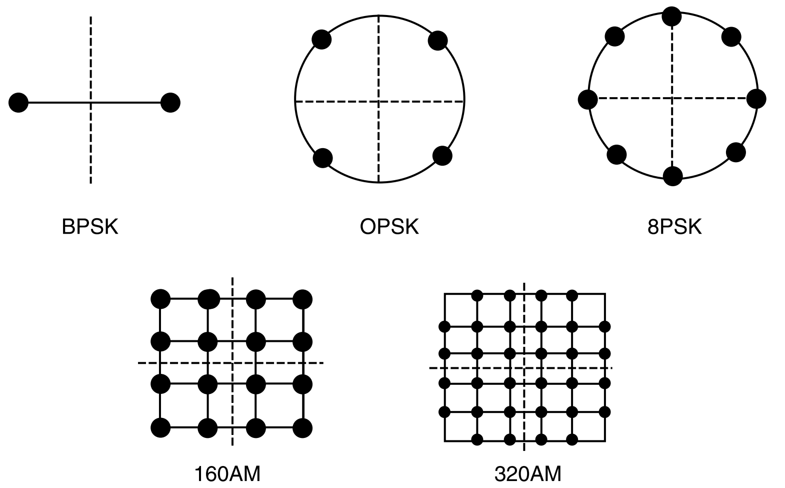


Figure 1.5 Constellation diagrams.

unmodulated carrier must be transmitted or a differential phase shift (DQPSK) modulation must be used. In either case the constellation is the same.

The upper right-hand drawing shows 8PSK modulation, where the constellation points are 45º apart. With 8PSK, 3 bits are transmitted every time I Hz of bandwidth is used.

The lower two drawings in Figure 1.5 show constellation diagrams in which the amplitude and phase are changed simultaneously. These modulation schemes are called QAM. In the lower left-hand drawing there are 16 possible phase and amplitude positions, so that 4 bits are transmitted every time 1 Hz of bandwidth is used. In the lower right-hand drawing, there are 32 possible phase and amplitude positions, so that 5 bits are transmitted every time 1 Hz of bandwidth is used.

1.7 PART II: RF MEASUREMENT EQUIPMENT

Part II describes RF measurement equipment. Chapters 4–12 describe RF measurement equipment and techniques in the following order:

Chapter	Measurement Equipment
5	RF signal generators
6	Power meters
7	Frequency meters
8	VNAs
9	Spectrum analyzers
10	VSAs
11	Noise figure meters
12	Coaxial cables and connectors
13	Measurement uncertainty
14	Measurement on components without coax connectors

1.8 SUMMARY OF CHAPTER 5: RF SIGNAL GENERATORS

To test any RF device or system, an RF signal is required, which is provided by an RF signal generator.

The signal generator provides a single RF signal with characteristics selected by the user, which remain constant until the user changes them. Typical characteristics that can be adjusted are as follows:

Frequency
Power
Type of AM or FM modulation
Type of digital modulation

Digital modulation types can be specified for particular cell phone systems
New modulation techniques can be programmed into the signal generator

The signal generator can also be adjusted to supply a fixed set of multiple signals. Bit error rate (BER) testing on systems can also be done by the signal generator. Figure 1.6 shows an RF signal generator that provides this performance.

1.9 SUMMARY OF CHAPTER 6: POWER METERS

Power meters provide the most accurate measurement of RF power of any of the types of RF measurement equipment. Power meters can be stand-alone instruments, or they can be built into other instruments like signal generators, spectrum analyzers, and VSAs. Some power meters can display RF power as a function of time.

RF power meters provide absolutely *no* information about the frequency distribution of the RF power. The indicated RF power is the total power incident at the power meter. If the signal is a single frequency, the power meter displays its power. However, if multiple signals are present at different frequencies, the power meter displays the total RF power of all of the signals together. Figure 1.7 shows an RF power meter with its power sensor.

1.10 SUMMARY OF CHAPTER 7: FREQUENCY COUNTERS

RF frequency counters measure the frequency of a *single* RF signal. If more than one frequency is present, the power meter turns off its display.

At RF frequencies up to about 500 MHz, frequency counters simply count the cycles of the single frequency RF wave with a digital counter. Accuracy can be as good as 1 part in 1 million.

Digital counting circuits do not work above about 500 MHz. Thus, for counting higher RF frequencies, some type of downconversion is used.

One type of downconversion is “prescaling.” Prescaling involves simple division of the input frequency by an integer N to reduce the frequency to a value that can be counted by a digital counter. Typically, N ranges from 2 to 16. The counted prescaled value is then multiplied in a signal processing circuit by the integer N and displayed. This technique allows counting to about 1.5 GHz.

For counting to higher RF frequencies, a heterodyne converter is used. The counter contains a signal generator, a mixer, and a lower frequency digital counter. The RF signal to be counted is mixed down to a lower frequency that can be counted, and the displayed signal is the sum of the frequency of the lower frequency signal generator and the difference frequency of the mixer. Accuracy is determined by the frequency accuracy of the internal RF signal generator. Figure 1.8 shows an RF frequency counter.

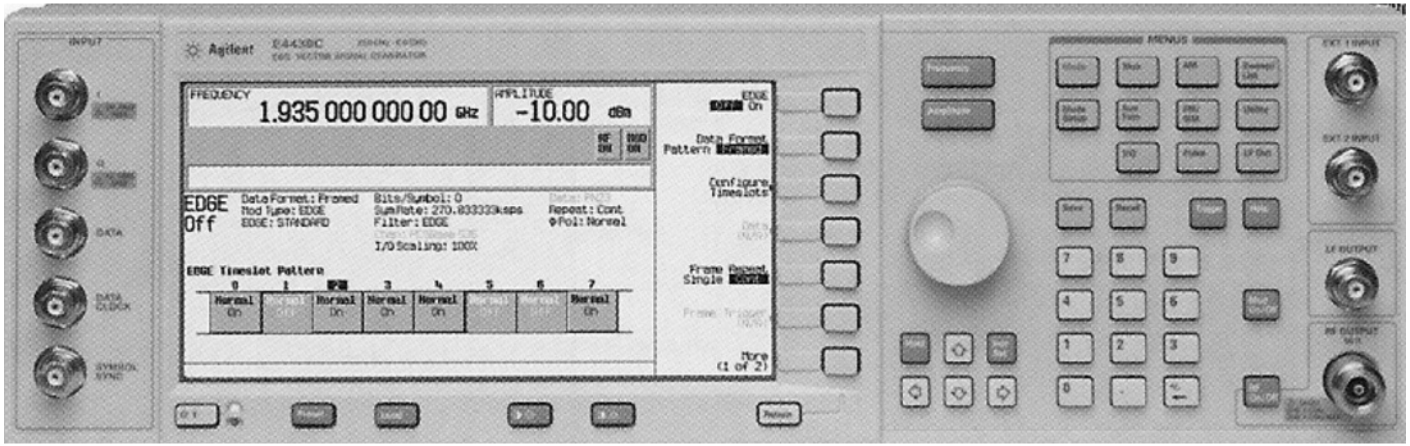


Figure 1.6 RF signal generator. Agilent Technologies © 2008. Used with permission.

Figure 1.7 Power meter. Agilent Technologies © 2008. Used with permission.

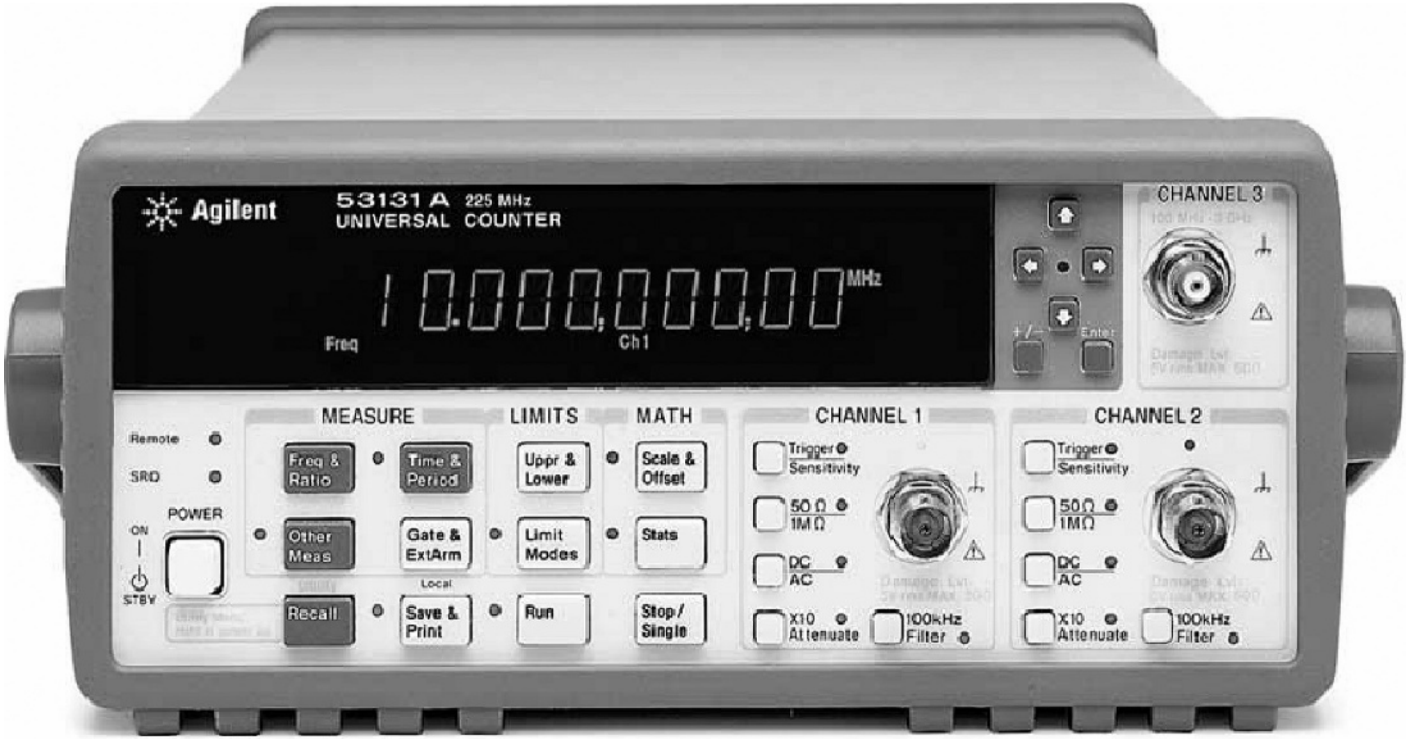


Figure 1.8 Frequency counter. Agilent Technologies © 2008. Used with permission.

1.11 SUMMARY OF CHAPTER 8: VNAs

An RF VNA measures the response of both RF devices and networks (which is a group of devices) as a function of the frequency of an applied continuous, nonmodulated, RF signal. The VNA measures the response of the network one frequency at a time, but it varies the measurement frequency over the user adjusted RF bandwidth very rapidly, making hundreds of measurements in 1 s.

The term vector designates the fact that the VNA measures both the amplitude and *phase* of the RF signal. Figure 1.9 shows a VNA.

The VNA measures the incident test signal, the reflected test signal, and the transmitted signal from the RF device. Then it automatically reverses the connections to measure the same quantities looking into the device from the opposite direction. The VNA can display these measured quantities as a function of frequency. However, it usually processes the information first to display derived quantities such as return loss, insertion loss, scattering parameters (S-parameters) in amplitude and phase, Smith Charts, group delay, and other performance characteristics.

The frequency range over which the VNA sweeps can be adjusted by the user. Alternately, the frequency can be fixed at a constant value and the power level can be swept so that the display shows the device or network performance as a function of power at a fixed frequency.

For ratio measurements, such as return loss or insertion loss, where two power levels are being compared to each other, the VNA's measurement accuracy can be improved to 0.1 dB or better by first calibrating the VNA to a set of standards, usually a short, open, load, and through (SOLT). This calibration can be done manually by the operator. It can also be done electronically using an add-on device that contains the standards and electronically operated relays to perform the calibration automatically. This electronic calibration eliminates operator error and also protects the standards from handling damage.

The accuracy of the VNA when it is used for absolute power measurements can be improved to ± 0.2 dBm by automatically calibrating the VNA with a power meter.

1.12 SUMMARY OF CHAPTER 9: SPECTRUM ANALYZERS

Spectrum analyzers can measure all of the individual frequencies that exist in any particular RF signal and display the power level of each frequency separately. They accomplish what the power meter and the frequency meter can only measure separately. Figure 1.10 displays an RF spectrum analyzer.

Note the difference between a spectrum analyzer and a VNA. The VNA analyzes the performance of a single RF device or combination of devices, either of which is called a "network." It measures the performance of the network one frequency at a time. The spectrum analyzer analyzes a signal to describe the power of each of the frequencies that make up the signal. The spectrum analyzer may be used to measure the distortion that the RF device creates on the different frequency components of the signal passing through it.

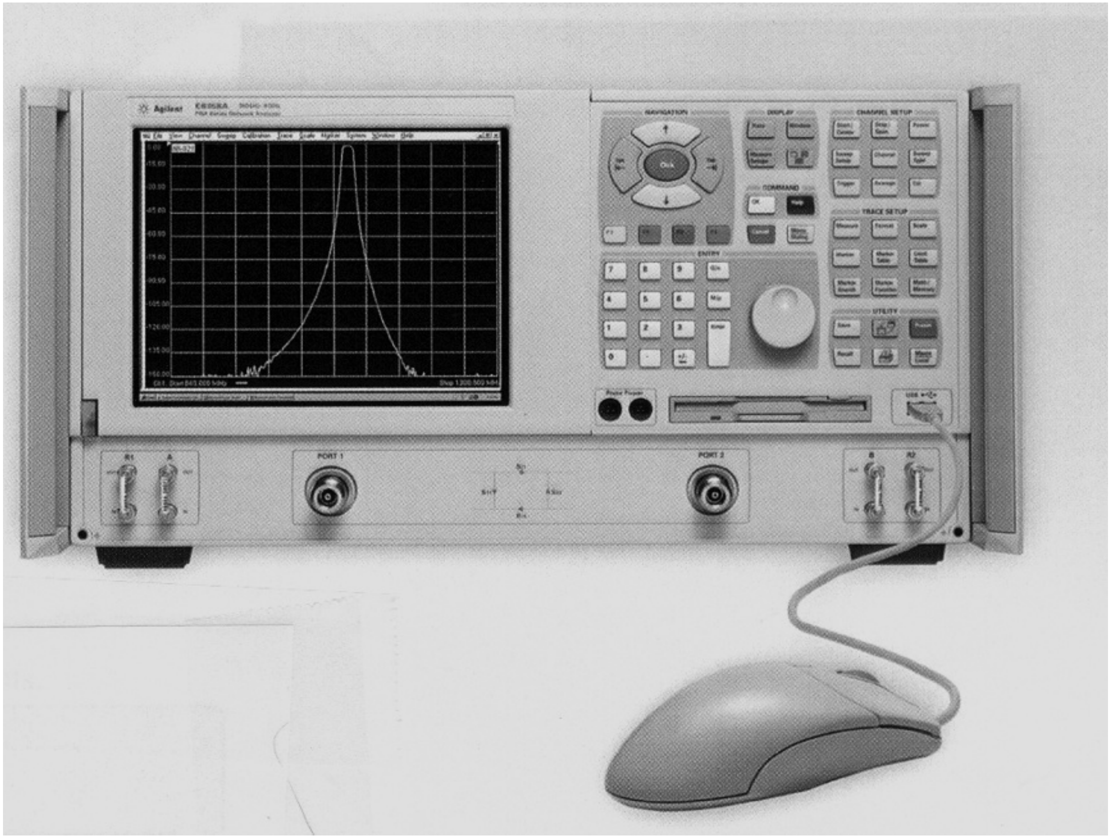


Figure 1.9 VNA. Agilent Technologies © 2008. Used with permission.

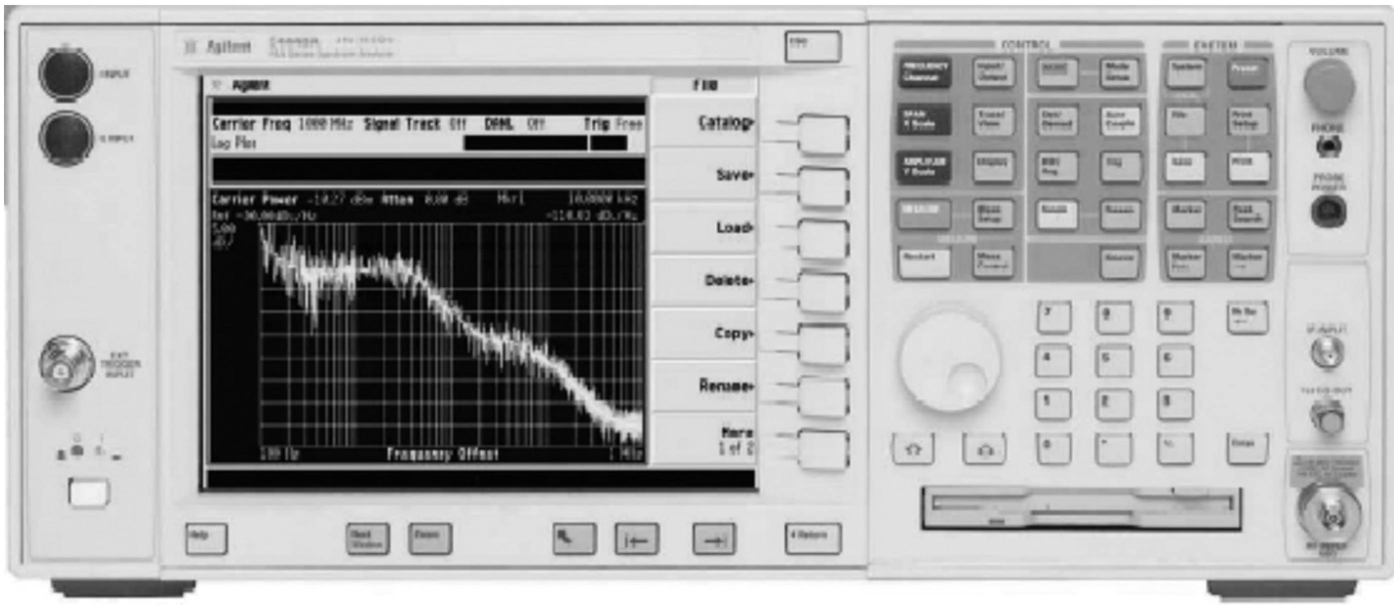


Figure 1.10 Spectrum analyzer. Agilent Technologies © 2008. Used with permission.

The spectrum analyzer not only displays the various frequencies and their power levels that make up an RF signal, but it can also analyze the display to provide specific facts about the signal. For example, it can determine the frequency range of 95% of the power in a given signal or how much of the power of a signal is spread into an adjacent channel frequency band that is assigned to another user. It can also measure the effect of device distortion on the specification requirements of different communication systems. With extra software and hardware added, it can measure complicated performance characteristics like oscillator phase noise and spectral regrowth. With additional hardware added, it can also demodulate an RF signal to permit it to be analyzed by VSA software, as described in the next section.

1.13 SUMMARY OF CHAPTER 10: VSAs

Like the spectrum analyzer, the VSA measures the characteristics of an RF signal, but it displays the signal characteristics in a different way. The VSA can be a stand-alone instrument, but it is most often implemented with a spectrum analyzer that provides the RF demodulating circuits and a software disk and laptop computer that converts the demodulated signal into the displays. Figure 1.11 shows this setup. The device under test (DUT) is shown in the center. The spectrum analyzer described in the previous section is used to demodulate the signal to be analyzed. Notice that its display is blank. The demodulated waveform is sent to a laptop computer, where the complex modulation is analyzed and displayed.

Figure 1.12 shows the display of a VSA when it is measuring an RF signal that has been modulated with $\pi/4$DQPSK modulation. The upper left-hand display is a vector diagram, which shows the amplitude and phase of the RF signal during the transition between measurement points. The upper right-hand display is an eye diagram. It is more complicated than the eye diagram of wired digital transmission systems, because of the multilevel value of the modulation. The lower right-hand display is a constellation diagram. These three displays give insight into the cause of the distortion, but they do not quantify it. Quantization is given by the error vector magnitude (EVM) shown in the lower left-hand display. These displays are explained in detail in Chapter 33.

1.14 SUMMARY OF CHAPTER 11: NOISE FIGURE METERS

Most modern spectrum analyzers can be equipped with special hardware and software to measure noise figure and gain of low noise receiver components such as low noise amplifiers (LNAs), input filters, cabling, and mixers.

A soft key switches the spectrum analyzer back and forth between its function as a spectrum analyzer and a noise figure meter. When it is in its noise figure meter mode, all hard keys except the numeric keypad are deactivated, and all control is by soft keys. A noise figure measurement setup using a spectrum analyzer is provided in Figure 1.13.

A LNA in the noise figure meter hardware is automatically connected between the spectrum analyzer input port and the spectrum analyzer mixer. This reduces the noise figure and increases the gain of the spectrum analyzer. The use of this amplifier

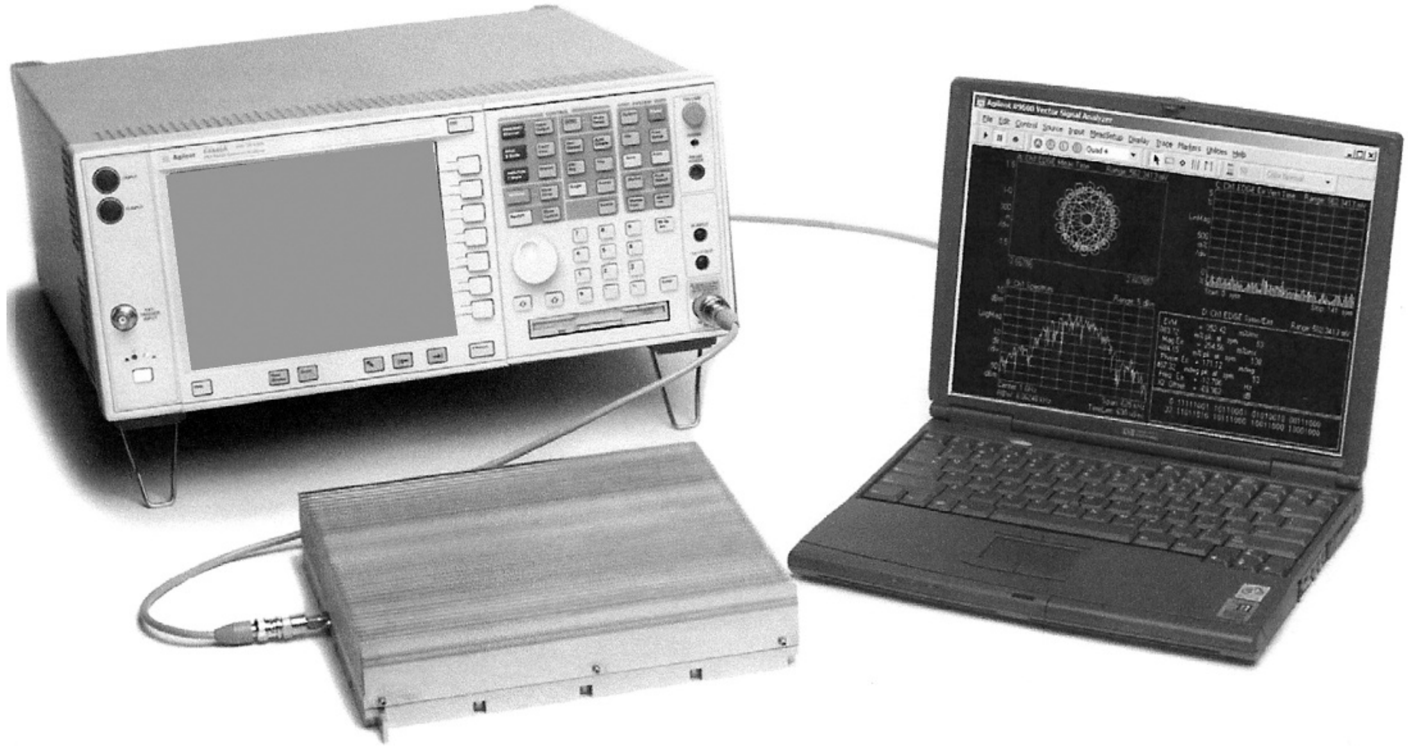


Figure 1.11 VSA. Agilent Technologies © 2008. Used with permission.

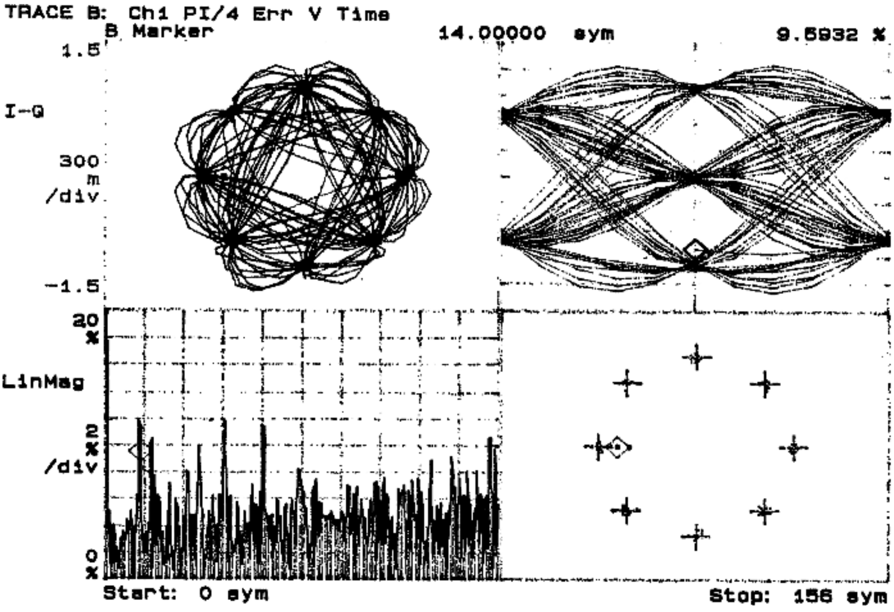


Figure 1.12 Various ways of analyzing modulation distortion.

reduces the effect of the spectrum analyzer noise figure on the noise figure measurements of the DUT.

To make the noise figure measurements, a known signal and a known noise must be sequentially connected to the input of the DUT. These signals are supplied by the noise source. The output signal must be then measured for each condition. The input signal/noise ratio (S/N) will therefore be known, and the output S/N can be calculated. Their ratio is the noise figure of the DUT.

1.15 SUMMARY OF CHAPTER 12: COAXIAL CABLES AND CONNECTORS

Chapter 12 describes the various coaxial transmission lines and connectors used to connect the RF test equipment with the RF devices under test. Recommended practices to insure measurement accuracy are also described.

1.16 SUMMARY OF CHAPTER 13: MEASUREMENT UNCERTAINTIES

The uncertainty of RF measurements and steps that can be taken to minimize them are explained in this chapter. The uncertainty of all RF measurements is affected by source and sensor mismatches. Steps to minimize this type of uncertainty are explained. Additional uncertainties are specific to each RF measurement type.

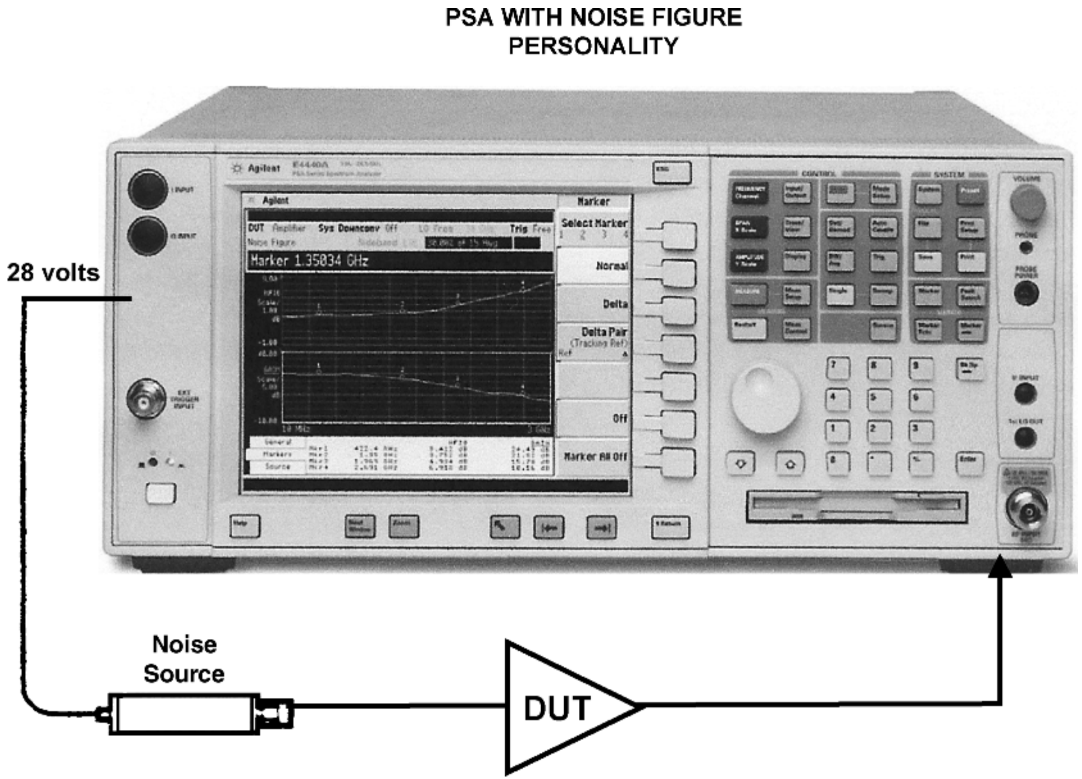


Figure 1.13 Noise figure test setup. Photo Agilent Technologies © 2008. Used with permission.

If great care is taken, RF power can be measured within an accuracy of ± 0.2 dB with a power meter. Ratioed measurements, such as the comparison of output power to input power of a device, can be measured to ± 0.05 dB with a VNA, if the VNA is calibrated with standards. The calibration can be done manually or electronically. The VNA can measure absolute power to only ± 1 dBm. However, it can be calibrated with a power meter to achieve power meter accuracy, with the disadvantage that the power meter calibration takes several minutes.

Spectrum analyzer power measurements have been greatly improved in the latest available models by including built-in power meter calibration. Power measurements with the spectrum analyzer can now be made with about ± 0.5 dBm uncertainty. Frequency can be measured with a spectrum analyzer to an uncertainty of about $\pm 3\%$ of the span.

1.17 SUMMARY OF CHAPTER 14: MEASUREMENT OF COMPONENTS WITHOUT COAXIAL CONNECTORS

All of the test equipment types that are discussed have coaxial fittings to which the device to be tested must be connected. However, many DUTs do not have coaxial input and output connectors. In order to make measurements on devices without coaxial connectors, the device has to be mounted in a test fixture with transitions between the device connections and coaxial connectors that can connect to the test equipment.

With this arrangement the test equipment will measure the device plus the test fixture. The measurements must then be corrected to give the characteristics of the device alone. The four methods of achieving this are discussed in this chapter.

1.18 PART III: MEASUREMENT OF INDIVIDUAL RF COMPONENTS

Part III describes RF measurement of individual RF devices. Chapter 15 shows a generic RF communication system block diagram. Chapters 16–24 describe the individual RF devices that make up the block diagram, and the measurements made on them, in the following order:

Chapter	RF Device
16	Signal control components
17	Phase locked oscillators (PLOs)
18	Upconverters
19	Power amplifiers
20	Antennas
21	RF receiver requirements
22	Filters
23	LNAs
24	Mixers

The measurement of noise figure and intermodulation products, which are common to most of the receiver components, are described in Chapters 25 and 26.

Overall receiver performance is calculated from the measurements of the individual RF parts in Chapter 27. RF integrated circuits (RFICs) and systems on a chip (SOC), in which several RF parts are fabricated on a single RF chip, are described in Chapter 28.

1.19 SUMMARY OF CHAPTER 15: RF COMMUNICATIONS SYSTEM BLOCK DIAGRAM

Figure 1.14 is a block diagram of an RF communication system. The block diagram is generic. It applies to any type of wireless RF communications system: cellular phone, wireless LAN, satellite communications system, and even a deep space probe. Any RF communications system must contain all of the devices shown. Of course, the performance requirements of each device vary from system to system.

PLO: generates the RF carrier at the correct frequency

Modulator: varies the frequency, amplitude, or phase of an intermediate frequency (IF) carrier to put information onto it

Upconverter: shifts the modulated IF signal to RF

Power amplifier: increases the power level of the modulated RF carrier

TX antenna: transmits the RF carrier in the direction of the receiver

RX antenna: collects the transmitted RF signal at the receiver

RF filter: allows only a specified range of RF frequencies to pass, and blocks all other frequencies

LNA: amplifies the weak received RF carrier

Mixer and IF amplifier: shifts the RF carrier to a lower frequency below the RF band, and amplifies it to a level where it can be demodulated

Demodulator: removes the information from the low frequency carrier

1.20 SUMMARY OF CHAPTER 16: SIGNAL CONTROL COMPONENTS

RF signal control components vary the frequency, power, and other characteristics of the RF signal. Because many of these control components use semiconductor devices for their operation, these devices will be discussed. Then, PIN diode attenuators will be explained.

1.21 SUMMARY OF CHAPTER 17: PLOs

The function of the PLO in a wireless communication system is to generate the RF signal that will carry the digital information, in the form of modulation of

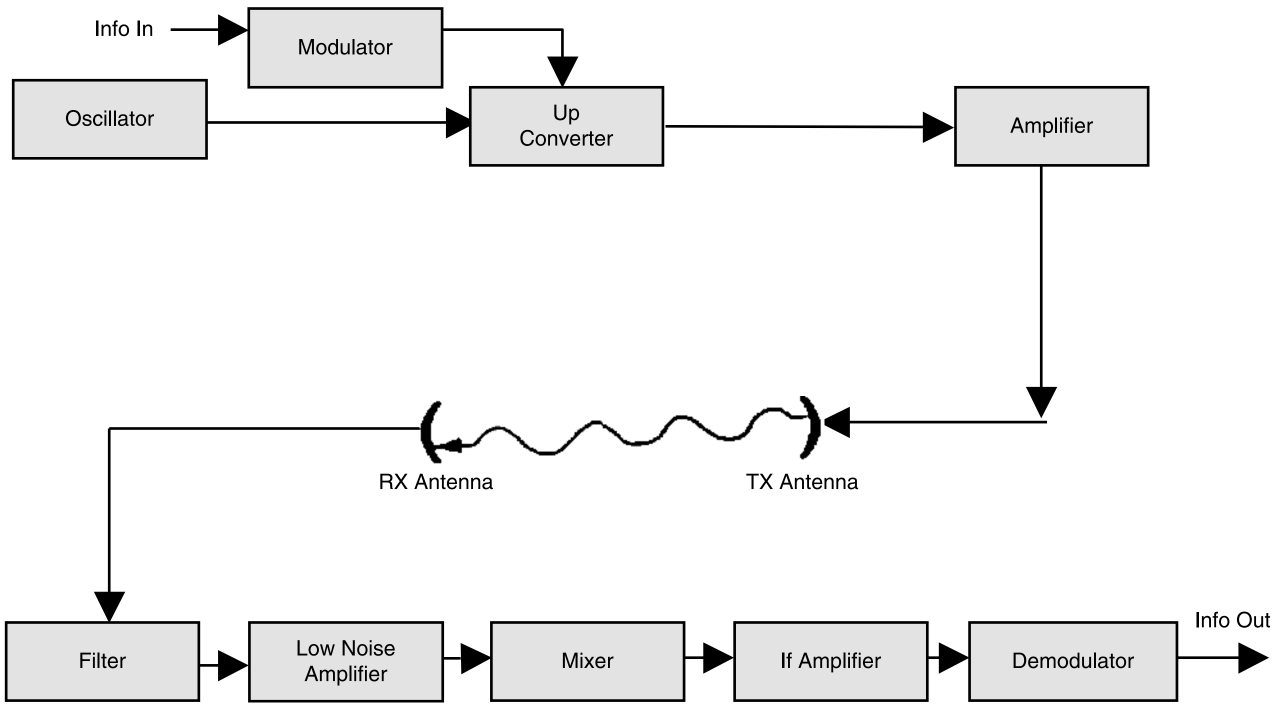


Figure 1.14 RF communication system block diagram.

amplitude, frequency, or phase, wirelessly from the transmitter location to the receiver location.

The most important characteristics of a PLO are its RF frequency stability, its capability of being rapidly tuned from one RF frequency to another, and phase noise.

The frequency stability requirements are 10^{-6} or better, which would be a stability of 1 kHz for a 1 GHz RF signal.

At frequencies below the RF band, the transmitter can be stabilized by using a quartz crystal as its resonant circuit. Unfortunately, quartz crystals do not have resonant frequencies in the RF band. Therefore, the RF PLO must divide its frequency to a value below RF, where its divided down frequency can be compared to the reference frequency of a quartz crystal.

Figure 1.15 shows a block diagram of an RF PLO. The PLO consists of two parts: a voltage controlled oscillator (VCO), shown in the shaded box, and a phased locked loop (PLL). The characteristics of the PLO that need to be measured are its frequency, output power, tuning sensitivity, and phase noise.

1.22 SUMMARY OF CHAPTER 18: UPCONVERTERS

Chapter 18 describes upconverters. The complicated modulations that are used in cellular phones and wireless data transmission systems are difficult to generate at RF frequencies. Thus, in most RF communication systems, the modulated signals are generated at low frequency with digital processing chips that do not work at RF and then upshifted to the desired RF frequency in an upconverter.

Figure 1.16 shows a block diagram of an upconverter. A stable frequency below the RF range, for example, 100 MHz, is generated with a simple quartz crystal oscillator. Digital information is then modulated onto this low frequency carrier in a digital IC. An RF PLO, such as that discussed in Chapter 17, is then used to generate an RF signal at 900 MHz, which is 100 MHz below the desired transmitted frequency. The modulated low frequency signal and the RF signal are then added together to form a sum frequency of 1000 MHz that is now carrying the digitally modulated signal. The upconverter also produces a difference frequency at 800 MHz, and this must be removed by a bandpass filter.

The details of how the upconverters work and the design and measurement of the upconverter are discussed in Chapter 18.

1.23 SUMMARY OF CHAPTER 19: POWER AMPLIFIERS

As the RF signal exits the upconverter, it is at the correct RF frequency, which is controlled by the PLO, and it is carrying the digital information to be transmitted that was applied to the RF carrier by the upconverter. However, the RF power level is only a few milliwatts; and when it is attenuated by the 90 dB or more of path loss, it would be lost in the noise of the RF receiver. Therefore, before the

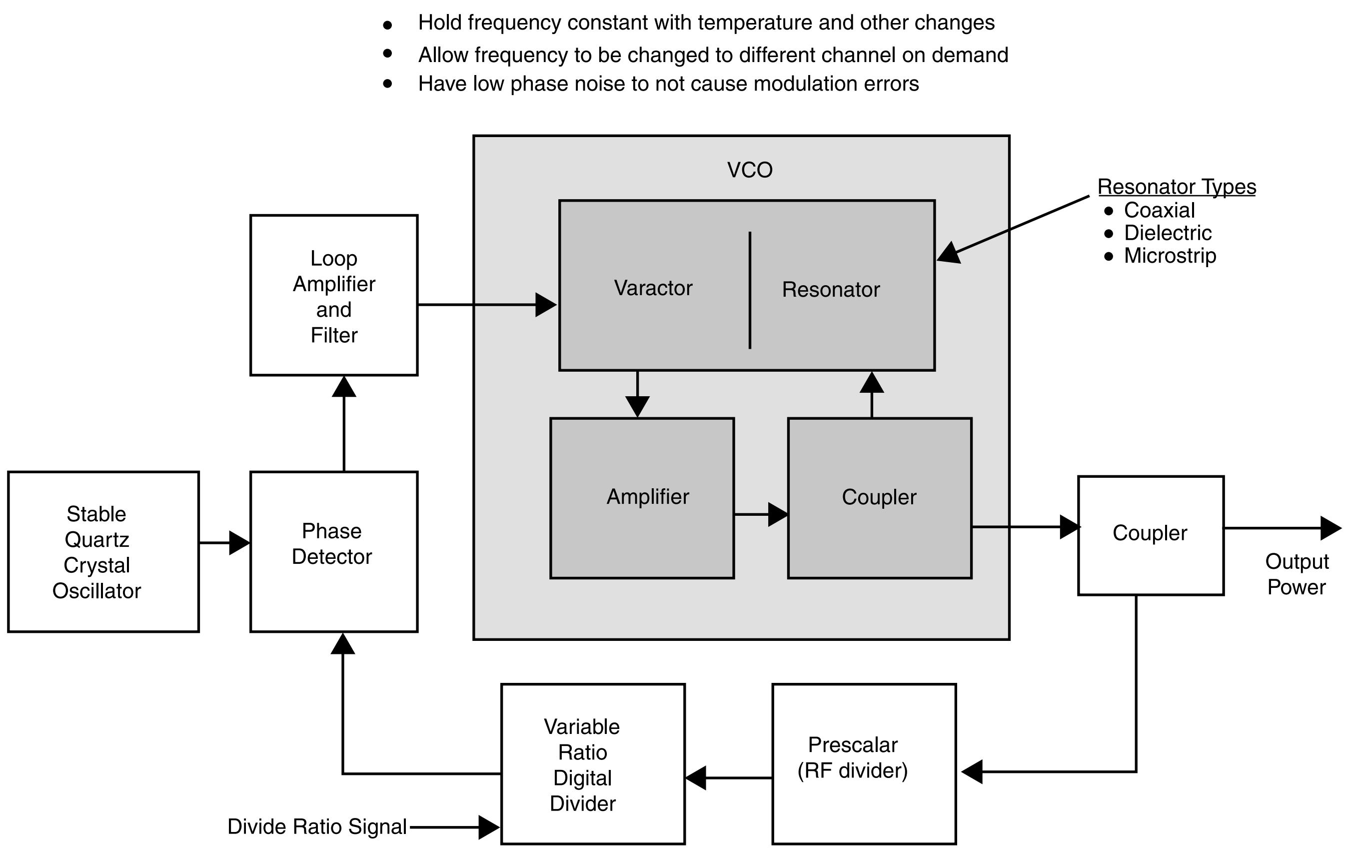


Figure 1.15 PLO.

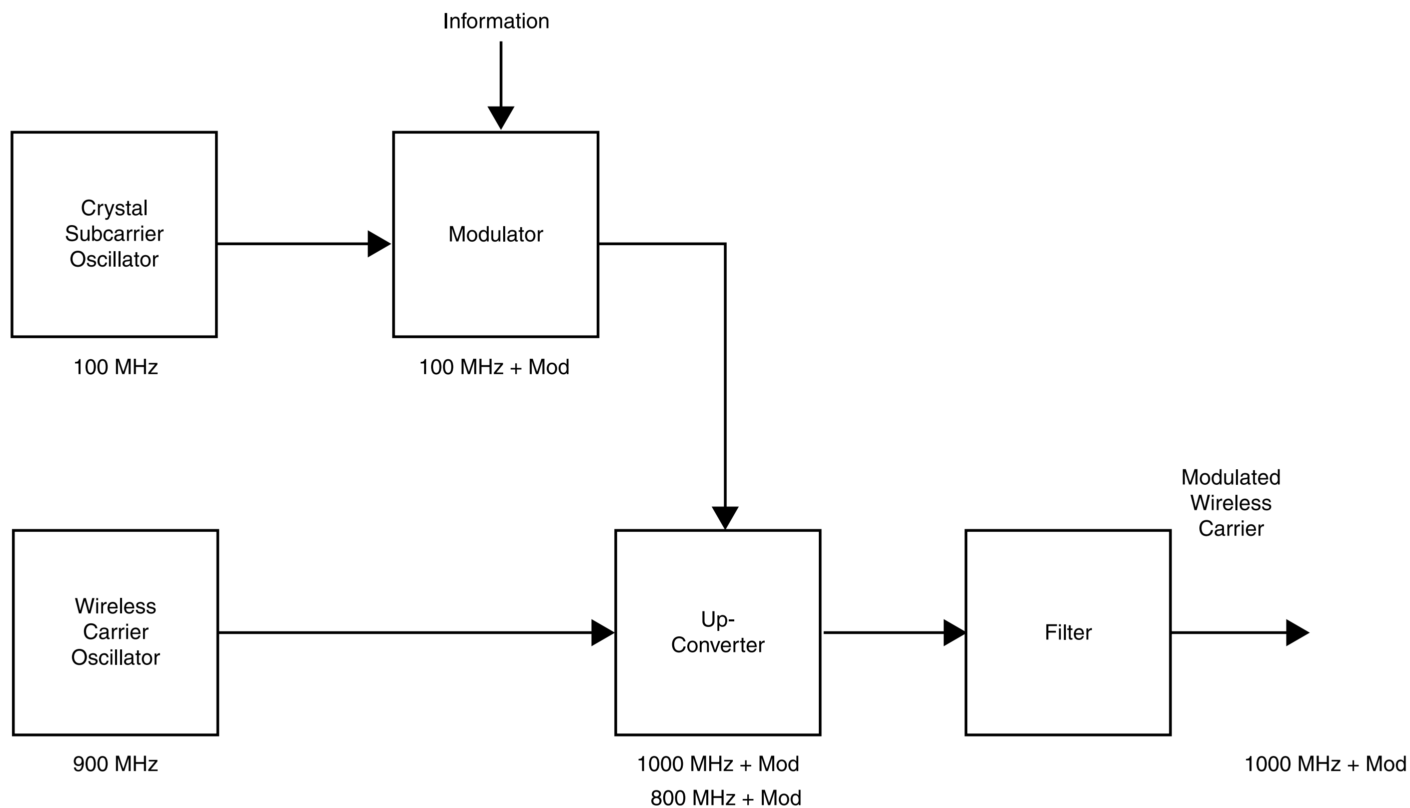


Figure 1.16 Modulator/upconverter.

modulated RF signal can be transmitted, it must be amplified in an RF power amplifier. The major performance requirements of the power amplifier are the following:

1. to amplify the RF power from the upconverter to 30–40 dBm,
2. to generate this power with high efficiency, and
3. to not distort the digital modulation during the amplifying process.

RF power amplifiers are either bipolar transistors or field effect transistors (FETs), but they are different from their low frequency counterparts because of "transit time" effects. Transit time effects occur because the electrons travel through the semiconductor material of the RF transistor at approximately 1/3000 of the velocity of light or 10^5 m/s. This is not a problem with low frequency transistors, but it is definitely a problem with RF transistors. To understand how critical the transit time effect is, realize that at 1 GHz, one RF cycle is 1 ns (10^{-9} s). In one cycle at 1 GHz, the electrons will travel 10^5 m/s $\times$ 10^{-9} s $=$ 100 microns (μm). For reasonable performance the electrons must move through the transistor in less than one-tenth of a cycle, which means the spacing between doping regions in the transistor must be less than 10 μm. At 10 GHz, the spacings must be less than 1 μm.

RF power amplifiers use two techniques to achieve the required transit times: reduced spacings between transistor elements and use of semiconductor materials like gallium arsenide (GaAs) and silicon germanium (SiGe), in which electrons move faster than they do in silicon.

Figure 1.17 shows a measurement of a typical RF power amplifier made with a VNA. For this measurement, the VNA is adjusted to measure and display gain and output power as a function of RF input power at a single frequency of 2.45 GHz. The VNA is calibrated with a power meter, so the output power measurement has only ±0.2 dBm uncertainty. The gain measurement is calibrated with the VNA standards, and so it has an uncertainty of only ±0.05 dB. The input power is swept over the power range from −7 to +13 dBm, so each horizontal scale division is 2 dBm. The left-hand graph shows the gain in decibels and the right-hand graph shows the output power in decibels relative to 1 mW. At the left-hand edge of each graph, the amplifier is operating in the linear range, where the RF output power is exactly proportional to the RF input power. At the right-hand edge of each graph, the amplifier is operating approximately at saturation. The markers on both graphs are set at the 1 dB compression point, where the gain has dropped from its linear value by 1 dB.

Figure 1.17 shows characteristics that are common to all RF amplifiers. Every RF amplifier has a nonlinear output power versus input power curve because the amplifier cannot generate more power that its battery supplies. Typical amplifier efficiency is about 50% at saturation, which is its maximum power output point. Most RF transistors draw the same power from their battery, regardless of whether they are operated at full power or at an input level that provides very little output power. At small output power levels, the RF output power is proportional to the RF input power. This is called the linear range. Operation near saturation causes distortion. Operation in the linear range causes low efficiency. The usual compromise is to use a 2× higher

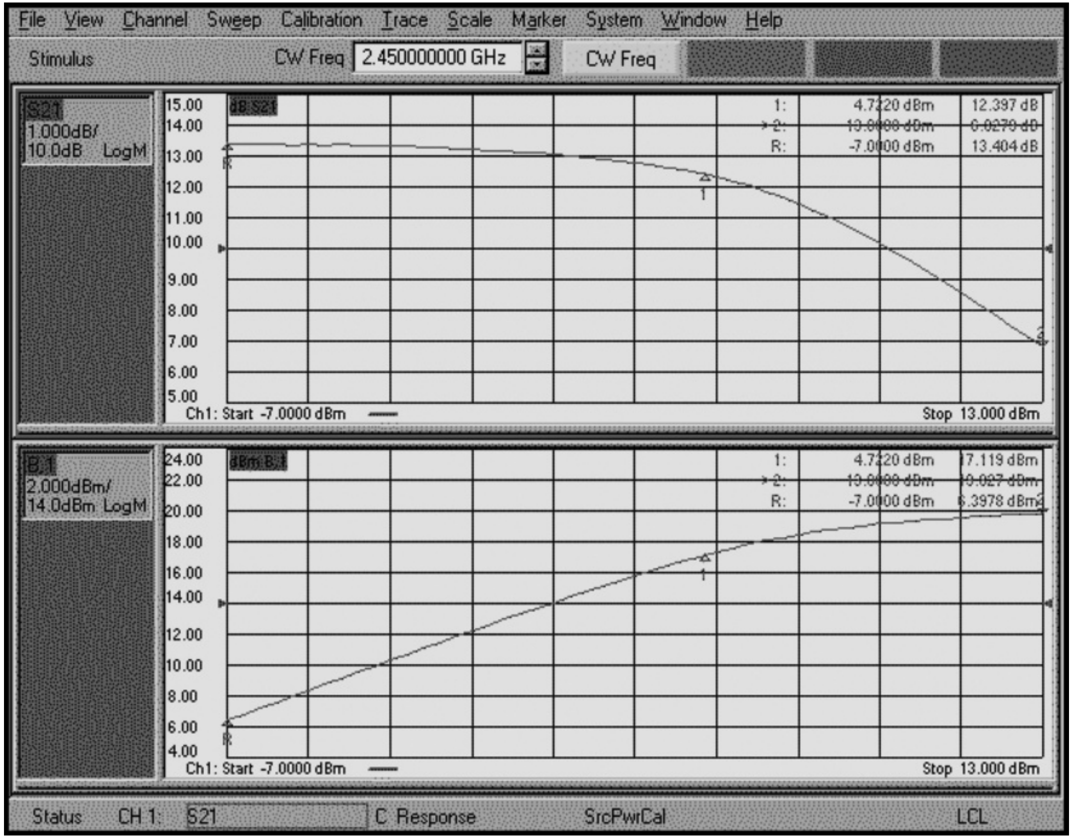


Figure 1.17 Power amplifier swept gain and output power.

power transistor at its 1 dB gain compression point (where the power has dropped by about half), where the distortions of the signal defined by spectral regrowth and modulation distortions are satisfactory.

1.24 SUMMARY OF CHAPTER 20: ANTENNAS

As Figure 1.14 demonstrates, an antenna must be used on both the transmitter and receiver end of any wireless system. These antennas may be the same or different on the two ends of the system, but in either case they serve different functions. The transmitter antenna launches the power in the direction of the receiver and concentrates it in this direction. The receiver antenna simply collects the power from the transmitter.

Specifications for the transmitter antenna are the following:

Gain
Beamwidth
Pattern
Polarization
Impedance match

Gain is a measure in dB of how well the antenna concentrates the power in the direction of the receiver, relative to an isotropic antenna. An isotropic antenna is defined as an idealized antenna that radiates power equally in all directions. Beamwidth is the angular width of the beam generated by the antenna. Gain and beamwidth are related. To achieve more gain, the width of the beam must be decreased.

The antenna pattern defines radiation in undesired directions that may jam other systems. Polarization defines the direction of the electric field of the radiation, whether directed vertically or horizontally to the Earth's surface. The impedance of free space, which is the ratio of the electric field to the magnetic field of the RF wave, is a physical constant equal to 377 Ω. Every antenna serves as an impedance transformer, transforming the impedance of the antenna at its RF connector to 50 or 75Ω.

The pattern, polarization, and impedance match are the same for the receiving antenna as for the transmitting antenna. However, for the receiving antenna the gain and beamwidth are replaced by the area of the antenna, which determines how much of the incident signal is received.

Figure 1.18 shows common RF antennas. The upper left drawing shows a half-wave dipole. This antenna is used on most mobile units, and it also serves as a building block for higher gain antennas. It consists of a feed line, shown as parallel wires, which are bent at right angles to the feed line in the antenna region. The total length of the antenna is 0.5 wavelength at the operating frequency. It has an almost isotropic pattern, except that it does not radiate along the antenna wires. Consequently, it

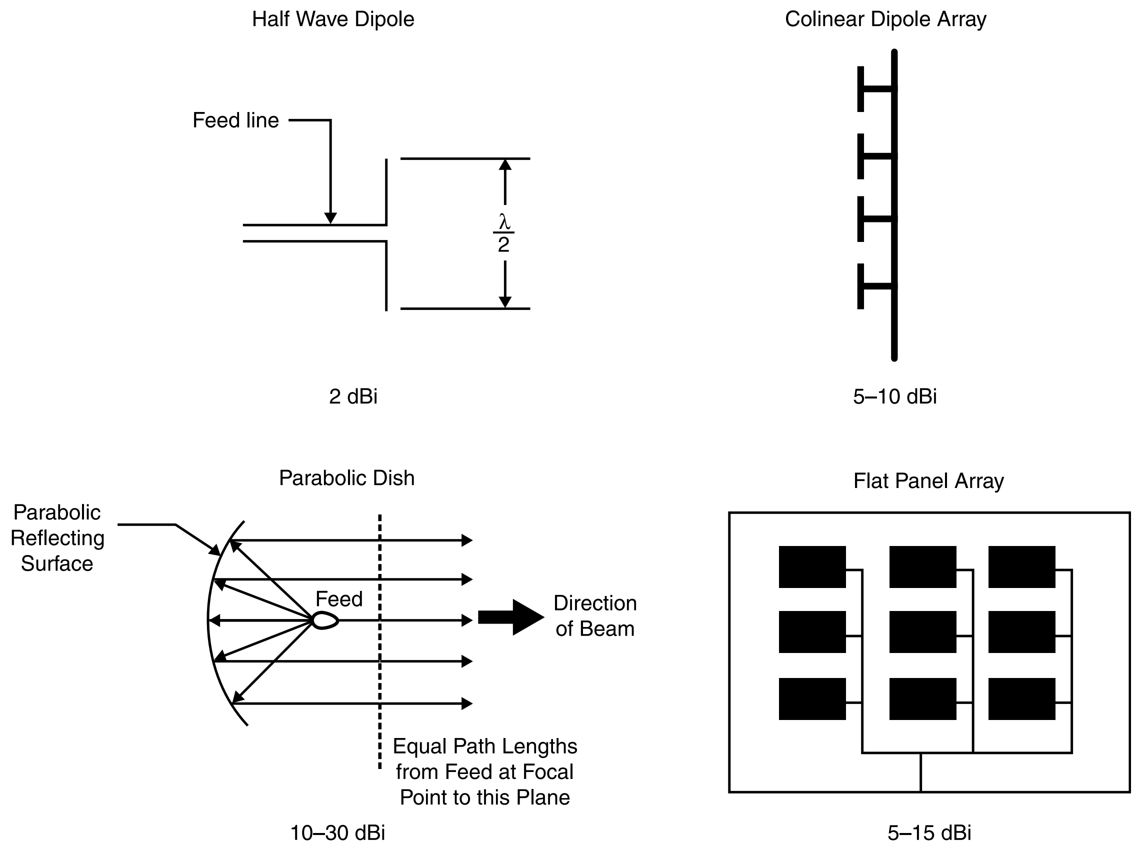


Figure 1.18 Types of antennas.

has a net gain in the direction at right angles to the antenna wires of 2.1 decibels isotropic (dBi). Its total length of 0.5 wavelength controls its impedance transformation from the 377 Ω value of free space to the value at its feed wires. If its length is 0.5 wavelength, the impedance is transformed to 62.5 Ω, which is easy to match to 50 Ω for RF applications or 75 Ω for television applications.

The half-wave dipole antenna also serves as a building block for higher gain antennas. The upper right drawing of Figure 1.18 shows a colinear dipole array, which is formed by several half-wave dipoles stacked vertically. The half-wave dipoles are 1 wavelength apart, so the signals radiating from all of them are in phase. This configuration is used for most base station antennas, although the details cannot be seen because the antenna is covered by a plastic tube to protect it from the environment. Stacking the antennas vertically reduces the radiation above the antenna and directly below the antenna where there are no users, and thus increases its gain into the cell site by the ratio of the number of antennas.

The lower left-hand drawing of Figure 1.18 shows a parabolic dish antenna. The parabolic dish is fed from the focal point of the parabolic reflecting surface. The parabolic shape has the characteristics that all rays from the feed point travel the same distance to a plane perpendicular to the axis of the dish, so that all of the reflections have the same phase, thus adding up in this direction. The gain of the parabolic antenna is approximately proportional to the square of its diameter in wavelengths. A 1 ft diameter parabolic dish has a gain of about 10 dB at 1 GHz, and it will have 100 times (20 dB) more gain at 10 GHz where the wavelength is one-tenth as great.

A simple rectangular patch that is about 0.5 wavelengths in length and that can be photoetched on a microstrip board has the same radiation characteristics as a half-wave dipole. This patch antenna, mounted on a high dielectric constant ceramic, provides a very small antenna that is popular with cellular phones and wireless data transmission mobile units. As the lower right-hand drawing of Figure 1.18 shows, multielement patch antennas, whose performance approaches that of the parabolic dish, can be fabricated for much less cost than the parabolic dish.

The properties of the antennas described earlier can be measured easily using a VNA, which can measure the input power to the antenna and the output power received from the antenna about 10 wavelengths away in the far field region and then calculate the gain. If the antenna is mounted on a rotating platform, its antenna pattern can be measured. The one requirement for all of these measurements is that they be made in an anechoic test room. Figure 1.19 shows such a room, which has absorbing material mounted on its walls, floors, and ceiling so that no reflected signal degrades the measurement results.

1.25 SUMMARY OF CHAPTER 21: RF RECEIVER REQUIREMENTS

The receiver in a wireless mobile unit must operate under a variety of conditions. When the mobile unit is at the edge of the coverage area, the receiver must have a low noise figure to receive the very low signal from the base station transmitter

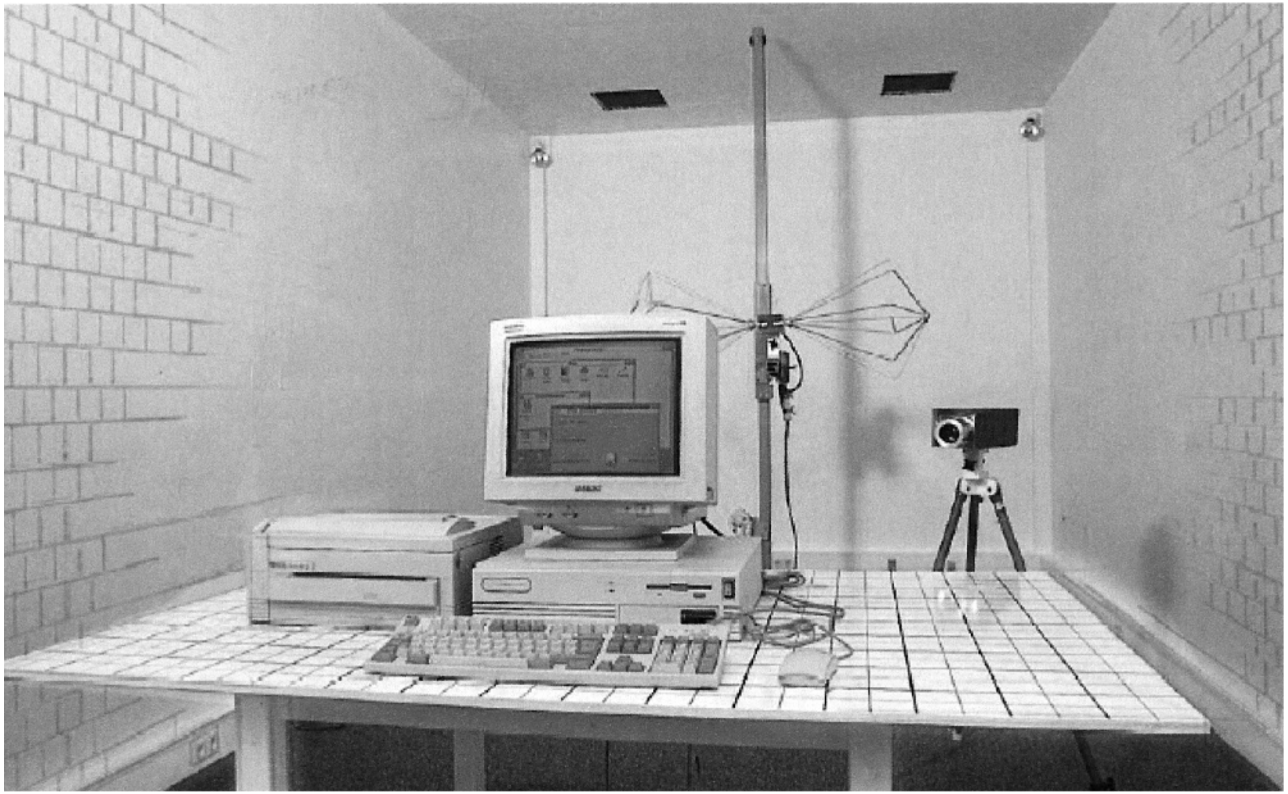


Figure 1.19 Antenna test setup in the anechoic chamber.

with a satisfactory S/N for achieving the required BER. When the mobile unit is close to the base station, the received signals intended for all the mobile units in the cell are very large, and two signals may mix in the mobile receiver to form a signal that jams the signal intended for the mobile. This jamming signal is called an "intermodulation product."

The received RF signal varies over a 90 dB dynamic range, depending on the transmitter–receiver separation and multipath fading. The receiver must provide adjustable gain, depending on the received signal level, to provide a constant output level of about 0 dBm for demodulation.

Every RF receiver is made up of four basic parts, whose performances are as follows:

1. RF filter: allows only a specified range of RF frequencies to pass and blocks all other frequencies
2. LNA: amplifies the weak received RF carrier
3. Mixer: shifts the RF frequency to a lower frequency where it can be more easily amplified and filtered
4. IF amplifier: amplifies the IF frequency to a power level where it can be demodulated

All components contribute to the gain or loss of the RF signal as it passes through the receiver. The filter and the RF amplifier contribute to the noise figure of the receiver. The LNA and the mixer contribute to the intermodulation products.

1.26 SUMMARY OF CHAPTER 22: RF FILTERS

Filters are used for different reasons in RF communications systems:

1. System filter: in the RF receiver to block out the signals from other systems
2. Upconverter filter: in the RF transmitter to remove the unwanted sideband of the upconverter
3. Harmonic filter: in the RF transmitter to reduce the harmonic content of the transmitting signal
4. Image noise filter: in the RF receiver to filter image noise generated by the receiver mixing process
5. User channel filter: just before the IF amplifier, to select individual user's signal

The characteristics of all filters include the following:

Passband frequency

Filter attenuation outside the passband

Attenuation in the passband

Attenuation in the skirt, which is the frequency range between full blocking and full passing of the signal

Figure 1.20 shows the attenuation versus frequency characteristic of the system filter in the RF receiver, which is used to block the RF signals from other systems. These measurements were made with the VNA shown in Figure 1.9. The filter was designed to pass signals in the 2.40–2.48 GHz frequency band used for wireless LANs. Within this range, the insertion loss, as shown by the markers, is less than 1.25 dB. Outside this band at ± 280 MHz, the attenuation is greater than 20 dB.

Other characteristics that need to be measured on filters are the mismatches measured at both the input and the output of the filter, and the phase shift through the filter.

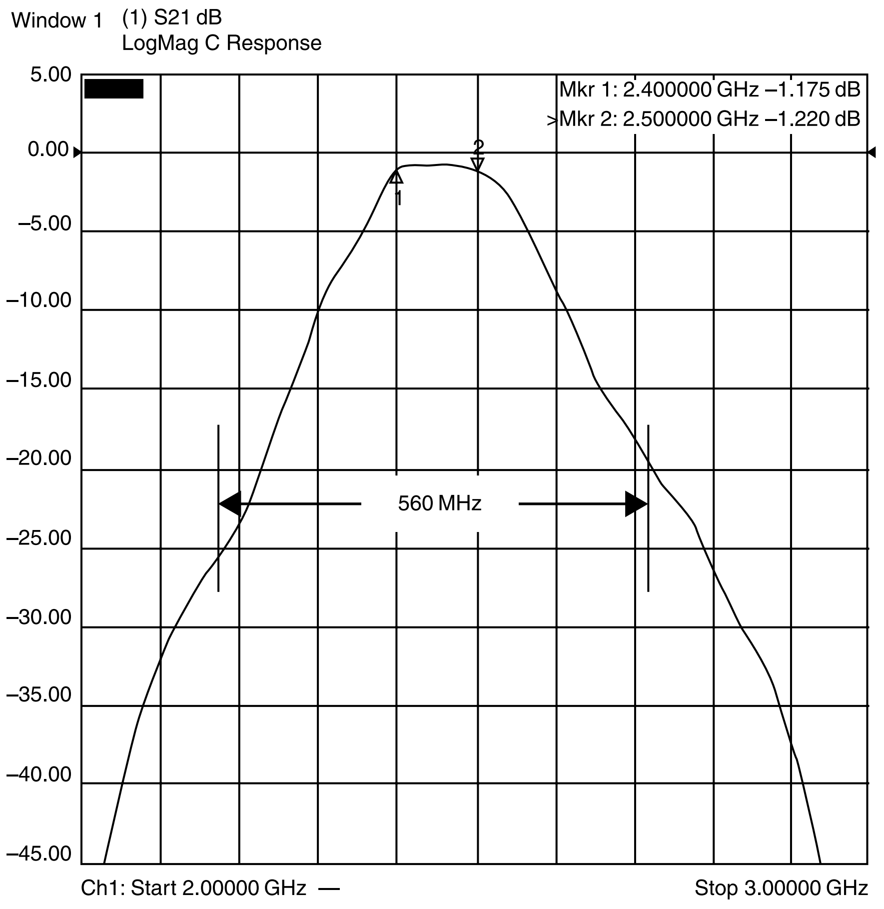


Figure 1.20 Insertion loss of the RF filter versus frequency.

1.27 SUMMARY OF CHAPTER 23: LNAs

The function of the LNA is to boost the RF power level of the incoming RF signal without adding additional noise to it. Figure 1.21 shows a block diagram of an LNA. The use of representative power levels will help explain the characteristics of the LNA. The input signal, which is received from the antenna and passed through the RF system filter, is −110 dBm, which is typical of the received cell phone signal when the cell phone is located at the edge of the cell during a multipath fade. The LNA has a gain of 30 dB, so the output power of the LNA is −80 dBm, as shown.

Noise from the environment also enters the LNA through the antenna. The received noise is −114 dBm/1 MHz of channel bandwidth if the antenna is pointed along the earth, as is the case with most cell phones and wireless data transmission systems. If the bandwidth of a single user channel is 100 kHz (0.1 MHz), the received noise is −124 dBm, so the S/N at the input to the LNA is 14 dB, as shown. The output noise would be expected to be −124 dBm + 30 dB = −94 dBm. Actually, the output noise is −90 dBm, which is 4 dB higher. This is because the LNA not only amplifies the noise at its input but also adds additional noise of its own. The difference between the S/N going into the LNA and the S/N coming out is called the "noise figure" of the LNA.

The noise figure of a passive device, like a filter or a length of transmission line, is equal to its attenuation. A significant part of the overall system noise figure is caused by the system filter that precedes the LNA.

To measure the noise figure of the LNA, a noise source is used. This noise source can be seen as part of the noise figure measurement setup shown in Figure 1.13. The noise source contains a special PN diode. When no voltage is applied to the diode, room temperature noise of −114 dBm/1 MHz is generated. When 28 V is applied to the noise diode, the noise output increases by about 14 dB to −100 dBm/1 MHz. The exact value of the noise when the diode is turned on, above the thermal noise value when the diode is turned off, is called the excess noise ratio (ENR).

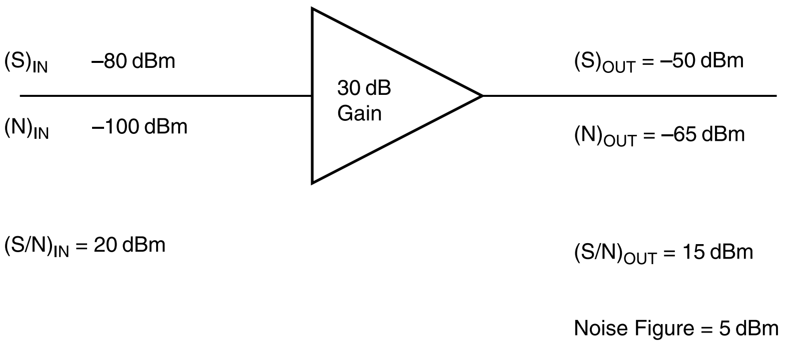


Figure 1.21 Low noise amplifiers. "Noise figure" is the ratio of the S/N going into a device compared to the S/N coming out.

A sensitive spectrum analyzer can measure the output of the LNA with the noise diode on or off and determine the output S/N. It can calculate the noise figure with its internal software.

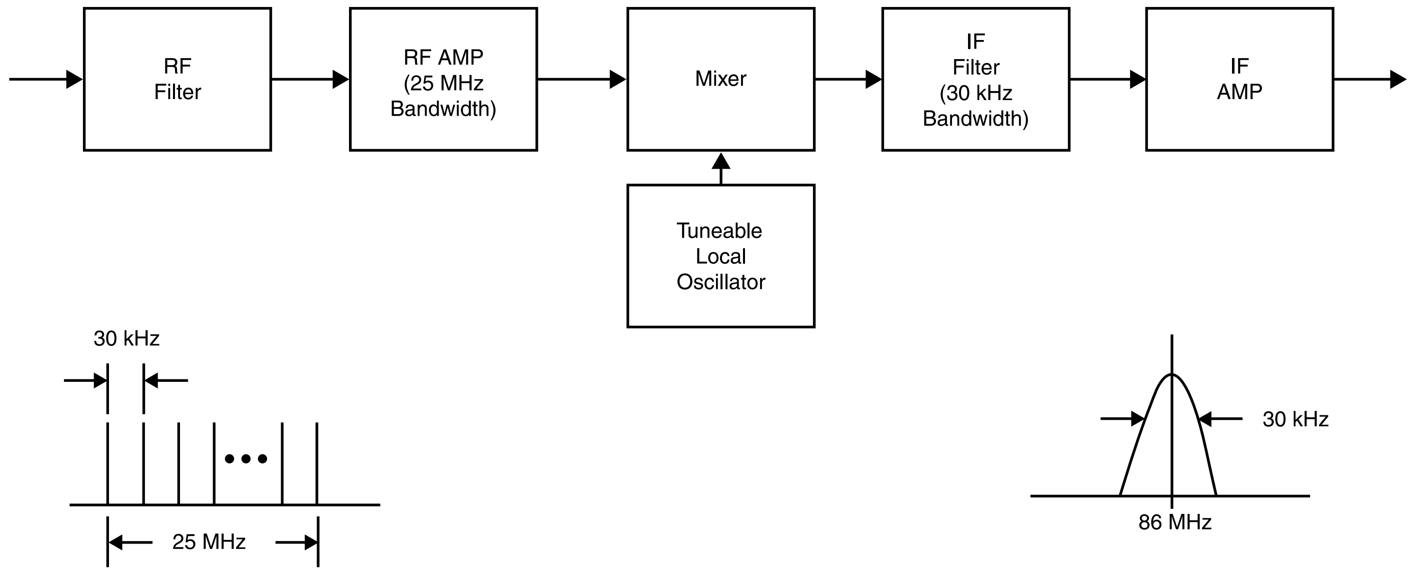
In a typical wireless communications system, the mobile unit is continually moving relative to the base station. The base station is sending out a constant RF power, so that the received signal at the mobile unit is continually changing over a 90 dB range as the mobile moves. The noise figure of the LNA is the critical factor controlling system performance when the mobile unit is at the edge of the coverage cell. However, as the mobile unit moves closer to the base station, the received signal is well above the noise level. When the mobile unit is midway between the edge of the cell and the base station, the S/N is 60 dB. However, as the mobile unit moves closer to the base station, the LNA faces another problem: intermodulation products. Intermodulation products and their measurement are discussed in detail in Chapter 26.

1.28 SUMMARY OF CHAPTER 24: MIXERS

The purpose of the mixer is to convert the modulated RF signal that is carrying information to a lower frequency where it can be more easily amplified up to a level of about 0 dBm, where the individual voice and/or data channels can be separated. All RF communications systems are licensed to use 25 MHz or more of the RF spectrum to serve hundreds of users. All of the users' signals in the system come through the RF filter and through the LNA. There is no practical way to filter an individual voice or data signal at RF frequencies. The selection of the individual user channels is accomplished in the mixer. Figure 1.22 shows how a mixer does this.

The numerical values shown are similar to those of an IS-136 cellular phone operating in the band from 869 to 894 MHz in North America. IS-136 is a TDMA system, where three voice channels use a frequency channel in different time slots. The channel frequency width is 30 kHz, so 832 TDMA channels can be fitted into the 25 MHz RF bandwidth, as shown in the lower left-hand sketch of Figure 1.22. All of these 832 channels pass through the RF filter and the LNA. The desired 30 kHz wide channel is selected by the mixer.

Assume initially that the lowest channel at 869 MHz is to be selected. The local oscillator is set to 783 MHz by the system, via proper setting of the digital divider in a PLO, which serves as the mixer local oscillator (LO) in the receiver. The desired 30 kHz wide TDMA channel is shifted to the difference frequency of 86 MHz (right-hand sketch, Fig. 1.22), and it passes through the IF filter which has a bandwidth of 30 kHz centered at 86 MHz. All of the other 831 IF TDMA channels are shifted down to the lower frequency range, but they cannot pass through the 30 kHz filter to the IF amplifier. Assume that the next call is assigned the highest frequency in the RF bandwidth at 894 MHz. The local oscillator is set at 808 MHz and shifts the 894 MHz RF signal down to 86 MHz, so it can pass through the IF filter.



RF	LO
869	783
881	795
894	808

Figure 1.22 Selection of individual voice channels.

For many years, the RF signal has been shifted down to the IF frequency range in the mixer, as shown in the example above. Many systems still use this design. However, most RF communications systems now use a “zero IF” (ZIF) mixer design, where the local oscillator is set to nearly the same frequency as the RF frequency, so that the IF frequency coming out of the mixer is nearly 0. The filtering and amplification of the desired channel are done by digital processing. This ZIF design significantly reduces the cost of the receiver.

1.29 SUMMARY OF CHAPTER 25: NOISE FIGURE MEASUREMENT

A typical noise figure test setup was shown in Figure 1.13. The measured noise figure of the LNA whose gain and S-parameters are discussed in Chapter 23 is provided in Figure 1.23.

The measured noise figure of the other components in the overall receiver are as follows:

Noise Figure and Gain of Individual Components and Complete Receiver at 2.45 GHz

Component	Noise Figure (dB)	Gain (dB)
RF filter	0.7	−0.7
LNA	4.4	20.5
RF filter + LNA	5.4	19.5
Mixer	8.9	0.5
Complete receiver	6.5	16.9

1.30 SUMMARY OF CHAPTER 26: INTERMODULATION PRODUCT MEASUREMENT

The receiver in a wireless mobile unit must operate under a variety of conditions. When the mobile unit is at the edge of the coverage area, the receiver must have a low noise figure to receive the very low signal from the base station transmitter with a satisfactory S/N for achieving the required BER. When the mobile unit is close to the base station, the received signals intended for all the mobile units in the cell are very large, and two signals may mix in a mobile receiver to form a signal that jams the signal intended for the mobile. This jamming signal is called an intermodulation product. Figure 1.24 shows three measured spectra of the output of an LNA, each at different input power levels, and shows the development of the intermodulation products. Figure 1.25 shows a graph of the fundamental and third-order intermodulation products as a function of the input fundamental signals and illustrates how the output IP3 (OIP3) value is defined.

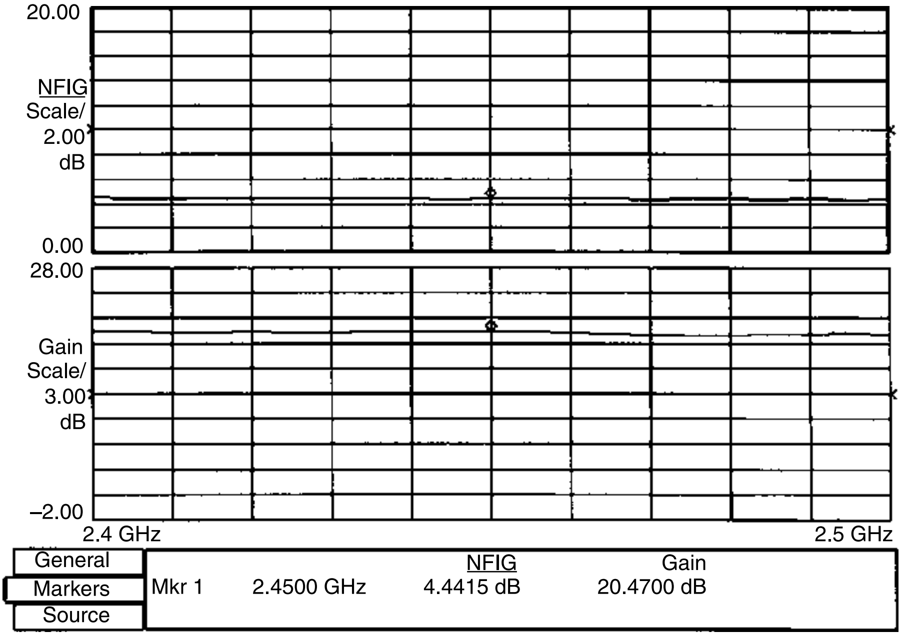


Figure 1.23 Measured noise figure and gain of a low noise amplifier.

1.31 SUMMARY OF CHAPTER 27: OVERALL RECEIVER

All of the individual receiver components (RF filter, LNA, and mixer) contribute to the overall gain, noise figure, and IP3 of the receiver in a complicated way, which are demonstrated by the following example:

Device	RF Filter	LNA	Mixer	Total
Noise figure (dB)	1.00	4.50	8.50	5.62
Gain (dB)	−1.00	19.00	2.00	20.00
IP3 (dB)	—	13.00	10.00	8.81

An available design program is described that allows the measured values of noise figure, gain, and intermodulation products to be combined to yield the overall system performance.

1.32 SUMMARY OF CHAPTER 28: RFICs and SOC

Many of the individual devices in an RF communications system are combined into RFIC chips. Figure 1.26 displays a photograph of the complete RF communications system shown in Figure 1.14 but integrated into two RFICs and two RF filters. The

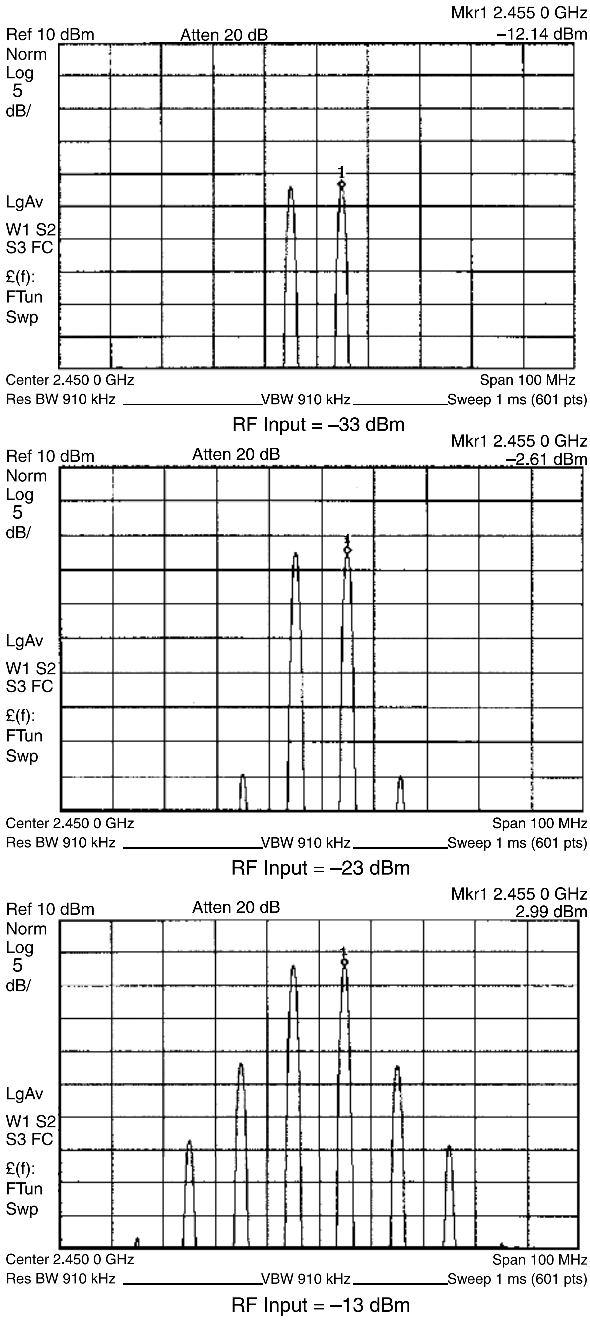


Figure 1.24 Two tone intermodulation products from a low noise amplifier.

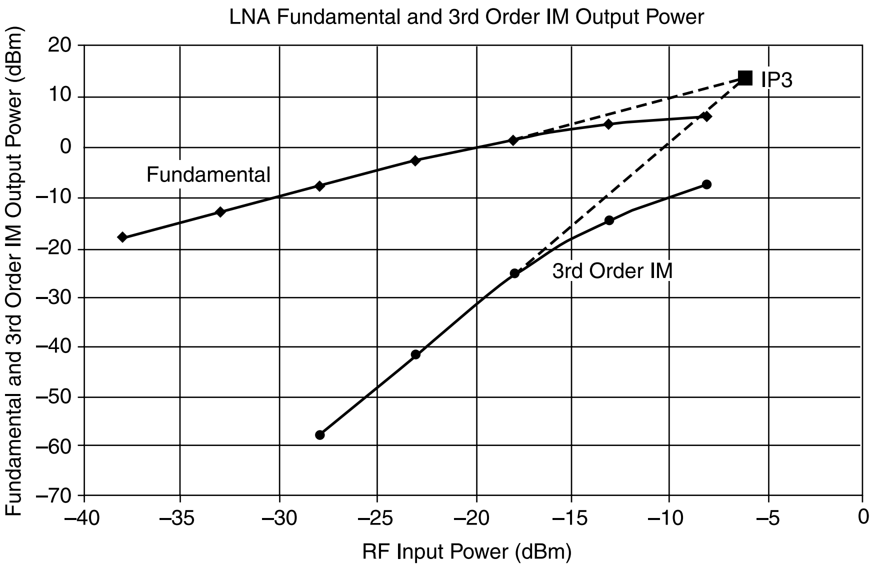


Figure 1.25 Calculation of IP3 for a low noise amplifier.

block diagram of this particular RFIC chip is also shown. In such cases, the RF measurements must be done on the complete RFIC.

1.33 PART IV: TESTING OF DEVICES AND SYSTEMS WITH DIGITALLY MODULATED RF SIGNALS

Part IV describes testing of RF devices with RF signals that are carrying digital modulation. RF devices may distort the digital signal. A particular RF device can distort different signals in different ways.

Chapter	Topic
29	Digital communications signals
30	Multiple access techniques—FDMA, TDMA, CDMA
31	Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA)
32	Adjacent channel power (ACP)
33	Constellation, vector, eye diagrams, and EVM
34	Complementary cumulative distribution function (CCDF)
35	BER
36	Measurement of GSM evolution signals

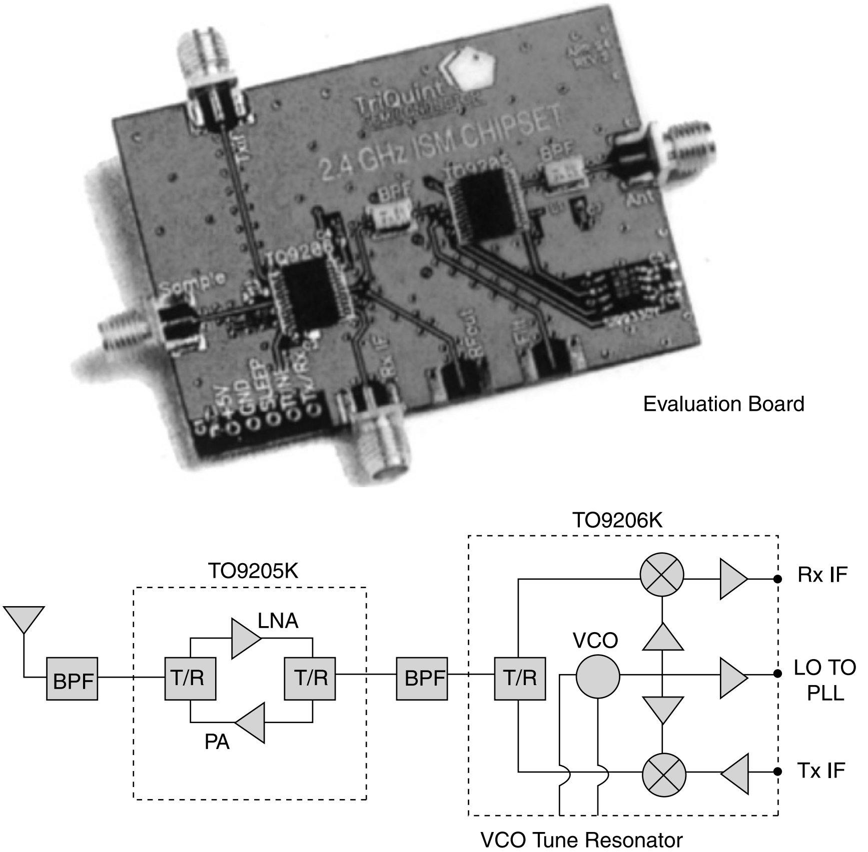


Figure 1.26 RFICs.

1.34 SUMMARY OF CHAPTER 29: DIGITAL COMMUNICATIONS SIGNALS

Digital communications systems carry voice, video, and digital data. At the beginning of 2006 about 90% of all cellular phone capacity was used for voice signals, but data transmission usage is growing rapidly. This chapter explains what the digital data rates are for voice, video, and data carrying signals.

The frequency and data rates for voice signals are as follows:

Analog sound waves from a human speaker: 30 Hz to 6 kHz (note 1)
Telephone signal: 0 Hz to 4 kHz (note 2)
Pulse code modulation (PCM) digitized telephone signal: 64 kbps (note 3)
Adaptive differential PCM (ADPCM) digitized telephone signal: 16 kbps (note 4)
Synthesized telephone signal: 2 kbps (note 5)

Cell phone compressed speech (note 6)
GSM: 13 kbps; CDMA: 9–13 kbps

Note 1: The frequency of the analog sound waves from a human speaker are determined by their vocal cords, diaphragm, tongue, and lips.

Note 2: The analog telephone voice signal is deliberately filtered, so that more voice channels can be transmitted over a given bandwidth.

Note 3: The PCM digitized telephone signal using 64 kbps sounds exactly like human voice on a telephone circuit.

Note 4: The ADPCM sends only the change in the signal from one sample to the next, but it requires a microprocessor on each end of the transmission channel.

Note 5: Synthesized speech is perfectly understandable but sounds like a machine.

Note 6: Compressed telephone speech using 13 kbps accurately reproduces accents of all world languages.

Forward error correction (FEC) bits are added to the digital speech signal to allow transmission errors to be corrected at the receiving end, increasing the bit rate by about 1.8 times. Additional signal control bits, which allow continuous signaling between the transmitter and the receiver, are also added, so that the total data transmission rate for telephone speech is about 2 times the digitized voice rate.

The frequencies and data rates for video signals are as follows:

Analog broadcast quality TV: 0–4 MHz
PCM digitized broadcast quality TV: 56 Mbps
MPEG-2 compressed video: 1.5–7 Mbps
MPEG-4 compressed video: 64 kbp for low definition cell phones
High-definition, digital broadcast TV: 18 Mbps

Live telephone calls and real-time TV signals must be transmitted as the signals are generated. These signals use "circuit switched" connections. Two-way telephone calls have a time delay of several seconds as the connection path is set up between the sender and the receiver. Two separate circuits are dedicated to the call, one in each direction of transmission, and each circuit is used an average of only 40% of the time.

When recorded voice, video, or data is being transmitted, it does not have to be received in real time, so packet switching is used. The digital transmission is broken up into groups of bits, called packets, each with a group of header bits specifying the receiving location and the serial number of the particular packet. All transmitting and receiving points are permanently connected to the network, so the connection delay time is eliminated and there is no idle time in the channels. Familiar wired examples of this type of data transmission are Ethernet and TCP/IP (an Internet protocol). With packet switching, error correction bits can be reduced to simple parity, which indicates that a group of bits has an error, but not which bit is incorrect, so the group of bits must be retransmitted. This correction technique is called automatic repeat request (ARQ).

Chapter 29 describes the details of all digital signals for cell phones and wireless LANs. These various signal protocols can be applied to the transmitted RF signal from the RF signal generator that is displayed in Figure 1.6.

1.35 SUMMARY OF CHAPTER 30: FDMA, TDMA, AND CDMA MULTIPLE ACCESS TECHNIQUES

This chapter describes multiple access techniques, which control how many users can use a licensed RF frequency band at the same time. The individual user channel bandwidth is much smaller than the total licensed RF bandwidth.

One basic multiple access technique is FDMA. It is used by all systems either as the only multiple access technique or in combination with other multiple access techniques. With FDMA, the total RF bandwidth is divided into smaller bands, each of which uses only the bandwidth required for a single user. A simple example is the original analog cell phone used in North America. The licensed bandwidth, divided between two competing service providers, was 25 MHz for each direction of transmission. Each user required 30 kHz for transmission in each direction, so the available number of user channels was $25\ \text{MHz}/30\ \text{kHz} = 832$ channels.

The RF electronics of the base station can be significantly simplified (and therefore reduced in cost) by dividing the transmission into time slots within a wider FDMA channel. This multiple access technique is called TDMA.

The multiple access technique providing the greatest user capacity in a cell phone environment for a given RF bandwidth is CDMA. With this multiple access technique, all users use the same RF frequency at the same time. However, each user is assigned a unique 128 bit code by the base station. Each user multiplies each bit of his digitized voice signal by his unique assigned code. The bandwidth of the transmission is spread in frequency by the voice data rate of 16 kbps $\times$ 128 bits, which is equal to approximately 2.5 Mbps. At the receiving end the signal is decoded to recover the original voice transmission. Every other user's coded RF signal is also received, but it is not decoded correctly and looks like noise that is $1/128 = 21$ dB below the correctly coded signal.

Figure 1.27 illustrates this coding and decoding process. The upper three signals are at the transmitter site. The top signal shows 2 bits of the information data stream. The middle signal shows the unique PN code assigned to the user. (Only 16 coding bits are shown in the drawing, instead of 128, to simplify the drawing.) The data signal is coded by an exclusive NOR process, which generates a digital 1 if the data bit and coding bit are the same and a digital 0 if they are different. This coded signal is shown on the third line. This bitstream is then modulated onto the RF carrier and transmitted.

The lower three lines in Figure 1.27 show the conditions at the receiver. The top line shows the demodulated coded bitstream, removed from the RF carrier. The middle line are PN coding bits, and they are the same as the coding bits used at the transmitter. The

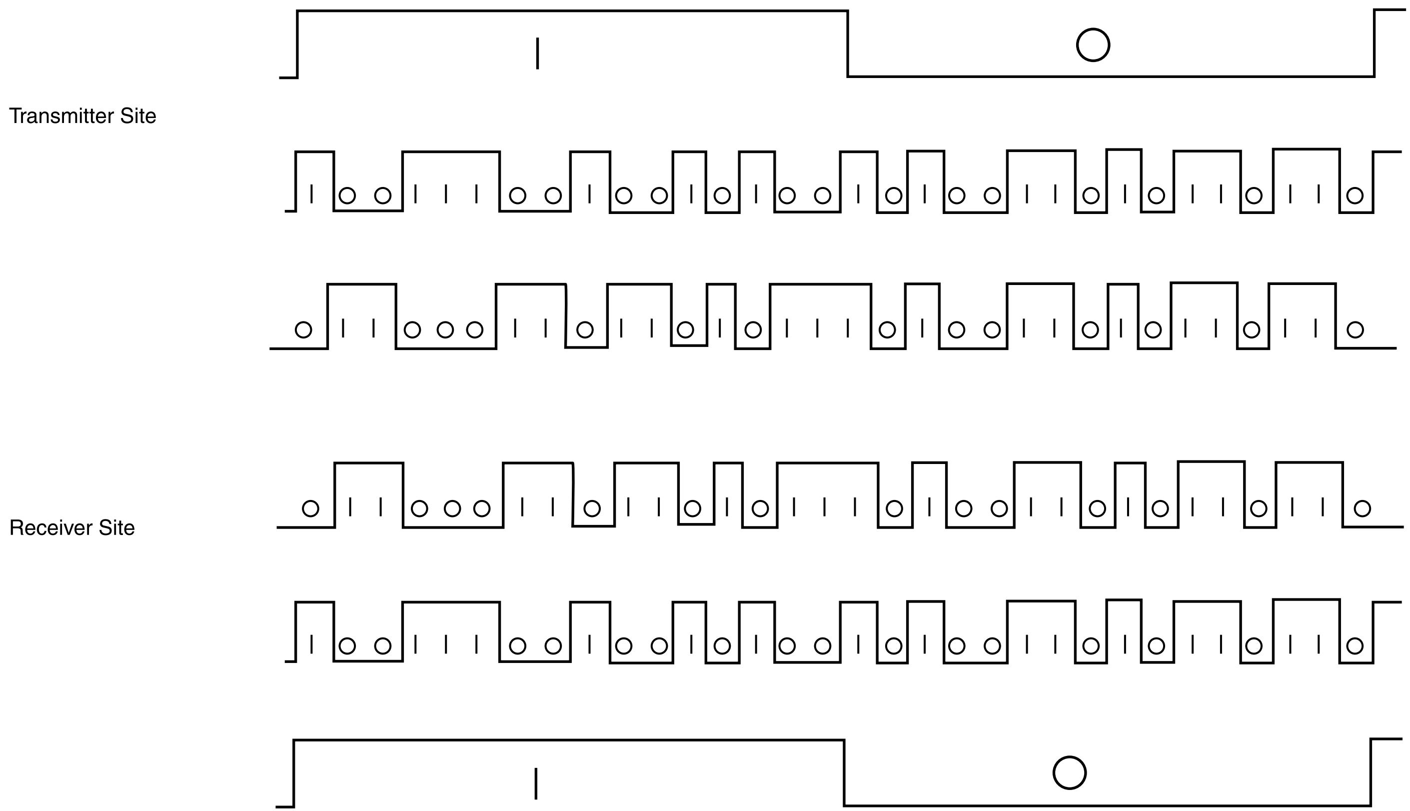


Figure 1.27 CDMA.

bottom line contains the decoded bits, which are the same as the original data bits at the transmitter. Other signals with different codes are not despread. Each of the other signals produces an interference of $1/128$ with the 128 chip spreading.

The above description of the CDMA process was for digitized voice signals. For data transmission the CDMA system uses only a short PN code of about 16 chips, and uses packet data techniques to accommodate multiple users.

A complete description of these multiple access techniques is given a Chapter 30, and the necessary measurements that must be made for TDMA and CDMA systems are explained.

1.36 SUMMARY OF CHAPTER 31: OFDM AND OFDMA

OFDM is a multiple access technique that provides greater data rates in a given RF frequency band than TDMA or CDMA. Features of OFDM include the following:

- There are multiple subcarriers to carry the digital bitstream.
- Four pilot tones at different frequencies across the bandwidth continuously monitor transmission quality.
- Modulation can be adjusted between BPSK, QPSK, 16QAM, and 64QAM.
- Various levels of FEC can be used, depending on signal transmission quality.
- The modulation type and FEC can be changed every 4 ms, based on transmission quality.
- OFDM has less spreading of power into adjacent channels than CDMA.

Figure 1.28 shows the spectrum of an OFDM signal carrying a single set of data. The available bandwidth is filled with a set of subcarriers. Fifty-two subcarriers are commonly used, spaced 312.5 kHz apart. Four of the subcarriers are pilot carriers, which give channel condition information and serve as a phase reference for the modulation. The data, with error correction and control bits added, is divided into sets and each set is modulated onto 1 of the 48 data channels. These 48 channels are modulated with BPSK, QPSK, 16QAM, or 64QAM, depending on the S/N of the system. The noise in the channels is determined by the number of other users on the system. The type of modulation is the same for all 48 channels, and it is changed with each 4 ms transmission. OFDM is currently used for short-range high-speed wireless LANs.

OFDM allows only one user on the channel at any given time. Multiple users are accommodated by using packet switching techniques. To accommodate multiple users more efficiently, OFDMA is used. OFDMA is a technique that allows multiple access on the same channel (a channel being a group of evenly spaced subcarriers as shown in Figure 1.26 for OFDM). It distributes the subcarriers among all users, so all users can transmit and receive at the same time. The subcarriers can be matched to each user to provide the best performance, meaning the least problems with fading and interference based on the location and propagation characteristics of each user.

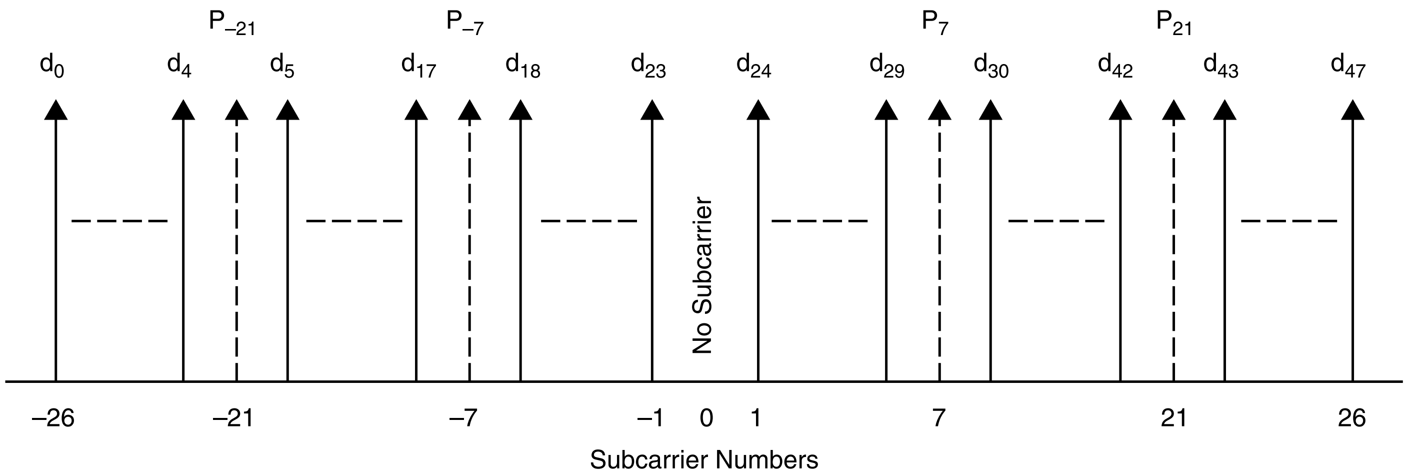


Figure 1.28 OFDM.

1.37 SUMMARY OF CHAPTER 32: ACP

Chapters 32–35 show various measurements defining the quality of modulated RF signals when they are processed by RF components. Chapter 32 describes ACP.

To accommodate the maximum number of users in a given licensed RF frequency band, it is desirable to leave a minimum amount of frequency band between each user's channel. When digital signals are modulated onto a RF carrier, some of their carrier power spreads out into adjacent user channels. The ratio of this interfering power to the power in the desired channel is called ACP.

Figure 1.29 shows the effect of power amplifier saturation on ACP. The upper left curve shows the test signal. By careful filtering, the power in the next lower adjacent frequency channel or in the next higher adjacent frequency channel is maintained 30 dB below the power in the desired channel.

The upper right-hand curve shows the signal coming out of the amplifier when it is operating in its linear range at 16 dB below saturation, where the output power is directly proportional to the input power. Note that there has been no growth in the ACPs when the linear amplifier is used.

The lower right-hand curve shows the ACP when the amplifier is operating within 3 dB of its maximum power capability. The ACP is now significantly greater and is only 25 dB below the power in the main channel. The lower right-hand curve shows the output power of the amplifier when it is operating at saturation. Now the ACP is only 18 dB below the power in the main channel. For most cellular phone systems, this performance is not satisfactory. The practical solution to this problem is to design the system so that the amplifier is never operated within 3 dB of its maximum output power.

1.38 SUMMARY OF CHAPTER 33: CONSTELLATION, VECTOR, AND EYE DIAGRAMS, AND EVM

RF devices can cause spectral regrowth and create interference between user channels. They can also distort the modulation information within the desired channel.

Figure 1.30 shows various ways of observing these distortions using a VSA. The upper figure shows the constellation diagram of a $\pi/4$DQPSK modulated RF signal. The pattern has eight phase positions, each 45° apart. The angle of each symbol point gives a phase of the RF signal, and the distance from the center to each symbol point gives the amplitude. The crosshairs show a perfectly demodulated signal; the data points show a set of actual signal values.

The lower left panel of Figure 1.30 is a vector diagram. It shows not only the constellation points but also the variation of phase and amplitude of the signal during the transition time between data points. The lower right panel of the figure shows an eye diagram, which is commonly used in analyzing a baseband data stream. The $\pi/4$DQPSK eye diagram is more complicated than the baseband case.

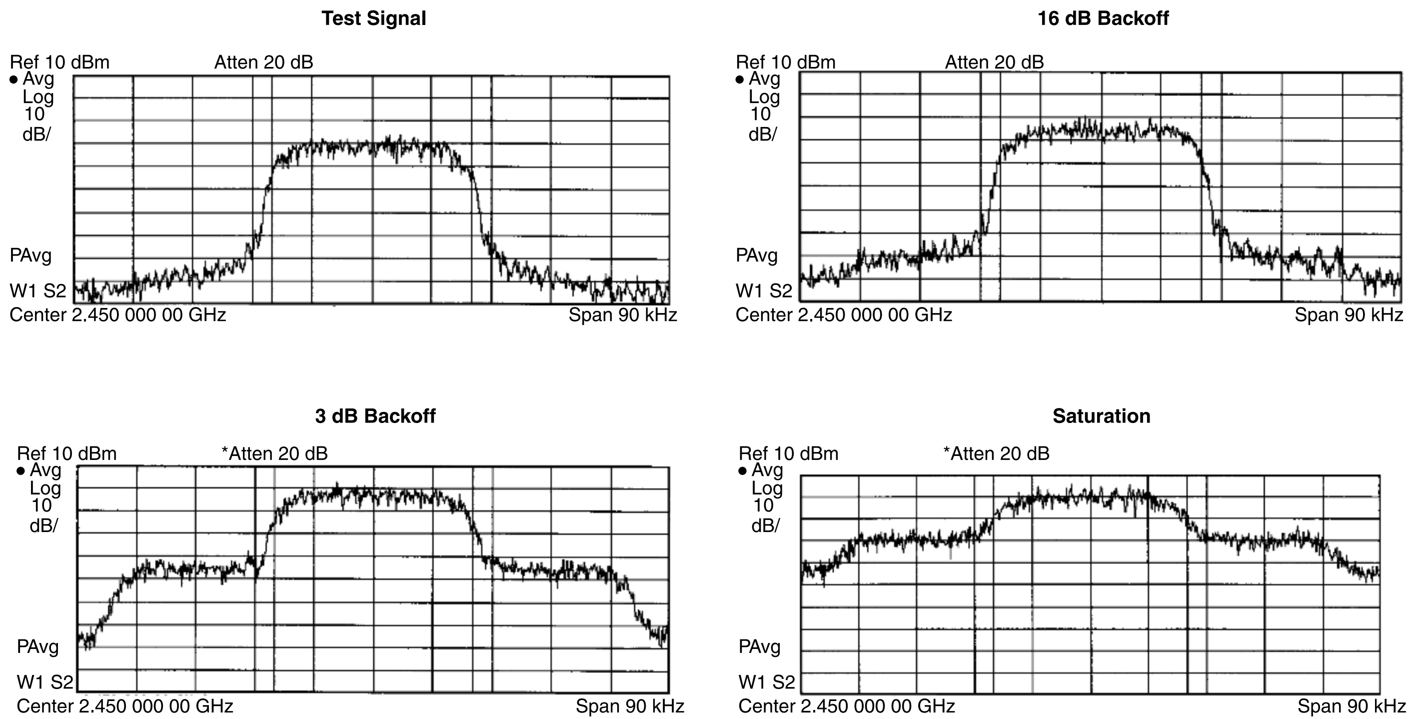


Figure 1.29 ACP of the $\pi/4$DQPSK signal for various amounts of backoff.

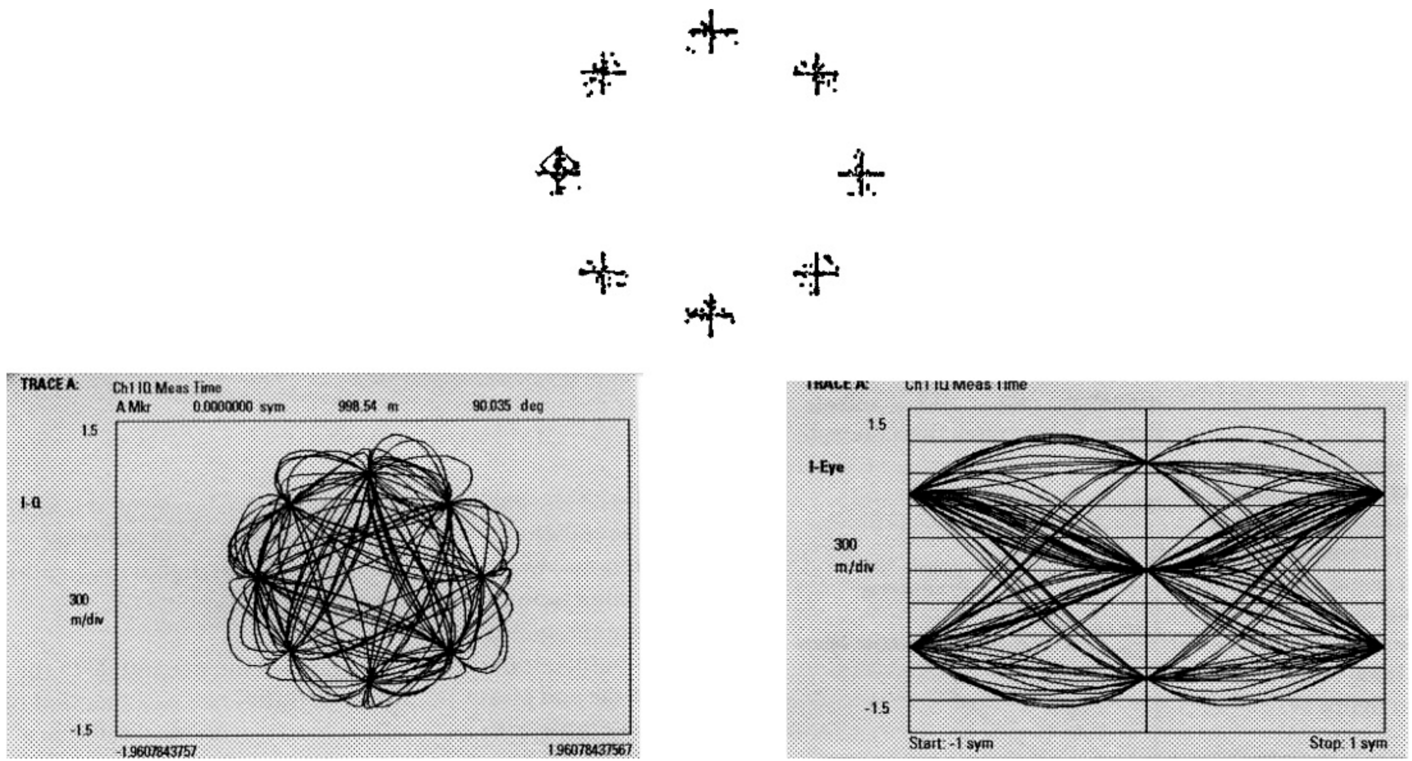


Figure 1.30 Constellation, vector, and eye diagrams.

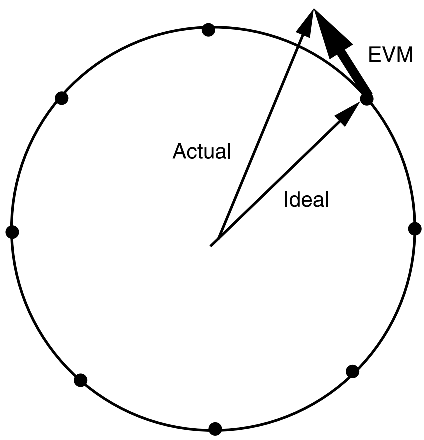


Figure 1.31 Explanation of EVM.

Any of the three displays provided in Figure 1.30 can be obtained by simply adjusting the VSA. With these diagrams a trained engineer can determine the cause of the signal distortion.

The analysis diagrams described above suggest a possible cause for the bit errors in a wireless data transmission system, but they give no quantitative information about how bad the distortion is.

The quantity EVM provides the necessary quantitative information. EVM is explained in Figure 1.31, which is a constellation diagram for $\pi/4$DQPSK modulation. The eight ideal points are shown. Each can be represented by a vector of normalized signal amplitude extending from the origin to one of the eight phase locations. The amplitude and phase of an actual signal point are also shown. Because of signal distortions, the amplitude of the vector and the phase are greater than they should be. Both of the phase and amplitude differences between the ideal and the actual signal could be measured, but an "error vector" is defined to simplify the analysis. The EVM can then be determined. Note that the amplitude of the EVM is affected by both phase and amplitude errors. The EVM is a single metric quantifying how bad the error is.

The allowed EVM in a particular system depends on how much information is to be obtained from the modulated signal. With QPSK modulation, where 2 bits/symbol are to be obtained, the allowed EVM is about 7 dB. With 64QAM modulation, where 6 bits/symbol are to be obtained, the allowed EVM is about 0.5 dB.

1.39 SUMMARY OF CHAPTER 34: CCDF

In certain RF wireless communication systems, such as CDMA, many signals intended for different users are transmitted on the same frequency at the same time. The individual signals are separated by using their CDMA code, as described

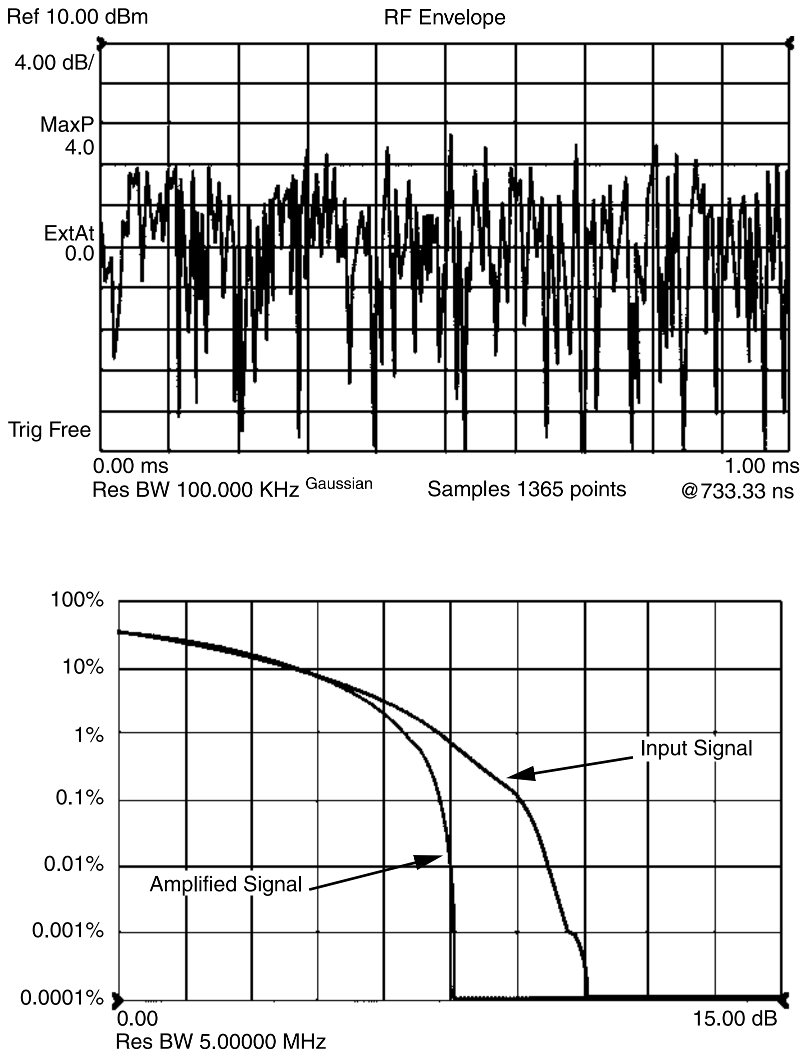


Figure 1.32 CCDF.

in Chapter 30. The top graph of Figure 1.32 shows the resulting signal as a function of time. An individual signal can be detected by despreading with its unique code. However, it is difficult to determine the degradation caused by RF components on this mixture of many signals using the analysis diagrams or the EVM measurement. Using a spectrum analyzer, a simple way of determining if an RF component is distorting the CDMA signal is to use the CCDF measurement shown in the bottom of Figure 1.32. CCDF simply shows the percentage of the time (on the vertical scale) that the signal is a specified dB above its mean value (on the horizontal scale). Two CCDF measurements are shown in the lower part of the top figure. One is the input RF signal to a power amplifier, and the other is the output RF signal from the amplifier. Notice that these two curves are quite different, indicating that the amplifier is distorting the signal, because of its saturation characteristic. A higher power amplifier with more "head room" would be required for the system to work properly.

1.40 SUMMARY OF CHAPTER 35: BER

The ultimate measurement that must be made on a digital communication system is the BER. In this measurement a known data stream is transmitted through the equipment. The received bitstream is compared to the transmitted bitstream and a BER is determined.

The unit under test (UUT) is usually a complete system. The digital test signal is a pseudorandom bit sequence (PRBS) that eliminates the need to time synchronize the transmitted and received bitstream, because the sequence has an easily detectable pattern at the start. PN9 or PN15 are common PRBS signals.

Figure 1.33 shows a typical BER measurement setup. An RF signal generator (see Fig. 1.6) generates an RF signal with the correct frequency, power level, and type of modulation. A PRBS signal is modulated onto the RF carrier. The signal is transmitted to a UUT as shown. The incoming RF signal passes through the receiver in the UUT, and the received bitstream is remodulated onto the UUT's transmitted RF signal. The transmitted signal is received, the PRBS digital bitstream is compared to the signal that was originally transmitted, and the BER is measured.

The BER test measures whether the UUT is performing to specifications, and it is basically a go–no go test. If the unit does not pass, the BER test gives no indication of the cause of the problem. To determine the cause of the problem, analysis diagrams and EVM measurements must be made.

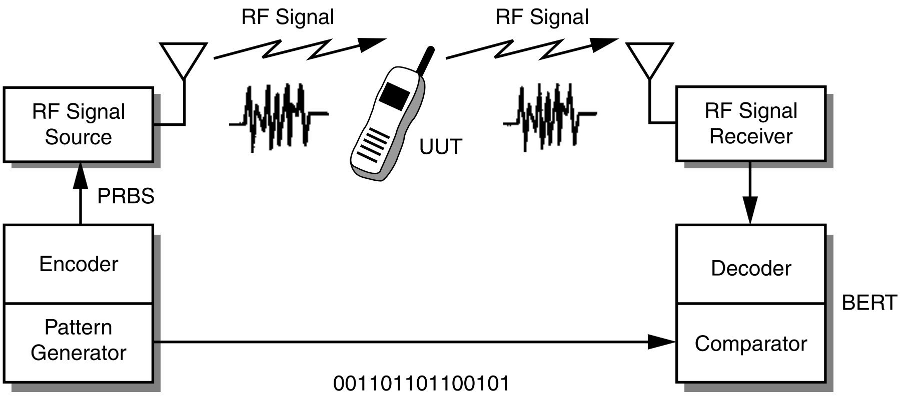


Figure 1.33 BER measurement.

1.41 SUMMARY OF CHAPTER 36: MEASUREMENT OF GSM EVOLUTION COMPONENTS

The VSA displays constellation, vector, and eye diagrams and measures EVM. However, it can also be supplied with software that will perform tests to specific system requirements, including making pass/fail measurements.

This type of measurement to system specs is illustrated in Chapter 36. Measurements are shown for the GSM evolution systems described in Chapter 30, including Enhanced Data Rates for GSM Evolution (EDGE), WCDMA, and HSDPA. Special Agilent software is used to control the VSA (Fig. 1.34). The test signals are provided by the RF signal generator described in Chapter 5, using special software to generate the EDGE, WCDMA, and HSDPA modulated RF signals. Measurements were made in the 1.9 GHz Personal Communication Services (PCS) frequency band.

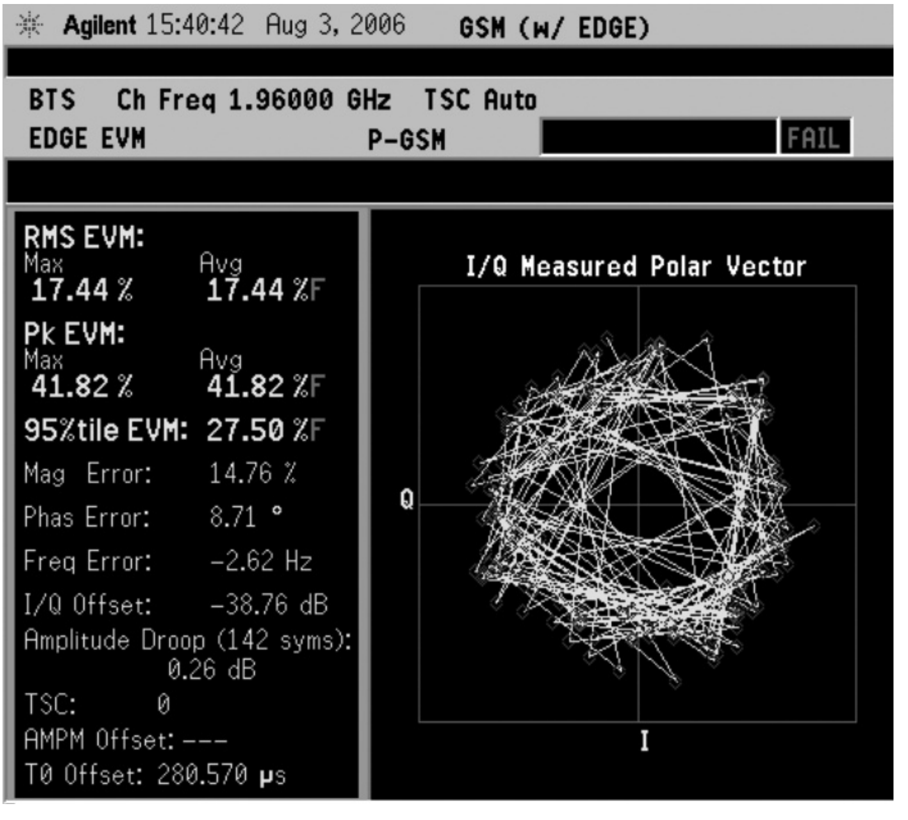


Figure 1.34 Edge polar vector at amplifier saturation.

1.42 ANNOTATED BIBLIOGRAPHY

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2. Micelli, A., Wireless Technicians Handbook, Artech House Norwood, MA. 2000.
3. Besser Associates, BesserNet.com, http://www.bessernet.com.
4. Besser, L. and Gilmore, R., Practical RF Circuit Design for Modern Wireless Systems, Vols. I and II, Artech House, Norwood, MA, 2003.

Reference 1 is an excellent reference on RF and wireless at an elementary level. It provides an overview of various cellular and wireless data systems.

Reference 2 is a good reference on cellular phone systems at the technician level.

Reference 3 is a free website with free interactive design programs, and it refers to many RF and wireless design articles.

Reference 4 provides an excellent background on passive and active RF circuit design principles.