Chapter

1

Fundamentals of Antennas

Ahmed A. Kishk

Center of Electromagnetic System Research (CEDAR)
Department of Electrical Engineering
University of Mississippi

An antenna is a device that is used to transfer guided electromagnetic waves (signals) to radiating waves in an unbounded medium, usually free space, and vice versa (i.e., in either the transmitting or receiving mode of operation). Antennas are frequency-dependent devices. Each antenna is designed for a certain frequency band. Beyond the operating band, the antenna rejects the signal. Therefore, we might look at the antenna as a bandpass filter and a transducer. Antennas are essential parts in communication systems. Therefore, understanding their principles is important. In this chapter, we introduce the reader to antenna fundamentals.

There are many different antenna types. The isotropic point source radiator, one of the basic theoretical radiators, is useful because it can be considered a reference to other antennas. The isotropic point source radiator radiates equally in all directions in free space. Physically, such an isotropic point source cannot exist. Most antennas' gains are measured with reference to an isotropic radiator and are rated in decibels with respect to an isotropic radiator (dBi).

1.1 Basis Parameters and Definitions of Antennas

Some basic parameters affect an antenna's performance. The designer must consider these design parameters and should be able to adjust, as needed, during the design process the frequency band of operation, polarization, input impedance, radiation patterns, gain, and efficiency. An antenna in the transmitting mode has a maximum power acceptance. An antenna in the receiving mode differs in its noise rejection properties. The designer should evaluate and measure all of these parameters using various means.

1.1.1 Input Impedance and Equivalent Circuits

As electromagnetic waves travel through the different parts of the antenna system, from the source (*device*) to the feed line to the antenna and finally to free space, they may encounter differences in impedance at each interface. Depending on the impedance match, some fraction of the wave's energy will reflect back to the source, forming a standing wave in the feed line. The ratio of maximum power to minimum power in the wave can be measured and is called the *standing wave ratio (SWR)*. An SWR of 1:1 is ideal. An SWR of 1.5:1 is considered to be marginally acceptable in low-power applications where power loss is more critical, although an SWR as high as 6:1 may still be usable with the right equipment. Minimizing impedance differences at each interface will reduce SWR and maximize power transfer through each part of the system.

The frequency response of an antenna at its port is defined as *input impedance* (Z_{in}). The input impedance is the ratio between the voltage and currents at the antenna port. Input impedance is a complex quantity that varies with frequency as $Z_{\text{in}}(f) = R_{\text{in}}(f) + jX_{\text{in}}(f)$, where f is the frequency. The antenna's input impedance can be represented as a circuit element in the system's microwave circuit. The antenna can be represented by an equivalent circuit of several lumped elements, as shown in Figure 1.1. In Figure 1.1, the equivalent circuit of the antenna is connected to a source, V_s, with internal impedance, $Z_s = R_s + jX_s$. The antenna has an input impedance of $Z_{\text{in}} = R_a + jX_a$. The real part consists

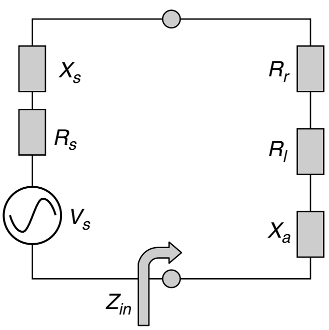

Figure 1.1 Equivalent circuit of an antenna

of the radiation resistance (R_r) and the antenna losses (R_l). The input impedance can then be used to determine the reflection coefficient (Γ) and related parameters, such as voltage standing wave ratio (VSWR) and return loss (RL), as a function of frequency as given in[1–4]

$$\Gamma = \frac{Z_{\text{in}} - Z_o}{Z_{\text{in}} + Z_o} \tag{1.1}$$

where Z_o is the normalizing impedance of the port. If Z_o is complex, the reflection coefficient can be modified to be

$$\Gamma = \frac{Z_{\text{in}} - Z_o^*}{Z_{\text{in}} + Z_o} \tag{1.2}$$

where Z_o^* is the conjugate of the nominal impedance. The VSWR is given as

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{1.3}$$

And the return loss is defined as

$$\text{RL} = -20\log|\Gamma| \tag{1.4}$$

Input impedance is usually plotted using a *Smith chart*. The Smith chart is a tool that shows the reflection coefficient and the antenna's frequency behavior (inductive or capacitive). One would also determine any of the antenna's resonance frequencies. These frequencies are those at which the input impedance is purely real; conveniently, this corresponds to locations on the Smith chart where the antenna's impedance locus crosses the real axis.

Impedance of an antenna is complex and a function of frequency. The impedance of the antenna can be adjusted through the design process to be matched with the feed line and have less reflection to the source. If that is not possible for some antennas, the impedance of the antenna can be matched to the feed line and radio by adjusting the feed line's impedance, thus using the feed line as an impedance transformer.

1.1.2 Matching and Bandwidth

In some cases, the impedance is adjusted at the load by inserting a matching transformer, matching networks composed of lumped elements such as inductors and capacitors for low-frequency applications, or implementing such a matching circuit using transmission-line technology as a matching section for high-frequency applications where lumped elements cannot be used.

The *bandwidth* is the antenna operating frequency band within which the antenna performs as desired. The bandwidth could be related to the antenna matching band if its radiation patterns do not change within this band. In fact, this is the case for small antennas where a fundamental limit relates bandwidth, size, and efficiency. The bandwidth of other antennas might be affected by the radiation pattern's characteristics, and the radiation characteristics might change although the matching of the antenna is acceptable. We can define antenna bandwidth in several ways. Ratio bandwidth (BW_r) is

$$BW_r = \frac{f_U}{f_L} \tag{1.5}$$

where f_U and f_L are the upper and lower frequency of the band, respectively. The other definition is the percentage bandwidth (WB_p) and is related to the ratio bandwidth as

$$BW_p = 200\frac{f_U - f_L}{f_U + f_L}\% = 200\frac{WB_r - 1}{WB_r + 1}\% \tag{1.6}$$

1.1.3 Radiation Patterns

Radiation patterns are graphical representations of the electromagnetic power distribution in free space. Also, these patterns can be considered to be representative of the relative field strengths of the field radiated by the antenna.[1–4] The fields are measured in the spherical coordinate system, as shown in Figure 1.2, in the θ and ϕ directions. For the ideal isotropic antenna, this would be a sphere. For a typical dipole, this would be a toroid. The radiation pattern of an antenna is typically represented by a three-dimensional (3D) graph, as shown in Figure 1.3, or polar plots of the horizontal and vertical cross sections. The graph should show sidelobes and backlobes. The polar plot can be considered as a planer cut from the 3D radiation pattern, as shown in Figure 1.4.

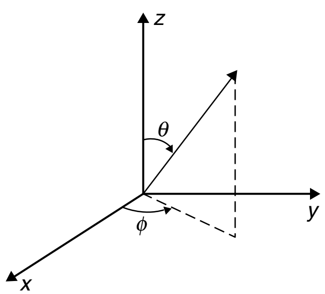

Figure 1.2 Spherical coordinates

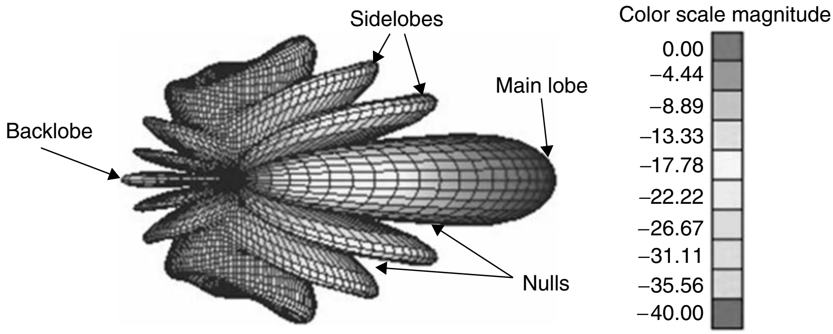

Figure 1.3 3D radiation pattern

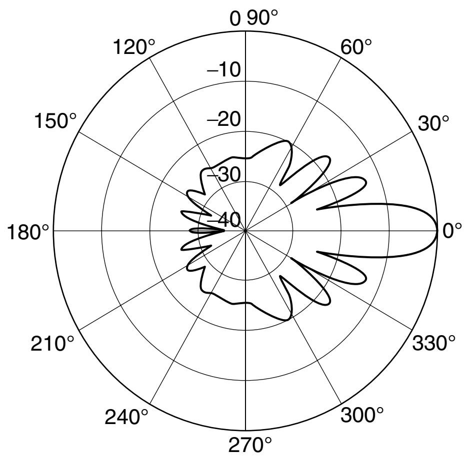

Figure 1.4 Polar plot radiation

The same pattern can be presented in the rectangular coordinate system, as shown in Figure 1.5. We should point out that these patterns are normalized to the pattern's peak, which is pointed to $\theta = 0$ in this case and given in decibels.

1.1.3.1 Beamwidth The beamwidth of the antenna is usually considered to be the angular width of the half power radiated within a certain cut through the main beam of the antenna where most of the power is radiating. From the peak radiation intensity of the radiation pattern, which is the peak of the main beam, the half power level is –3 dB below such a peak where the two points on the main beam are located; these points are on two sides of the peak, which separate the angular width of the half power. The angular distance between the half power points is defined as the *beamwidth*. Half the power expressed in decibels is –3 dB, so the

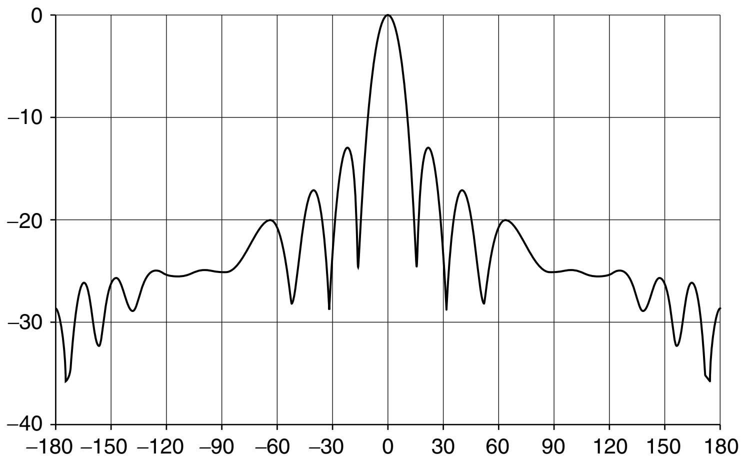

Figure 1.5 Rectangular plot of radiation pattern

half-power beamwidth is sometimes referred to as the 3-dB beamwidth. Both horizontal and vertical beamwidths are usually considered.

1.1.3.2 Sidelobes and Nulls No antenna is able to radiate all the energy in one preferred direction. Some energy is inevitably radiated in other directions with lower levels than the main beam. These smaller peaks are referred to as *sidelobes*, commonly specified in dB down from the main lobe.

In an antenna radiation pattern, a null is a zone in which the effective radiated power is at a minimum. A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as suppressing interfering signals in a given direction.

Comparing the *front-to-back ratio* of directional antennas is often useful. This is the ratio of the maximum directivity of an antenna to its directivity in the opposite direction. For example, when the radiation pattern is plotted on a relative dB scale, the front-to-back ratio is the difference in dB between the level of the maximum radiation in the forward direction and the level of radiation at 180°. This number is meaningless for an omnidirectional antenna, but it gives one an idea of the amount of power directed forward on a very directional antenna.

1.1.4 Polarization of the Antenna

The *polarization* of an antenna is the orientation of the electric field (*E-plane*) of the radio wave with respect to the Earth's surface and is determined by the physical structure and orientation of the antenna. It has nothing in common with the antenna directionality terms: horizontal, vertical, and circular. Thus, a simple straight wire antenna will have one polarization when mounted vertically and a different polarization when mounted horizontally. Electromagnetic wave polarization filters are structures that can be employed to act directly on the electromagnetic wave to filter out wave energy of an undesired polarization and to pass wave energy of a desired polarization.

Reflections generally affect polarization. For radio waves, the most important reflector is the ionosphere—the polarization of signals reflected from it will change unpredictably. For signals reflected by the ionosphere, polarization cannot be relied upon. For line-of-sight communications, for which polarization can be relied upon, having the transmitter and receiver use the same polarization can make a huge difference in signal quality; many tens of dB difference is commonly seen, and this is more than enough to make up the difference between reasonable communication and a broken link.

Polarization is largely predictable from antenna construction, but especially in directional antennas, the polarization of sidelobes can be quite different from that of the main propagation lobe. For radio antennas, polarization corresponds to the orientation of the radiating element in an antenna. A vertical omnidirectional WiFi antenna will have vertical polarization (the most common type). One exception is a class of elongated waveguide antennas in which a vertically placed antenna is horizontally polarized. Many commercial antennas are marked as to the polarization of their emitted signals.

Polarization is the sum of the E-plane orientations over time projected onto an imaginary plane perpendicular to the direction of motion of the radio wave. In the most general case, polarization is elliptical (the projection is oblong), meaning that the polarization of the radio waves emitting from the antenna is varying over time. Two special cases are *linear polarization* (the ellipse collapses into a line) and *circular polarization* (in which the ellipse varies maximally). In linear polarization, the antenna compels the electric field of the emitted radio wave to a particular orientation. Depending on the orientation of the antenna mounting, the usual linear cases are horizontal and vertical polarization. In circular polarization, the antenna continuously varies the electric field of the radio wave through all possible values of its orientation with regard to the Earth's surface. Circular polarizations (CP), like elliptical ones, are classified as right-hand polarized or left-hand polarized using a "thumb in the direction of the propagation" rule. Optical researchers use the same rule of thumb, but point it in the direction of the emitter, not in the direction of propagation, and so their use is opposite to that of radio engineers. Some antennas, such the helical antenna, produce circular polarizations. However, circular polarization can be generated from a linearly polarized antenna by feeding the antenna by two ports with equal magnitude and with a 90° phase difference between them. From the linear field components in the far zone, the circular polarization can be presented as

$$E_c(\theta,\phi) = \frac{E_\phi(\theta,\phi) + jE_\theta(\theta,\phi)}{\sqrt{2}} \tag{1.7}$$

$$E_x(\theta,\phi) = \frac{E_\phi(\theta,\phi) - jE_\theta(\theta,\phi)}{\sqrt{2}} \tag{1.8}$$

where E_c is the copolar of the circular polarization, in this case, the left-hand CP, and E_x is the cross-polarization, or the right-hand CP.

In practice, regardless of confusing terminology, matching linearly polarized antennas is important, or the received signal strength is greatly reduced. So, horizontal polarization should be used with horizontal antennas and vertical with vertical. Intermediate matching will cause the loss of some signal strength, but not as much as a complete mismatch. Transmitters mounted on vehicles with large motional freedom commonly use circularly polarized antennas so there will never be a complete mismatch with signals from other sources. In the case of radar, these sources are often reflections from rain drops.

In order to transfer maximum power between a transmit and receive antenna, both antennas must have the same spatial orientation, the same polarization sense, and the same axial ratio. When the antennas are not aligned or do not have the same polarization, power transfer between the two antennas will be reduced. This reduction in power transfer will reduce the overall system efficiency and performance as well. When transmit and receive antennas are both linearly polarized, physical antenna misalignment will result in a polarization mismatch loss, which can be determined using the following formula:

$$\text{Loss (dB)} = 20 \log (\cos\phi) \tag{1.9}$$

where ϕ is the difference in alignment angle between the two antennas. For 15°, the loss is approximately 0.3 dB; for 30°, the loss is 1.25 dB; for 45°, the loss is 3 dB; and for 90°, the loss is infinite.

In short, the greater the mismatch in polarization between a transmitting and receiving antenna, the greater the apparent loss will be. You can use the polarization effect to your advantage on a point-to-point link. Use a monitoring tool to observe interference from adjacent networks, and rotate one antenna until you see the lowest received signal. Then bring your link online and orient the other end to match polarization.

This technique can sometimes be used to build stable links, even in noisy radio environments.

1.1.5 Antenna Efficiency

Antenna efficiency is the measure of the antenna's ability to transmit the input power into radiation.[1–4] Antenna efficiency is the ratio between the radiated powers to the input power:

$$e = \frac{P_r}{P_{\text{in}}} \tag{1.10}$$

Different types of efficiencies contribute to the *total* antenna efficiency. The *total* antenna efficiency is the multiplication of all these efficiencies. Efficiency is affected by the losses within the antenna itself and the reflection due to the mismatch at the antenna terminal. Based on the equivalent circuit on Figure 1.1, we can compute the radiation efficiency of the antenna as the ratio between the radiated powers to the input power, which is only related to the conduction losses and the dielectric losses of the antenna structure as

$$e_r = \frac{P_r}{P_{\text{in}}} = \frac{R_r}{R_{\text{in}}} = \frac{R_r}{R_r + R_l} \tag{1.11}$$

Due to the mismatch at the antenna terminal, the reflection efficiency can be defined as

$$e_{\text{ref}} = (1 - |\Gamma|^2) \tag{1.12}$$

Then the total efficiency is defined as

$$e = e_r e_{\text{ref}} \tag{1.13}$$

In this formula, antenna radiation efficiency only includes conduction efficiency and dielectric efficiency and does not include reflection efficiency as part of the total efficiency factor. Moreover, the IEEE standards state that "gain does not include losses arising from impedance mismatches and polarization mismatches."[5]

Efficiency is the ratio of power actually radiated to the power input into the antenna terminals. A dummy load may have an SWR of 1:1 but an efficiency of 0, as it absorbs all power and radiates heat but not RF energy, showing that SWR alone is not an effective measure of an antenna's efficiency. Radiation in an antenna is caused by radiation resistance, which can only be measured as part of total resistance, including loss resistance. Loss resistance usually results in heat generation rather than radiation and reduces efficiency. Mathematically, efficiency is calculated as radiation resistance divided by total resistance.

1.1.6 Directivity and Gain

The *directivity* of an antenna has been defined as "the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions." In other words, the directivity of a nonisotropic source is equal to the ratio of its radiation intensity in a given direction, over that of an isotropic source[1–4]:

$$D = \frac{U}{U_i} = \frac{4\pi U}{P_r} \tag{1.14}$$

where D is the directivity of the antenna; U is the radiation intensity of the antenna; U_i is the radiation intensity of an isotropic source; and P_r is the total power radiated.

Sometimes, the direction of the directivity is not specified. In this case, the direction of the maximum radiation intensity is implied and the maximum directivity is given as

$$D_{\max} = \frac{U_{\max}}{U_i} = \frac{4\pi U_{\max}}{P_r} \tag{1.15}$$

where $D_{\max}$ is the maximum directivity and $U_{\max}$ is the maximum radiation intensity.

A more general expression of directivity includes sources with radiation patterns as functions of spherical coordinate angles θ and ϕ:

$$D = \frac{4\pi}{\Omega_A} \tag{1.16}$$

where Ω_A is the beam solid angle and is defined as the solid angle in which, if the antenna radiation intensity is constant (and maximum value), all power would flow through it. Directivity is a dimensionless quantity because it is the ratio of two radiation intensities. Therefore, it is generally expressed in dBi. The directivity of an antenna can be easily estimated from the radiation pattern of the antenna. An antenna that has a narrow main lobe would have better directivity than the one that has a broad main lobe; hence, this antenna is more directive. In the case of antennas with one narrow major lobe and very negligible minor lobes, the beam solid angle can be approximated as the product of the half-power beamwidths in two perpendicular planes:

$$\Omega_A = \Theta_{1r}\Theta_{2r} \tag{1.17}$$

where, Ω_{1r} is the half-power beamwidth in one plane (radians) and Ω_{2r} is the half-power beamwidth in a plane at a right angle to the other (radians). The same approximation can be used for angles given in degrees as follows:

$$D \approx 4\pi \frac{\left(\frac{180}{\pi}\right)^2}{\Theta_{1d}\Theta_{2d}} = \frac{41253}{\Theta_{1d}\Theta_{2d}} \tag{1.18}$$

where Ω_{1d} is the half-power beamwidth in one plane (degrees) and Ω_{2d} is the half-power beamwidth in a plane at a right angle to the other (degrees). In planar arrays, a better approximation is[6]

$$D \approx \frac{32400}{\Theta_{1d}\Theta_{2d}} \tag{1.19}$$

Gain as a parameter measures the directionality of a given antenna. An antenna with low gain emits radiation with about the same power in all directions, whereas a high-gain antenna will preferentially radiate in particular directions. Specifically, the *gain, directive gain,* or *power gain* of an antenna is defined as the ratio of the intensity (power per unit surface) radiated by the antenna in a given direction at an arbitrary distance divided by the intensity radiated at the same distance by a hypothetical isotropic lossless antenna. Since the radiation intensity from a lossless isotropic antenna equals the power into the antenna divided by a solid angle of 4π steradians, we can write the following equation:

$$G = \frac{4\pi U}{P_{\text{in}}} \tag{1.20}$$

Although the gain of an antenna is directly related to its directivity, antenna gain is a measure that takes into account the efficiency of the antenna as well as its directional capabilities. In contrast, directivity is defined as a measure that takes into account only the directional properties of the antenna, and therefore, it is only influenced by the antenna pattern. If, however, we assume an ideal antenna without losses, then antenna gain will equal directivity as the antenna efficiency factor equals 1 (100% efficiency). In practice, the gain of an antenna is always less than its directivity.

$$G = \frac{4\pi U}{P_{\text{in}}} = e_{\text{cd}} \frac{4\pi U}{P_r} = e_{\text{cd}} D \tag{1.21}$$

Equations 1.20 and 1.21 show the relationship between antenna gain and directivity, where e_{cd} is the antenna radiation efficiency factor, D the directivity of the antenna, and G the antenna gain. We usually deal with *relative* gain, which is defined as the power gain ratio in a specific direction of the antenna to the power gain ratio of a reference antenna in the same direction. The input power must be the same for both antennas while performing this type of measurement. The reference antenna is usually a dipole, horn, or any other type of antenna whose power gain is already calculated or known.

$$G = G_{\mathrm{ref}} \frac{P_{\max}}{P_{\max}\big|_{\mathrm{ref}}} \tag{1.22}$$

In the case that the direction of radiation is not stated, the power gain is always calculated in the direction of maximum radiation. The maximum directivity of an actual antenna can vary from 1.76 dB for a short dipole to as much as 50 dB for a large dish antenna. The maximum gain of a real antenna has no lower bound and is often –10 dB or less for electrically small antennas.

Antenna absolute gain is another definition for antenna gain. However, absolute gain does include the reflection or mismatch losses:

$$G_{\mathrm{abs}} = e_{\mathrm{eff}} G = e_{\mathrm{refl}} e_{\mathrm{cd}} D \tag{1.23}$$

As defined before, e_{refl} is the reflection efficiency, and e_{cd} includes the dielectric and conduction efficiency. The term e_{eff} is the total antenna efficiency factor.

Taking into account polarization effects in the antenna, we can also define the partial gain of an antenna for a given polarization as that part of the radiation intensity corresponding to a given polarization divided by the total radiation intensity of an isotropic antenna. As a result of this definition for the partial gain in a given direction, we can present the total gain of an antenna as the sum of partial gains for any two orthogonal polarizations:

$$G_{\mathrm{total}} = G_\theta + \mathrm{U}_\phi \tag{1.24}$$

$$G_\theta = \frac{4\pi U_\theta}{P_{\mathrm{in}}} \quad \& \quad G_\phi = \frac{4\pi U_\phi}{P_{\mathrm{in}}} \tag{1.25}$$

The terms U_θ and U_ϕ represent the radiation intensity in a given direction contained in their respective E-field component.

The gain of an antenna is a passive phenomenon; power is not added by the antenna but simply redistributed to provide more radiated power in a certain direction than would be transmitted by an isotropic antenna. An antenna designer must take into account the antenna's application when determining the gain. High-gain antennas have the advantage of longer range and better signal quality but must be aimed carefully in a particular direction. Low-gain antennas have shorter range, but the orientation of the antenna is inconsequential. For example, a dish antenna on a spacecraft is a high-gain device (must be pointed at the planet to be effective) whereas a typical wireless fidelity (WiFi) antenna in a laptop computer is low-gain (as long as the base station is within range, the antenna can be in any orientation in space). Improving horizontal range at the expense of reception above or below the antenna makes sense.

1.1.7 Intermodulation

Generally, an antenna is considered a passive linear device. However, when such a device is excited by high enough power, it acts slightly as a nonlinear device. The nonlinearity is normally caused by metal-to-metal joints and nonlinear materials in the antenna structure. Therefore, when signals with multiple frequencies are fed into nonlinear devices, intermodulation product terms whose frequencies are different to those of the input signal are generated. A typical passive intermodulation signal level is from –180 to –120 dBc (dBc relative to carrier power).[7–8]

An antenna's intermodulation degrades a wireless system's performance if the system has the following features:

- High transmitted power is adopted.
- The system is equipped with high receiver sensitivity.
- One antenna is used for both transmitting and receiving.
- Signals at more than one frequency are transmitted.

Base stations normally have this entire feature set. Base stations, therefore, suffer from passive intermodulation (PIM). High-power signals excite the antenna of the base station, and intermodulation components cause back reflection to the receiver due to the antenna's PIM. Since the receiver is highly sensitive and is able to sense very weak signals, the intermodulation signals cause interference. The problem becomes worse if the intermodulation term falls inside the receiving band because the interference cannot be removed by filtering. For example, for the P-GSM-900 system whose downlink band is from 935 MHz to 960 MHz and whose uplink band is from 890 MHz to 915 MHz, the 3rd order intermodulation term at the base station side may be $2 \times 935 - 960 = 910$ MHz, which falls inside the uplink band. On the other hand, the PIM problem is not that serious at a client terminal, such as a cell phone, a personal digital assistant (PDA), or a laptop with wireless capability, and is normally ignored. On the client side, the transmitted power is not that high due to limited battery capacity and for electromagnetic safety reasons, and thus the PIM reflected to the receiver is weaker than that at the base station. The relatively low-power transmission does not reduce the quality of uplink as the base station is equipped with a highly sensitive receiver. In addition, the receiver sensitivity is not high at a client terminal, and the reflected PIM level is thus lower than the noise level. Similarly, the relatively lower receiver sensitivity does not degrade the downlink performance as a high-power signal is transmitted from the base station.

An antenna's PIM can be measured by a dedicated analyzer. For example, Summitek Instruments provides such an analyzer. Figure 1.6 shows the block diagram of a PIM analyzer that measures the PIM of a two-port device. It has two measurement modes called reverse measurement and forward measurement. As shown in Figure 1.6, a two-tone high-power signal is fed into Port 1 of the device under test (DUT). The RF switch is in the "Rev" position for the reverse measurement mode or in the "Fwd" position for the forward measurement. For the measurement of an antenna's PIM, the reverse measurement is used not only because an antenna is a one-port device but also because the reverse measurement corresponds to the operation condition of a base station antenna.

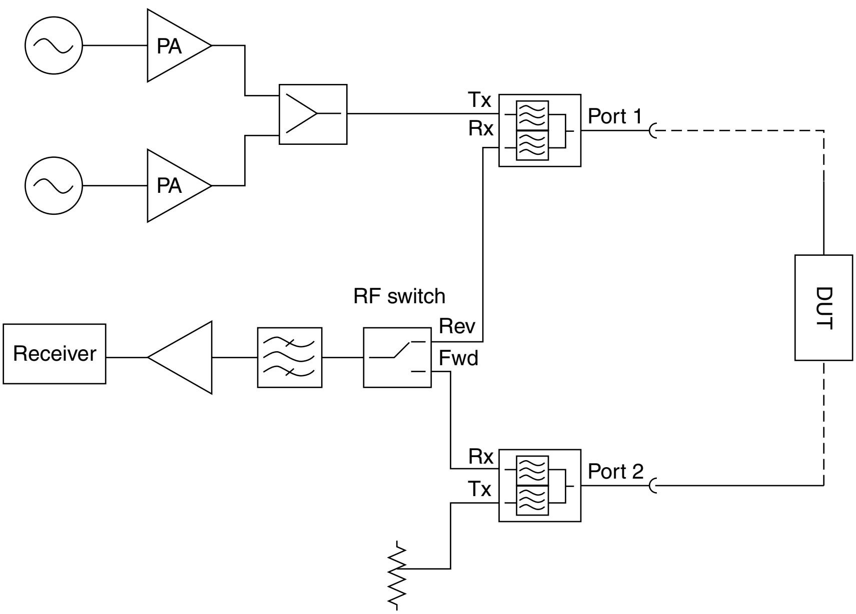

Figure 1.6 Block diagram of a PIM analyzer

1.2 Important Antennas in This Book

Here we introduce several antennas that are recently developed and could be considered as relatively new. These antennas are conventional microstrip antennas as narrow band planar printed antennas, suspended planar antennas as wideband antennas, and planar monopole as an ultra-wideband antenna (UWB).

1.2.1 Patch Antennas

The microstrip patch antenna is a popular printed resonant antenna for narrow-band microwave wireless links that require semihemispherical coverage. Due to its planar configuration and ease of integration with microstrip technology, the microstrip patch antenna has been studied heavily and is often used as an element for an array.

Common microstrip antenna shapes are square, rectangular, circular, ring, equilateral triangular, and elliptical, but any continuous shape is possible.[9] Figure 1.7 shows the parameters of circular and rectangular patches. Some patch antennas eschew a dielectric substrate and suspend a metal patch in air above a ground plane using dielectric spacers; the resulting structure is less robust but provides better bandwidth.

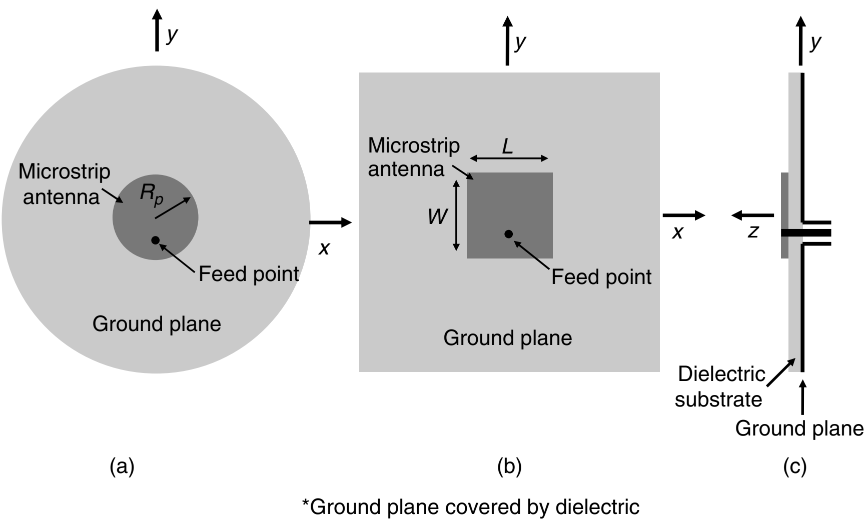

Figure 1.7 (*a*) Circular patch, (*b*) rectangular patch, and (*c*) side view

Advantages:

- Planer (and can be made conformal to shaped surface)
- Low profile
- Ease of integration with microstrip technology
- Can be integrated with circuit elements
- Ability to have polarization diversity (can easily be designed to have vertical, horizontal, right-hand circular (RHCP), or left-hand circular (LHCP) polarizations)
- Lightweight and inexpensive

Disadvantages:

- Narrow bandwidth (typically less than 5%), requiring bandwidth-widening techniques
- Can handle low RF power
- Large ohmic loss

The most common microstrip antenna is a rectangular patch. The rectangular patch antenna is approximately a one-half wavelength long section of rectangular microstrip transmission line. When air is the antenna substrate, the length of the rectangular microstrip antenna is approximately one-half of a free-space wavelength. If the antenna is loaded with a dielectric as its substrate, the length of the antenna decreases as the relative dielectric constant of the substrate increases. The resonant length of the antenna is slightly shorter because of the extended electric *fringing fields*, which increase the antenna's electrical length slightly. The dielectric loading of a microstrip antenna affects both its radiation pattern and impedance bandwidth. As the dielectric constant of the substrate increases, the antenna bandwidth decreases. This increases the antenna's Q factor and, therefore, decreases the impedance bandwidth.

Feeding Methods:

- Coaxial probe feeding
- Microstrip transmission line
- Recessed microstrip line
- Aperture coupling feed[10–11]
- Proximity-coupled microstrip line feed (no direct contact between the feed and the patch[12])

Bandwidth can be increased using the following techniques:

- Using thick and low permittivity substrates
- Introducing closely spaced parasitic patches on the same layer of the fed patch (15% BW)
- Using a stacked parasitic patch (multilayer, BW reaches 20%)
- Introducing a U-shaped slot in the patch (to achieve 30% BW)[13]
- Aperture coupling (10% BW, high backlobe radiation)[10–11]
- Aperture-coupled stacked patches (40–50% BW achievable)[14]
- L-probe coupling[15]

The size of the patch antenna can be reduced by using the following techniques:

- Using materials with high dielectric constants
- Using shorting walls
- Using shorting pins[16]

To obtain a small size wide-bandwidth antenna, these techniques can be combined.

1.2.2 Suspended Plate Antennas

A suspended plate antenna (SPAs) is defined as a thin metallic conductor bonded to a thin grounded dielectric substrate, as shown in Figure 1.8. Suspended plate antennas have thicknesses ranging from 0.03 λ_1 to 0.12 λ_1 (λ_1 is the wavelength corresponding to the minimum frequency of the well-matched impedance bandwidth) and a low relative dielectric constant of about 1. SPAs have a broad impedance bandwidth and unique radiation performance.[17]

The use of thick dielectric substrates is a simple and effective method to enhance the impedance bandwidth of a microstrip patch antenna by reducing its unloaded Q-factor. As the impedance bandwidth increases, however, surface wave losses also increase, which reduces radiation efficiency. To suppress the surface waves a low permittivity of the substrate is required.

Advantages:

- Easy to fabricate
- Not expensive
- Large bandwidth
- No surface waves

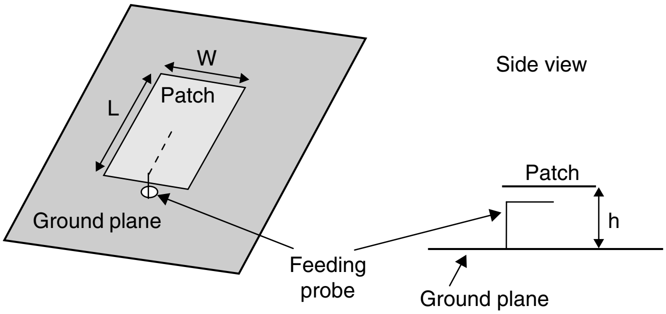

Figure 1.8 Suspended plate antenna patch fed by an L-shaped probe

Disadvantages:

- High cross polarization
- Thick Antenna compared to conventional microstrip antenna

Feeding Methods:

- Coaxial probe (poor matching BW is only 8%)

  Bandwidth can be improved using these techniques:[17]

- A dual probe-feeding arrangement consisting of a feed probe and a capacitive load[18]
- Long U-shaped slot, cut symmetrically from the plate (BW is 10%–40%)
- L-shaped probe (BW reaches 36%)[19]
- T-shaped probe (BW reaches 36%)
- A half-wavelength feeding strip
- A center-fed SPA with a symmetrical shorting pin
- Stacked suspended plate antenna[20]

1.2.3 Planer Inverted-L/F Antennas

A planar inverted-L/F antenna is an improved version of the monopole antenna. The straight wire monopole is the antenna with the most basic form. Its dominant resonance appears at around one-quarter of the operating wavelength. The height of quarter-wavelength has restricted their application to instances where a low-profile design is necessary.[17]

Figure 1.9 shows the geometry of a narrow-strip monopole with a horizontal bent portion, and the planer inverted-F antenna (PIFA) is shown in Figure 1.10.

A PIFA can be considered a kind of linear inverted-F antenna (IFA), with the wire radiator element replaced by a plate to expand bandwidth.

Advantages:

- Reduced height
- Reduced backward radiation
- Moderate to high gain in both vertical and horizontal polarizations

Disadvantages:

- Narrow bandwidth

The shorting post near the feeding probe of the PIFA antennas is a good method for reducing the antenna size, but this results in the narrow impedance bandwidth.

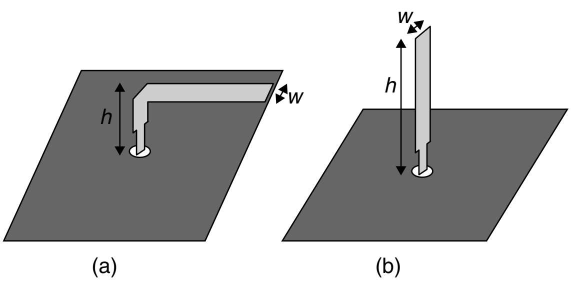

Figure 1.9 Geometry of a (*a*) narrow-strip monopole with a horizontal bent portion (*b*) monopole

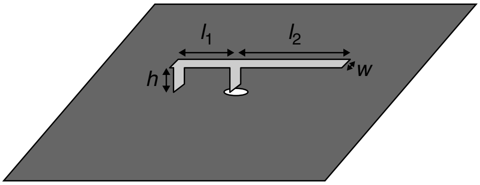

Figure 1.10 Geometry of the PIFA

Bandwidth can be improved using these techniques:

- Using thick air substrate
- Using parasitic resonators with resonant lengths close to the resonant frequency[21]
- Using stacked elements[22]
- Varying the size of the ground plane[23]

The size of the PIFA can be reduced using these techniques:

- Using an additional shorting pin[24]
- Loading a dielectric material with high permittivity[25]
- Capacitive loading of the antenna structure[26]
- Using slots on the patch to increase the antenna's electrical length[27]

1.2.4 Planer Dipoles/Monopoles

Dipoles and monopoles are the most widely used antennas. The monopole is a straight wire vertically installed above a ground plane; it is vertically polarized and has an omnidirectional radian in the horizontal plane. To increase the impedance bandwidth of the monopole antenna, planer elements can be used to replace the wire elements.[28]

Planer designs with different radiator shapes have been widely used in which the bandwidth reaches 70%. These shapes include[17]

- Circular (BW from 2.25–17.25 GHz)
- Triangular
- Elliptical (BW from 1.17–12 GHz)
- Rectangular (BW of 53%)
- Ring
- Trapezoidal (80% BW)
- Roll monopoles (more than 70% BW)

The square planar monopole with trident-shaped feeding strip (shown in Figure 1.11) was introduced[29] with a bandwidth of about 10 GHz (about 1.4–11.4 GHz). This bandwidth is three times the bandwidth obtained using a simple feeding strip.

A compact wideband cross-plate monopole antenna (shown in Figure 1.12) has been proposed.[30] This antenna has a cross-sectional area only 25% that of a corresponding planar cross-plate monopole antenna and can generate omnidirectional or near omnidirectional

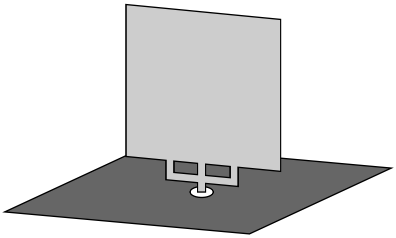

Figure 1.11 Geometry of the planar monopole antenna with a trident-shaped (three-branch) feeding strip

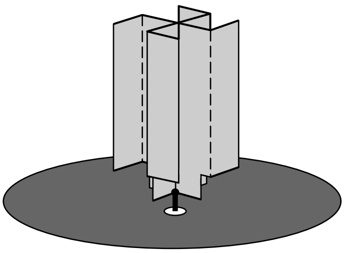

Figure 1.12 A compact wideband cross-plate monopole antenna

radiation patterns for frequencies across a wide operating bandwidth of about 10 GHz (1.85–11.93 GHz).

1.3 Basic Measurement Techniques

Performing measurements of the antenna parameters to verify the simulated design is very important. Measurements are also needed to verify that the antenna achieves its requirements. The parameters of the antenna that need to be measured are the input impedance, radiation pattern, directivity, gain, and efficiency. Here, we will briefly state the techniques used for these parameters. We are going to avoid some of the laborious old techniques that were used for lack of modern equipment and instead concentrate on the techniques that use modern equipment.

1.3.1 Measurement Systems for Impedance Matching

Antenna impedance can be measured using a *vector network analyzer*. A vector network analyzer is able to separate the forward wave, V^+, and the reflected wave, V^-, from an antenna at a reference plane where calibration is done, and thus the reflection coefficient is provided, which is the ratio between the reflected to incident waves as $G = V^-/V^+$. Then, the impedance at the reference plane can be computed as $Z = Z_c\,(1+\Gamma)/(1-\Gamma)$, where Z_c is the characteristic impedance of the cable connecting to the antenna. Consequently, before starting to measure the DUT, the network analyzer has to be calibrated using the slandered techniques of standard short, open, and matching loads. One of the most important parameters that calibration establishes is the reference plane, which is critical for phase information. This is a single port measurement.

In some cases, two port measurements are needed to measure the reflection coefficients for the two ports and the mutual coupling between them. These are referred to as the *S-parameter measurements*. This measurement determines the mutual coupling between two antennas or, for some antennas, determines the isolation between two ports of a dually polarized antenna.

1.3.2 Measurement Setups for Far-Zone Fields

For far-field measurements, the distance between the transmitter and receiver has to be large enough to be sure that the transmitter is in the far zone of the antenna under test. To perform these measurements indoors, you have to provide an environment that ensures the antenna does not interact with the surroundings and operates within the environment as if in free space. To achieve this, an anechoic chamber is used with its walls covered with proper absorbing materials that reduce or eliminate the reflections from the walls. The absorbing materials have a certain bandwidth or, in other words, a certain lower frequency bound. The lower frequency is reduced as the absorbing material size is increased.

1.3.2.1 Far-Field System To measure the far-zone field, the transmitting and receiving antennas are put into an anechoic chamber, using a spacing that satisfies each other's far-zone requirement. Figure 1.13 shows an anechoic chamber instrumentation block diagram. This distance guarantees the wave impinging on the receiving antenna can be approximated as a plane wave. Generally, the far-field distance, d, is considered to be

$$d = \frac{2D^2}{\lambda} \tag{1.26}$$

where D is the antenna diameter and λ is the wavelength of the radio wave. Separating the antenna under test (AUT) and the instrumentation antenna by this distance reduces the phase variation across the AUT enough to obtain a reasonably good antenna pattern.

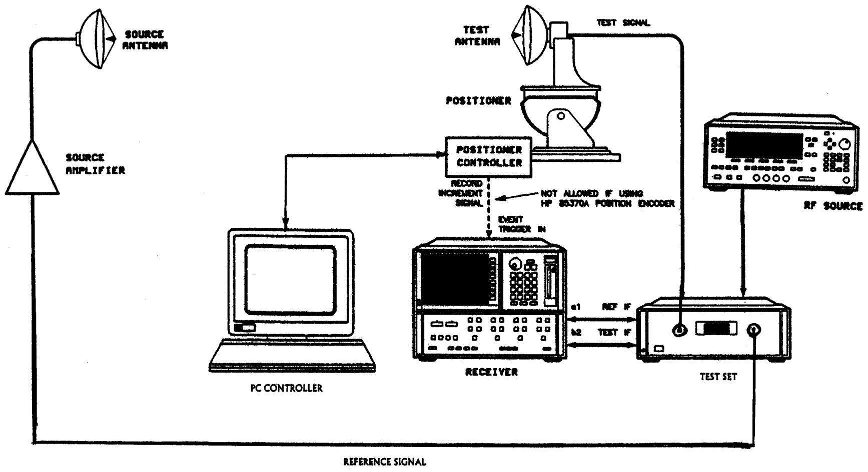

Figure 1.13 Anechoic chamber instrumentation block diagram

The antenna under test will rotate while the other antenna, referred to as the *testing probe*, is fixed. If the measurement is carried out in a transmitting mode, the antenna under test transmits signals while rotating two dimensionally or three dimensionally depending on the rotating mechanism. At the same time, the testing probe receives signals and the measurement system records the data. On the other hand, if the measurement is carried out in a receiving mode, the testing probe transmits signals and the antenna under test receives signals while rotating. This measurement gives the radiation pattern of the antenna under test, if the polarization is the same as that of the testing probe, which could be vertically polarized, horizontally polarized, or circularly polarized. In case the far-zone requirement is difficult to satisfy, a parabolic reflector antenna is used to generate a plane wave. Such a system is referred to as a *compact range*.

1.3.2.2 Near-Field System To measure the near-zone field, the antenna under test is normally fixed and operates in either a transmitting or receiving mode, whereas the testing probe scans on a surface. The scanning surface could be a flat plane, a cylindrical surface, or a spherical surface depending on the mechanical scheme of the measurement system. Near the antenna under test, the system records the measured data.[5,31]

Planar near-field measurements are conducted by scanning a small probe antenna over a planar surface, as in Figure 1.14*a*. These measurements are then transformed to the far-field by use of a *Fourier Transform*, or more specifically, by applying a method known as *stationary phase* *to the Laplace Transform*. Three basic types of planar scans exist in near-field measurements. The probe moves in the Cartesian coordinate system, and its linear movement creates a regular rectangular sampling grid with a maximum near-field sample spacing of $\Delta x = \Delta y = \lambda/2$. Cylindrical near-field ranges measure the electric field on a cylindrical surface close to the AUT, as shown in Figure 1.14*b*. Cylindrical harmonics are used to transform these measurements to the far-field. Spherical near-field ranges measure the electric field on a spherical surface close to the AUT, as shown in Figure 1.14*c*. Spherical harmonics are used to transform these measurements to the far-field.

Similar to the far-zone measurement, the obtained field data has the same polarization as that of the testing probe. Normally, the testing probe is linearly polarized, and thus the measurement is often carried out twice for the two orthogonal polarization components on the sampling surface. This offers a convenient way to measure the radiation patterns of an electrically large antenna, which you may not be able to measure in an anechoic chamber.

Agilent provides high-quality microwave instrumentation, and combining Agilent's microwave instrumentation with NSI's software and systems expertise provides a solution that is unrivaled in the antenna measurement industry. The basic near-field range system block diagram shown in Figure 1.15 is similar to the University of Mississippi's available planar near-field system.

1.3.2.3 Circularly Polarized Systems By choosing different testing probes in the far-zone measurement, there are three ways to measure the far-zone circularly polarized field. If the measurement system could get

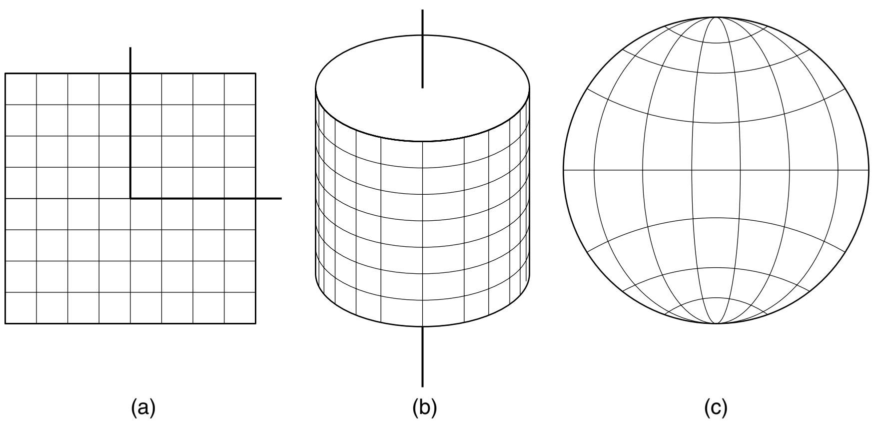

Figure 1.14 Near-field scanning: (*a*) planar scanning, (*b*) cylindrical scanning, and (*c*) spherical scanning

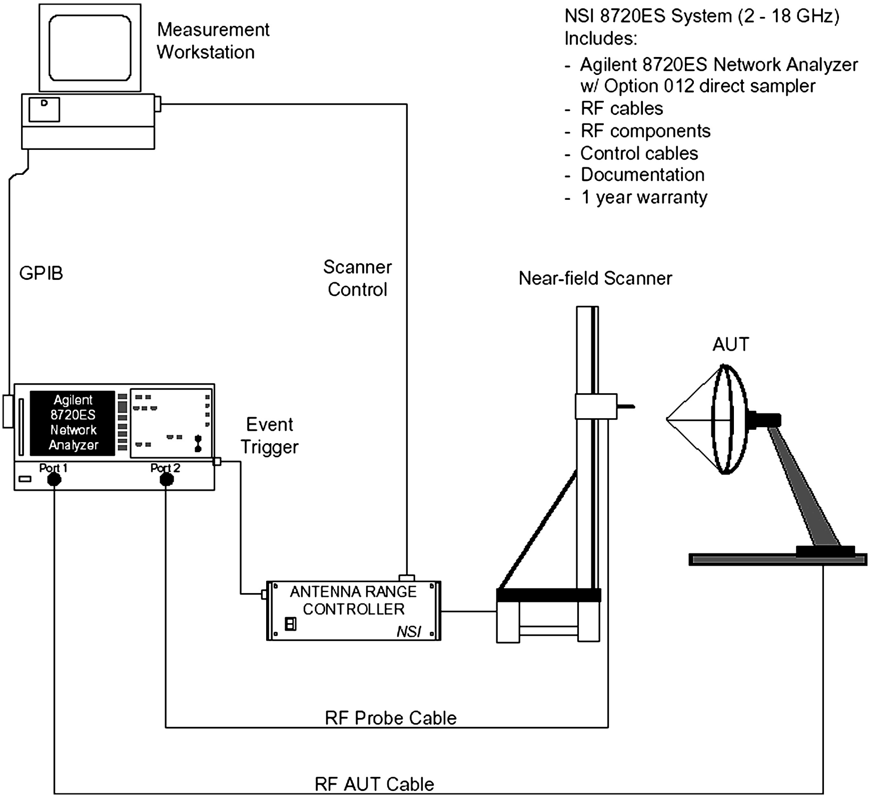

Figure 1.15 NSI VNA antenna measurement system based on the NSI Model 200 V- 5'×5' Near-Field Vertical Scanner and the Agilent 8720ES Vector Network Analyzer

both the magnitude and phase of the received data, the testing probe can be linearly polarized. After the measurement for the two orthogonal polarization components, the left-hand or right-hand circular polarization component can be computed using the complex data collected as given in Eq. 1.7 and Eq. 1.8. If the measurement system can only get the magnitude but not the phase of the data, the measurement may be carried out twice, once using the left-hand polarized testing probe and then once using the right-hand polarized probe, to get the two circularly polarized components (copular and cross-polar, respectively). These two methods require two measurements. Another convenient way of avoiding having to perform two measurements is to use a linearly polarized testing probe rotating at a rate much faster than that of the antenna under test. The resulting pattern is an oscillating pattern called an *axial ratio pattern*, as shown in Figure 1.16. The difference of the two envelops gives the axial ratio. This method can be applied to a system

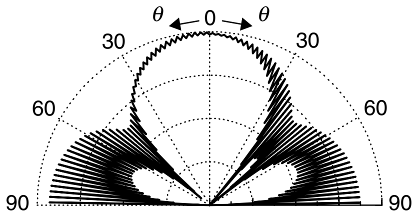

Figure 1.16 Example of an axial ratio pattern

that is able to get only the magnitude of the data. The two envelops are presented by E_1 and E_2 as

$$\begin{aligned} E_1(\theta,\phi) &= E_c(\theta,\phi) + E_x(\theta,\phi) \\ E_2(\theta,\phi) &= E_c(\theta,\phi) - E_x(\theta,\phi) \end{aligned} \tag{1.27}$$

From E_1 and E_2 the axial ratio that is used as a measure of the quality of the circular polarization is given as

$$|\mathrm{AR}(\theta,\phi)| = 20\log\left|\frac{E_1(\theta,\phi)}{E_2(\theta,\phi)}\right| \tag{1.28}$$

Usually the AR is measured for the main beam and is given as

$$|\mathrm{AR}| = |\mathrm{AR}(0,0)| \tag{1.29}$$

1.3.3 Measurement Systems for Intermodulation

The intermodulation phenomenon exists in nonlinear devices working in a high-power environment. Intermodulation is widely discussed for the design of power amplifiers. Similarly, for a base station transmitting antenna, which emits high power, the intermodulation exists due to the metal/metal joint and material nonlinearity. The intermodulation is a kind of interference that should be suppressed. Suppose two closely located fundamental frequencies, f_1 and f_2, are transmitted by the antenna; due to nonlinearity, the radiated field has components at the frequencies of f_1, f_2, $2f_1$, $2f_2$, $3f_1$, $3f_2$, f_1+f_2, f_1-f_2, $2f_1-f_2$, $2f_2-f_1$, and so on. Since f_1 and f_2 are close to each other, the 3rd order intermodulation components at $2f_1-f_2$ and $2f_2-f_1$ are very close to the fundamental frequencies and are difficult to remove using filters, thus introducing interferences.

To measure the 3rd order intermodulation, the antenna under test operates at a transmitting mode and the testing probe operates at a receiving mode. The testing probe should have a very good linearity within a large dynamic range of power levels in order not to introduce measurement errors. When measuring, the antenna under test is excited by a given power level at two close fundamental frequencies, and the fundamental and 3rd order intermodulation components are measured and recorded on the receiving side. The operation is repeated for different input power levels, and finally it gives two curves—one is the received power level of the fundamental component versus input power, and the other one is the received power level of the 3rd order intermodulation component versus input power. From the two curves, we can obtain the 3rd order intercept point, which indicates the power dynamic range of the antenna under test for linear operation. Figure 1.17 shows an example of measurement systems for intermodulation in an anechoic chamber, which is installed at the City University of Hong Kong, SAR, China.

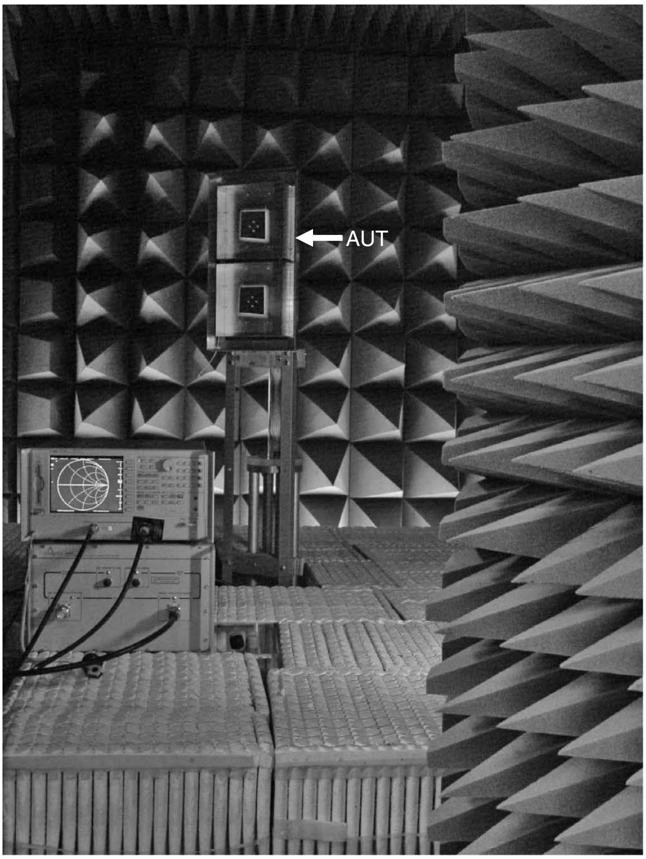

Figure 1.17 Example of measurement systems for passive intermodulation (Facility is available at the State Key Laboratory of Millimeter Waves at City University of Hong Kong.)

1.4 System Calibration

Gain and Polarization Calibrations of Standard Antennas This calibration service is offered primarily for determining the absolute on-axis gain and polarization of standard gain horns, which, in turn, are used as reference standards in determining the gain and polarization of other antennas by the gain comparison technique. The antennas need not be identical. This method is the most accurate technique known for absolute gain and polarization measurements. For gain measurements, the uncertainties are typically 0.10–0.15 dB. Uncertainties of 0.05 dB/dB for polarization axial ratio measurements are typical.

Near-Field Scanning Techniques With this technique, gain, pattern, and polarization parameters are calculated from near-field amplitude and phase measurements taken over a surface close to the test antenna. The absolute gain can be determined to within about 0.2 dB, the polarization axial ratio to within about 0.10 dB/dB, and sidelobe levels down to –50 dB or –60 dB. The exact uncertainties in these parameters will depend on such factors as the frequency, type, and size of antenna. Calibrated probes are normally required for these measurements. In order to achieve accurate results with the planar, cylindrical, or spherical near-field method, the transmitting or receiving properties of the probe must be known. With this information, the measured data can be corrected for the nonideal pattern and polarization properties of the probe. Probes are characterized by a three-step process: (1) The on-axis gain and polarization properties are measured using the technique described; (2) the far-field amplitude and phase patterns are measured for two nominally orthogonal polarizations of the incident field; and (3) the on-axis and pattern data are combined to obtain the probe correction coefficients at the desired lattice points for the measurement surface specified.[5, 31]

1.5 Remarks

In this chapter, we briefly presented the fundamental parameters of the antenna so beginning engineers can quickly grasp the meaning of antenna parameters. We also gave examples of different printed and simple antennas and their advantages and disadvantages. In addition, we touched on the measurement techniques for antenna parameters. We indicated the significance of the calibration of these systems to provide reliable measurements. The reader who needs more detail should refer to the references provided.

References

1. C. A. Balanis, *Antenna Theory Analysis and Design*, New York: John Wiley & Sons, Inc., 2005; C. A. Balanis, *Modern Antenna Handbook*, New York: John Wiley & Sons, Inc., 2008.
2. S. Drabowitch, A. Papiernik, H. D. Griffiths, and J. Encinas, *Modern Antennas,* 2nd edition, New York: Springer, 2005.
3. J. de Kraus and R. J. Marhefka, *Antennas for All Applications,* 3rd edition, New York: McGraw-Hill Science/Engineering/Math, 2001.
4. W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design,* New York: John Wiley & Sons, Inc., 1981.
5. *ANSI/IEEE Standard Test Procedure for Antennas,* ANSI/IEEE Std 149, New York: John Wiley Distributors, 1979.
6. Richard C. Johnson and Henry Jasik, *Antenna Engineering Handbook*, 2nd edition, New York: McGraw-Hill Book Company, 1984.
7. Summitek Instruments, www.summitekinstruments.com.
8. S. Hienonen, "Studies on microwave antennas: passive intermodulation distortion in antenna structures and design of microstrip antenna elements," Dissertation, Helsinki University of Technology Radio Laboratory, Espoo Finland, March 2005.
9. Ramesh Garg, R. B. Garg, P. Bhartia, Prakash Bhartia, Apisak Ittipiboon, and I. J. Bahl, *Microstrip Antenna Design Handbook*, New York: Artech House Inc., 2000.
10. P. L. Sullivan and D. H. Schaubert, "Analysis of an aperture coupled microstrip antenna," *IEEE Transaction on Antennas and Propagation*, vol. 34, no. 8 (August 1986).
11. D. M. Pozar, "A reciprocity method of analysis for printed slot and slot-coupled microstrip antennas," *IEEE Transaction on Antennas and Propagation*, vol. 34, no. 12 (August 1986).
12. K. Wu, J. Litva, and R. Fralich, "Full wave analysis of arbitrarily shaped line-fed microstrip antennas of arbitrary shape," *Proc. IEE, Pt. H*, vol. 138 (1991): 421–428.
13. A. K. Schackelford, K. F. Lee and K. M. Luk, "Design of small-size wide-bandwidth microstrip patch antenna," *IEEE Antennas and Propagation Magazine*, vol. 45, no. 1 (February 2003).
14. P. Besso, D. Finotto, D. Forigo, and P. Gianola, "Analysis of aperture-coupled multi-layer microstrip antennas," *IEEE Antennas and Propagation Society International Symposium Digest*, vol. 3 (28 June to 2 July 1993): 122 –1227.
15. K. M. Luk, C. L. Mak, Y. L. Chow, and K. F. Lee, "Broadband microstrip patch antenna," *Electronics Letters*, vol. 34 (1998): 1442–1443.
16. K. F. Lee and R. Chair, "On the use of shorting pins in the design of microstrip patch antennas," *Transactions—Hong Kong Institution of Engineers,* vol. 11, no. 4 (2004).
17. Z. N. Chen and M. Y. W. Chia, *Broadband Planar Antennas,* New York: John Wiley & Sons, Inc., 2006.
18. G. Mayhew-Ridgers, J. W. Odendaal, and J. Joubert, "Single-layer capacitive feed for wideband probe-fed microstrip antenna elements," *IEEE Transactions on Antennas and Propagation,* vol. 51, no. 6 (June 2003): 1405–1407.
19. Z. N. Chen, "Impedance characteristics of probe-fed L-shaped plate antenna," *Radio Science*, vol. 36, no. 6 (2001): (1377–1383).
20. Z. N. Chen, M. Y. W. Chia, and C. L. Lim, "A stacked suspended plate antenna," *Microwave and Optical Technology Letters,* vol. 37, no. 5 (June 5, 2003): 337–339.
21. P. K. Panayi, M. Al-Nuaimi, and L. P. Ivrissimtzis, "Tuning techniques for the planar inverted-F antenna," *IEE National Conference on Antennas and Propagation,* no. 461 (30 March–1 April 1999).
22. M. Tong, M. Yang, Y. Chen, and R. Mittra, "Design and analysis of a stacked dual-frequency microstrip planar inverted-F antenna for mobile telephone handsets using the FDTD," *IEEE Antennas and Propagation Society International Symposium*, vol. 1 (2000): 270–273.

23. M. C. Huynh and W. Stutzman, "Ground plane effects on the planar inverted—F antenna (PIFA) performance," *IEE Proc. Microwave Antennas and Propagation,* vol. 150, no. 4 (August 2003): 209–213.
24. L. Zaid and R. Staraj, "Miniature circular GSM wire patch on small ground plane," *Electronic Letters,* vol. 38 (February 2002): 153–154.
25. T. K Lo and Y. Hwang, "Bandwidth enhancement of PIFA loaded with very high permittivity material using FDTD," *IEEE Antennas and Propagation Society International Symposium,* vol. 2 (June 1998): 798–801.
26. T. K Lo, J. Hoon, and H. Choi, "Small wideband PIFA for mobile phones at 1800 MHz," *IEEE Vehicular Technology Conference,* vol. 1 (May 2004): 27–29.
27. C. R. Rowell and R. D. Murch, "A capacitively loaded PIFA for compact mobile telephone handsets," *IEEE Trans. Antennas and Propagation,* vol. 45, no. 5 (May 1997): 837–842.
28. N. P. Agrawall, G. Kumar, and K. P. Ray, "Wide-band planer monopole antenna," *IEEE Transactions on Antennas and Propagation,* vol. 46, no. 2 (1998): 294–295.
29. K. Wong, C. Wu, and S. Su, "Ultra-wideband square planar metal-plate monopole antenna with a trident-shaped feeding strip," *IEEE Transactions on Antennas and Propagation,* vol. 53, no. 4 (April 2005): 1262–1268.
30. K. Wong, C. Wu, and F. Chang, "A compact wideband omnidirectional cross-plate monopole antenna," *Microwave and Optical Technology Letters,* vol. 44, no. 6 (March 20, 2005).
31. G. E. Evans, *Antenna Measurement Techniques,* New York: Artech House Inc., 1990.