AN4190
Application note

Antenna selection guidelines

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Introduction

The antenna is a very important component of communication systems. By definition, an antenna is a device used to transform an RF signal, travelling on a conductor, into an electromagnetic wave in free space (transmit mode), and to transform an RF electromagnetic wave into an electrical signal (receive mode).

The choice of antenna is very important for a transmitting - receiving communication system. The antenna must be able to radiate or receive efficiently so the power supplied is not wasted.

This application note describes the most important parameters to consider when deciding what kind of antenna to use in a short range device application.

In the first section of this application note the antenna theory is covered. The main antenna parameters such as radiation pattern, gain, impedance matching, bandwidth, size and others are discussed.

In the second part of this document different antenna types are presented.

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1 Antenna theory

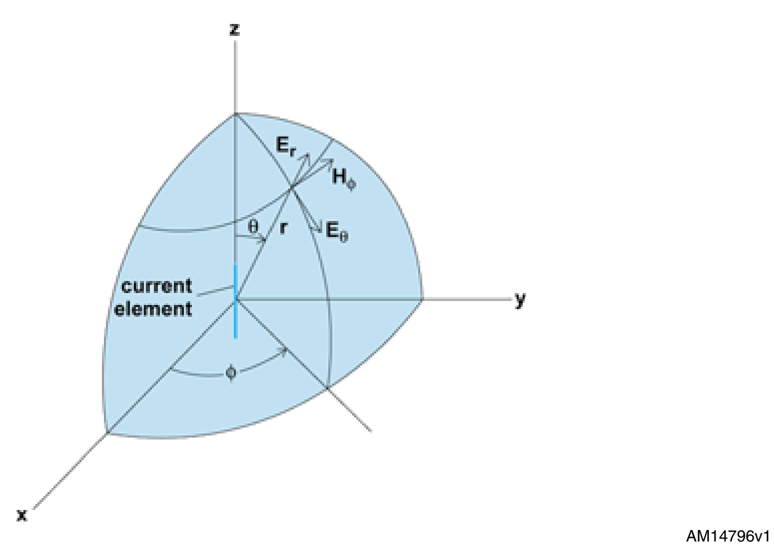
Antenna performance parameters and the language used to describe antennas can be confusing and sometimes even misleading. While much can be said in general about what constitutes a good antenna, most designs reflect some sort of compromise or trade-off between the various desirable attributes because antenna design involves conflicting goals. Therefore, it is crucial that antenna specifications are reviewed in light of the intended application. A more complete and accurate understanding of the terminology associated with antennas allows the most appropriate antenna for a given task to be specified. A great deal of effort has been made over the years to standardize antenna terminology. The “de facto” standard is the IEEE Standard Definitions of Terms for Antenna, so in this document the main antenna parameters as defined in this standard are given.

The purpose of this document is to give a brief and easy description of antenna parameters. For a complete and rigorous description of antenna behavior, the reader is requested to refer to the book “Antenna theory: analysis and design” [*1*].

1.1 Antenna and radiation pattern

An antenna radiation pattern is defined in the IEEE standard as “the spatial distribution of a quantity which characterizes the electromagnetic field generated by an antenna”. In other words, an antenna radiation pattern or antenna pattern is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates, as shown in *Figure 1*. Radiation properties include power flux density, radiation intensity, field strength, and directivity phase or polarization.

Figure 1. Coordinate system for antenna analysis



In most cases, the radiation pattern is determined in the far field region and is represented as a function of the directional coordinates. That is, in spherical coordinates the distribution of the quantity over Θ and Φ for fixed radius (see *Figure 1*).

The interpretation of an antenna's radiation pattern can become problematic because of the three-dimensional nature of the information. The complexity of a three-dimensional plot of a radiation pattern can sometimes obfuscate details. In practice, a three-dimensional plot of a radiation pattern is of limited value in presenting quantitative information. Therefore, two-dimensional “cuts” of the radiation pattern are often presented. In particular, cuts in the so-called E and H planes are often presented.

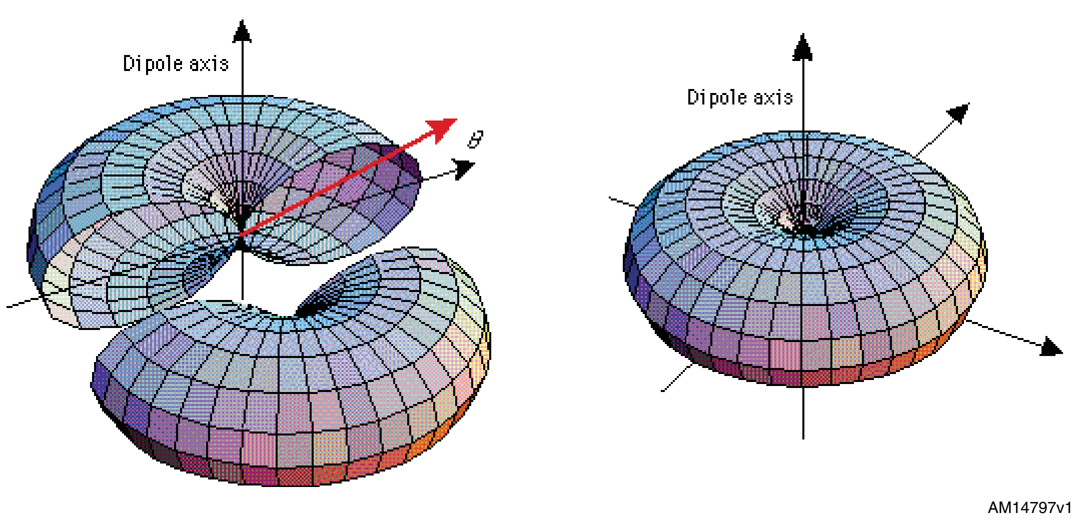
1.1.1 Isotropic, directional and omnidirectional patterns

An *isotropic* radiator is defined as a “hypothetical” lossless antenna having equal radiation in all directions. Although it is ideal and not physically realizable, it is taken as a reference for expressing the directive properties of actual antennas.

A *directional* antenna is one having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others.

An *omnidirectional* antenna is defined as one having an essentially non-directional pattern in a given plane and a directional pattern in any orthogonal plane. An omnidirectional pattern is a special type of directional pattern. An example of an antenna with an omnidirectional radiation pattern in the x - y plane is shown in *Figure 2*.

Figure 2. x - y plane omnidirectional antenna pattern



1.1.2 Principal patterns

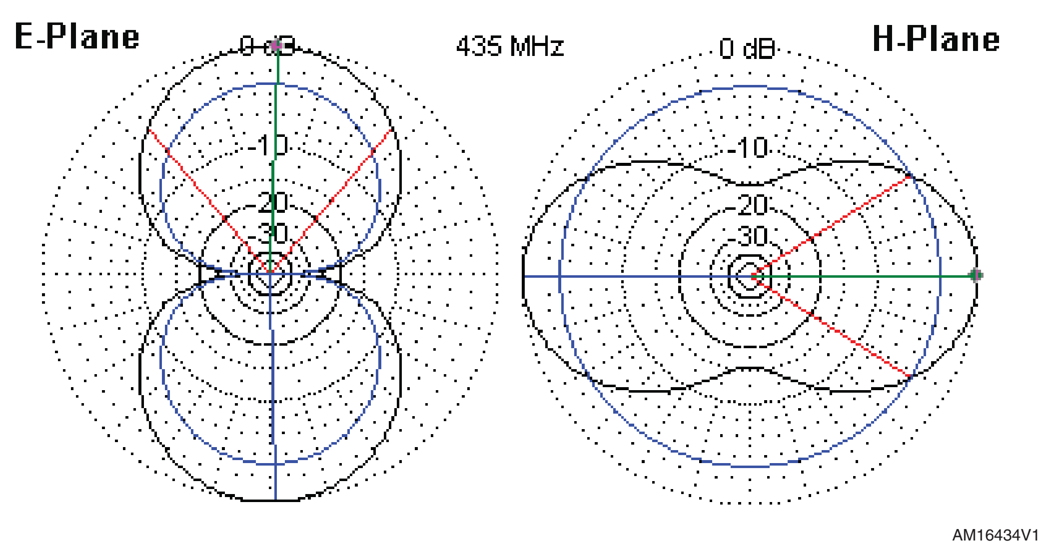
For a linearly polarized antenna, performance is often described in terms of its principal E and H plane patterns.

The E plane is defined as the plane containing the electric field vector and the direction of maximum radiation.

The H plane is the plane containing the magnetic field vector and the direction of a maximum radiation.

The principal E and H planes are orthogonal planes. It is often sufficient to examine only E and H plane cuts of the three-dimensional radiation pattern. An example of E and H plane radiation patterns is shown in *Figure 3*.

Figure 3. E and H plane radiation patterns



1.1.3 Field regions

Various parts of a radiation pattern are referred to as lobes, which may be sub-classified into major or main, minor, side and back lobes.

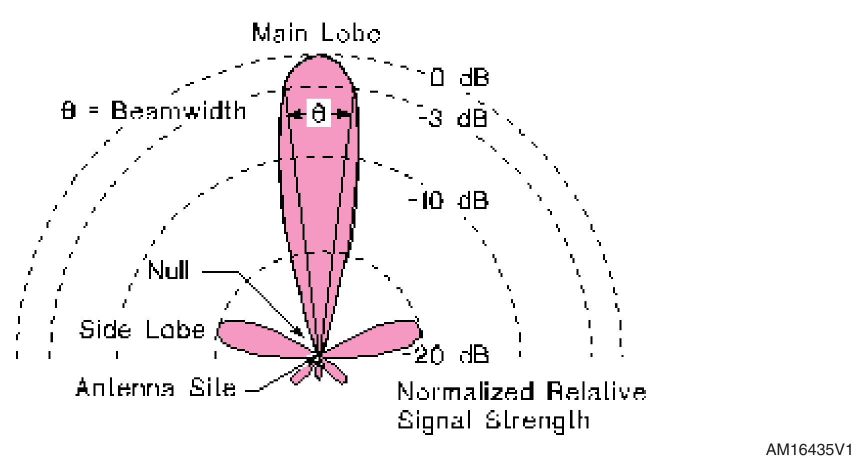
A *radiation lobe* is a portion of the radiation pattern bounded by regions of relatively weak radiation intensity. *Figure 4* demonstrates a symmetrical three-dimensional polar pattern with a number of radiation lobes.

A *major lobe* (also called main beam) is defined as the radiation lobe containing the direction of maximum radiation.

A *minor lobe* is any lobe except the major lobe. Minor lobes usually represent radiation in undesired directions and they should be minimized.

The *beamwidth* is the angle, expressed in degrees, between the half power (-3 dB) points of the main lobe, when referenced to the peak effective radiated power of the main lobe.

Figure 4. Field regions



1.1.4 Radiation pattern lobes

The space surrounding an antenna is usually sub-divided into three regions:

- Reactive near field
- Radiating near field, also called Fresnel region
- Far field, also called Fraunhofer region.

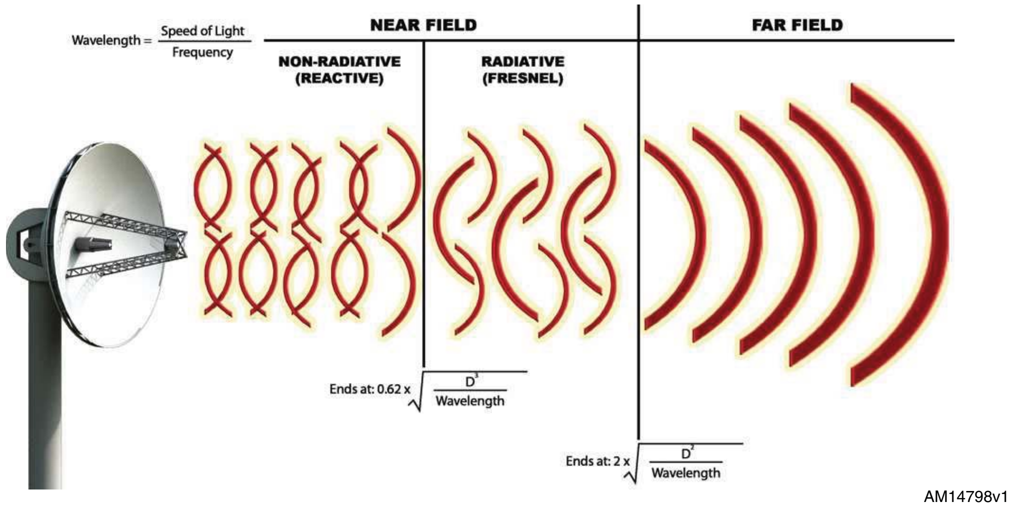
In the *reactive near field region* of an antenna, the non-radiating field components dominate. The term reactive near field arises from the fact that for a non-resonant antenna such as an electrically small dipole, reactive power circulates between the reactive near field and the source, an external matching network, or both. The strict IEEE definition is “that portion of the near field region immediately surrounding the antenna, wherein the reactive field dominates”. Therefore, for dipole-like antennas, the energy in this region is predominantly either electric or magnetic. For electrically small antennas, the reactive near field is taken to extend to a distance of approximately $R \sim \lambda / 2\pi$ from the antenna.

In the *radiating near field*, the radiation fields predominate but the angular field distribution is dependent on the distance from the antenna. The strict IEEE definition is “that portion of the near field region of an antenna between the far field and the reactive portion of the near field region, wherein the angular field distribution is dependent upon distance from the antenna”. If the antenna is large, compared to a wavelength, the outer boundary of the radiating near field is taken to be $R \sim 2D^2 / \lambda$.

The *far field region* of an antenna is the region surrounding an antenna which is sufficiently far from the antenna such that only the radiating field components are significant. In other words, the far field is that region of the field of an antenna where the angular field distribution is essentially independent of the distance from a specified point in the antenna region. In the far field, the field components are orthogonal and an equipartition of energy between electric and magnetic stored energy exists.

In *Figure 5* the separation between the three different regions is shown.

Figure 5. Near and far field regions



1.2 Radiation density and intensity

Electromagnetic waves are used to transport information through a wireless medium or a guiding structure, from one point to the other. It is, then, natural to assume that power and energy are associated with electromagnetic fields. It is possible to demonstrate [*1*] that the power density associated with the electromagnetic fields of an antenna in its far field region is predominately real and is referred to as *radiation density.*

Radiation *intensity* in a given direction, instead, is defined as the power radiated from an antenna per unit solid angle. The radiation intensity is a far field parameter, and can be obtained multiplying the radiation density by the square of the distance.

1.3 Directivity

Directivity of an antenna is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divided by 4Π If the direction is not specified, the direction of maximum radiation intensity is implied.

For an isotropic source, it is very obvious that the directivity is unity since its power is radiated equally well in all directions. For all other sources, the maximum directivity is always greater than unity. It is a relative “figure of merit” which gives an indication of the directional properties of the antenna as compared with those of an isotropic source.

1.4 Antenna gain

Gain is perhaps the most widely used descriptor for antenna performance. However, more than one definition or interpretation is in common use. Most antennas are passive devices and hence do not have power gain in the sense that an amplifier may exhibit power gain. But when viewed from the standpoint of a distant receiver, a particular antenna may radiate much more power in a given direction than an isotropic antenna. Therefore, gain is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4Π So it is very important to understand: **“the gain of a passive antenna doesn't represent any real power gain”**.

Gain is sometimes referenced to something other than a hypothetical isotropic source. Most commonly, gain is referenced to a half-wave linear filamentary dipole. If the gain is referred to the isotropic source, the unit is written as “dBi”. If, therefore, the gain is referred to the half-wave dipole antenna, the unit is written as “dBd”. The gain in dBd = gain in dBi - 2.15 dB.

Gain is defined by the narrow viewpoint of a localized receiver as the ratio of input power required using a perfectly efficient (lossless) isotropic antenna to achieve a particular intensity at a specific location to that required when using the antenna in question. Therefore, an antenna with 3 dB of gain in a particular direction would require half as much power as an isotropic source to achieve the same intensity. Therefore, it can be seen that for the purposes of a link budget, the gain of an antenna can be treated the same as the gain of an active device such as an amplifier.

Note that the total power radiated from an antenna is related to the total input power by a coefficient called antenna radiation efficiency. The greater the radiation efficiency, the greater the energy transmitted or received. According to the IEEE standard, gain doesn't include losses arising from impedance mismatches (reflection losses) and polarization mismatch (losses). This means, therefore, that the gain takes into account only the loss of the dielectric and conduction system of the same antenna. The reflection losses and the polarization mismatch are very important losses and they need to be included in the link calculation of a communication system to determine the received or radiated power.

1.5 Antenna efficiency

If an antenna is taken as a device which accepts power from a source and radiates it into space, the ratio of the power radiated into space to the power accepted from the source is the efficiency ($\eta_{radiation}$), sometimes termed the radiation efficiency. It is defined in the IEEE reference as the ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter. The power that is accepted by the antenna but not radiated is dissipated in the form of heat.

The total antenna efficiency η_0 is used to take into account losses at the input terminals and within the structure of the antenna. In general, the overall efficiency can be written as:

Equation 1

$$\eta_0 = \eta_r \cdot \eta_c \cdot \eta_d$$

where:

η_0 = total efficiency (dimensionless)

η_r = reflection (mismatch) efficiency = $(1 - |\Gamma|^2)$ (dimensionless)

η_c = conduction efficiency (dimensionless)

η_d = dielectric efficiency (dimensionless)

Γ = voltage reflection coefficient at the input terminal of the antenna [$\Gamma = (Z_{in} - Z_o)/(Z_{in} + Z_o)$ where Z_{in} = antenna input impedance, Z_o = characteristic impedance of the transmission line].

Usually η_c and η_d are very difficult to compute.

The radiation efficiency is rarely, if ever, published in any antenna manufacturer's literature. There are several reasons for this: first, radiation efficiency is exceedingly difficult to measure accurately. Second, the radiation efficiency of an antenna is implicitly contained in the complete specifications of the gain of an antenna.

1.6 Antenna bandwidth

The *bandwidth* of an antenna is defined as the range of frequencies within which the performance of the antenna, with respect to some characteristics, conforms to a specific standard. The bandwidth can be considered to be the range of frequencies, on either side of a center frequency (usually the resonance frequency for a dipole), where the antenna characteristics are within an acceptable value of those at the center frequency.

Because the characteristics of an antenna do not necessarily vary in the same manner or are even critically affected by the frequency, there is no unique characterization of the bandwidth. The specifications are set in each case to meet the needs of the particular application. Usually there is a distinction made between pattern and input impedance variations. Accordingly, pattern bandwidth and impedance bandwidth are used to emphasize this distinction. Associated with pattern bandwidth are gain, side lobe level, and polarization, while input impedance and radiation efficiency are related to impedance bandwidth.

1.7 Antenna polarization

Polarization of an antenna in a given direction is defined as the polarization of the wave transmitted by the antenna. When the direction is not stated, the polarization is taken to be the polarization in the direction of maximum gain. In practice, polarization of the radiated energy varies with the direction from the center of the antenna, so that different parts of the pattern may have different polarizations.

Polarization of a radiated wave is defined as that property of an electromagnetic wave describing the time varying direction and relative magnitude of the electric filed vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation. Polarization, then, is the curve traced by the end point of the arrow representing the instantaneous electric field.

Polarization may be classified as linear, circular or elliptical (see *Figure 6*). If the vector that describes the electric field at a point in space as a function of time is always directed along a line, the field is said to be linearly polarized (horizontally or vertically). In general, however, the figure that the electric field traces is an ellipse, and the field is said to be elliptically polarized. Linear (see *Figure 6*) and circular (see *Figure 7*) are special cases of elliptical polarization, and they can be obtained when the ellipse becomes a straight line or a circle, respectively. The figure of the electric field is traced in a clockwise or counterclockwise sense. Clockwise rotation of the electric field vector is designated as right-hand polarization and counterclockwise as left-hand polarization.

Figure 6. Vertical, horizontal,3 and elliptic polarization

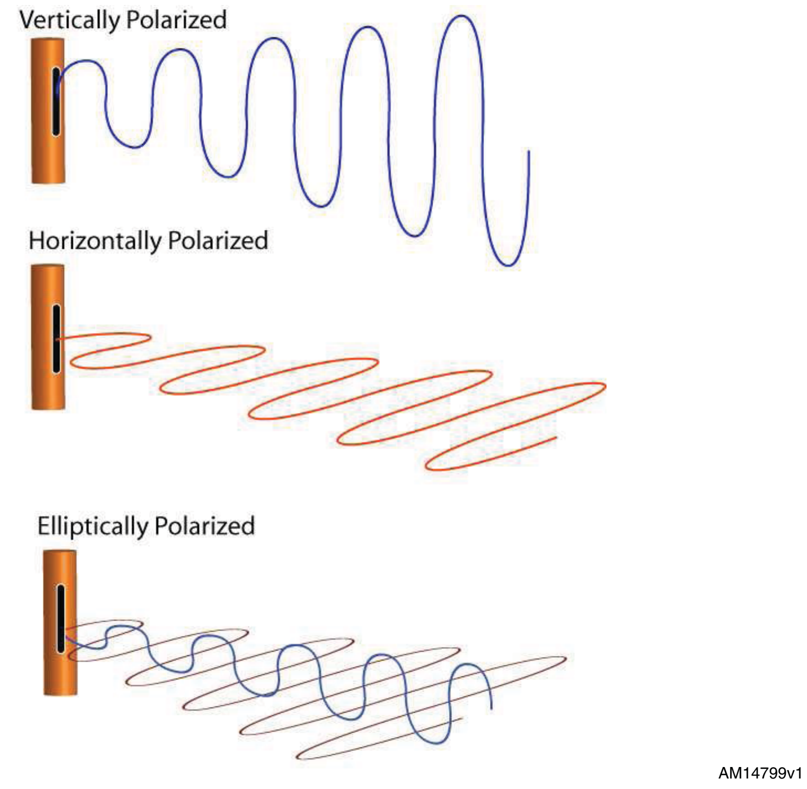
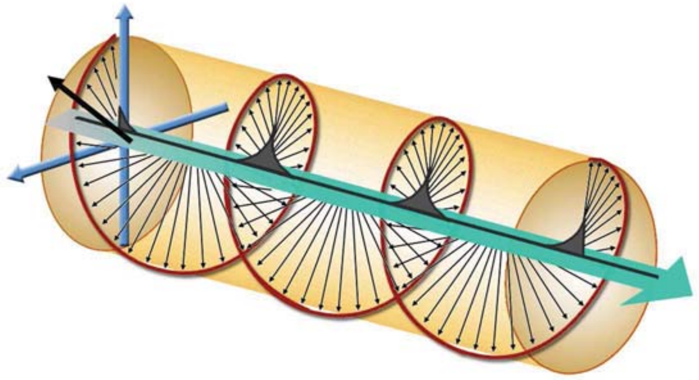


Figure 7. Circular polarization



If the polarization of the receiving antenna is not the same as the polarization of the incoming (incident) wave, the power extracted from the incoming signal is not maximum because of the *polarization loss*. It is very important in a communication system to use antenna with the same polarization and placed physically in such a way as to not change their characteristics. If the antennas are linear polarized, do not place the two antennas orthogonally relative to one another, if the antennas are circular polarized, use both antennas or right polarized or left polarized.

In *Table 1* the ratio from the power received from a receiver antenna and the maximum power transmitted from a transmit antenna as a function of the polarization is shown. If the antennas are the same, all the transmitted power is received, if the antennas are opposite, for instance vertical in TX and horizontal in RX, the power received is zero.

Table 1. Ratio of power received to maximum power

Transmit antenna polarization	Receive antenna polarization	Ratio of power received to maximum power	
		Ratio	Ratio [dB]
Vertical	Vertical	1	0
Vertical	45 or 135 degree	½	-3
Vertical	Horizontal	0	-∞
Vertical	Circular (right or left)	½	-3
Horizontal	Horizontal	1	0
Horizontal	45 or 135 degree	½	-3
Horizontal	Circular (right or left)	½	-3
Circular (right-hand)	Circular (right-hand)	1	0
Circular (right-hand)	Circular (left-hand)	0	-∞
Circular (right or left)	45 or 135 degree	½	-3

1.8 Input impedance

The ability of an antenna to accept power from a source is determined by the input impedance the antenna presents. For maximum power transfer, the input impedance should exactly match the output impedance of the source. Strictly speaking, for maximum power transfer the input impedance of the antenna must be the complex conjugate of the source's output impedance. Essentially, all the RF sources exhibit real output impedance, with the vast majority having output impedance of 50 Ω The 50 Ω system impedance level was chosen as the standard coaxial cable impedance and represents a good compromise between dissipative loss and power handling. On the other hand, over a broad bandwidth, the complex input impedance of an antenna differs greatly from 50 Ω

The complex reflection coefficient at the input of the antenna is:

Equation 2

$$\Gamma = (Z_{input} - Z_o) / (Z_{input} + Z_o)$$

where:

Z_{input} = antenna's complex input impedance

Z_0 = source/system impedance

The power reflected is equal to the incident (forward) power multiplied by the square of the magnitude of the complex input reflection coefficient. The reflected power is the fraction of the total power provided to the antenna that returns to the load.

The quality of the input impedance match of the antenna is generally specified by one of two parameters: return loss or standing wave ratio (SWR), sometimes called voltage standing wave ration (VSWR). The return loss indicates how much of the incident power is not reflected or doesn't return from a load. It is the square of the magnitude of the reflection coefficient, usually expressed in logarithmical form as:

Equation 3

$$\mathrm{R.L.} = 20\log_{10}(|\Gamma|)$$

For instance, a return loss of -3.0103 dB indicates that half of the incident power is reflected. Usually a return loss lower than -10 dB is acceptable for a good matching, in this case less than 1% of the signal is reflected.

The standing wave ratio is defined as the ratio of voltage, minimum to maximum, on the input transmission line. It is defined as:

Equation 4

$$\mathrm{VSWR} = (1 + |\Gamma|) / (1 - |\Gamma|)$$

One utility in the VSWR for describing input matching is that while the magnitude of the reflection coefficient ranges from 0 to –infinity in logarithmical form, the magnitude of the VSWR ranges from 1 to infinity in linear form. The VSWR then is particularly useful for describing input match when the match is not very good. A VSWR of 5.83 corresponds to -3.01 dB return loss. A good matched antenna is one that has a VSWR lower than 2.

1.9 Effective isotropic radiated power

Effective isotropic radiated power (EIRP), also called equivalent isotropic radiated power, is the amount of radiated power measured in a single direction (that is, for a fixed Θ and Θ).

Typically, for an antenna radiation pattern measurement, if a single value of EIRP is given, this is the maximum value of the EIRP over all measured angles.

The EIRP can also be thought of as the amount of power that a perfectly isotropic antenna would need to radiate to achieve the measured value.

The EIRP can be related to the power transmitted from the radio (P_t), the network and mismatch losses (L), and the antenna gain (G) by:

Equation 5

$$\mathrm{EIRP} = P_t - L + G$$

In built-up areas, regulations may restrict the EIRP of a transmitter to prevent exposure of personnel to a high power electromagnetic field; however, the EIRP is normally restricted to minimize interference to services on similar frequencies.

2 Antennas for low power applications

For wireless communication systems, the antenna is one of the most critical components. A good design of the antenna can relax system requirements and improve overall system performance. A typical example is a TV, for which the overall broadcast reception can be improved by utilizing a high performance antenna.

A good antenna requires it to be the right type for the application. It must also be matched and tuned to the transmitter and receiver.

An introduction and brief discussion of some forms of the various antenna types that can be used for low power applications is given here.

2.1 Linear antenna

Wire antennas, linear or curved, are some of the oldest, simplest, cheapest, and in many cases most versatile, antennas for many applications. They are familiar to the layman because they are seen virtually everywhere - on automobiles, buildings, ships, aircraft, spacecraft and so on. There are various shapes of linear antenna such a straight wire (dipoles, monopoles), loop, helix and so on.

2.1.1 Dipole antenna

A dipole antenna is a radio antenna that can be made of a simple wire, with a center fed driven element. It consists of two metal wire-rod conductors, in line with each other, with a small space between them. The radio frequency voltage is applied to the antenna at the center, between the two conductors. These antennas are the simplest practical antennas from a theoretical point of view.

The half-wave dipole antenna is the basis of many other antennas and is also used as a reference antenna for the measurement of antenna gain and radiated antenna density. At the frequency of resonance, i.e. at the frequency at which the length of the dipole equals a half-wavelength, we have a minimum voltage and a maximum current at the termination in the center of the antenna, as shown in *Figure 8*; the impedance is minimal. This is a simple antenna that radiates its energy out toward the horizon (perpendicular to the antenna). The resulting 3D pattern looks kind of like a donut or a bagel with the antenna sitting in the hole and radiating energy outward (see *Figure 9*). The strongest energy is radiated in the plane perpendicular to the antenna. The gain of the half-dipole is approximately 2.2 dBi.

Figure 8. Half-wave dipole antenna voltage and current distribution

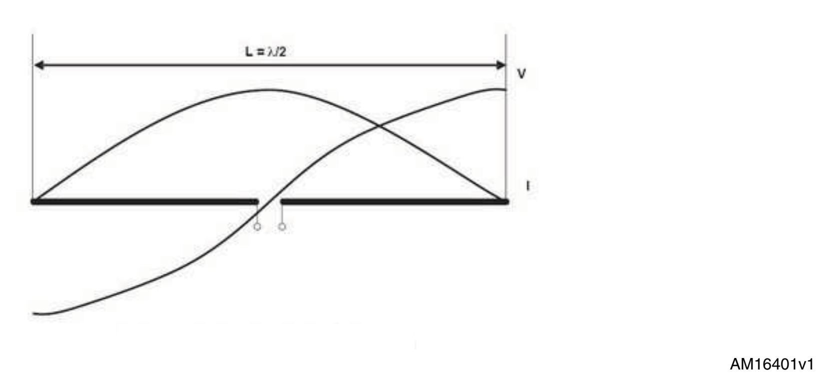
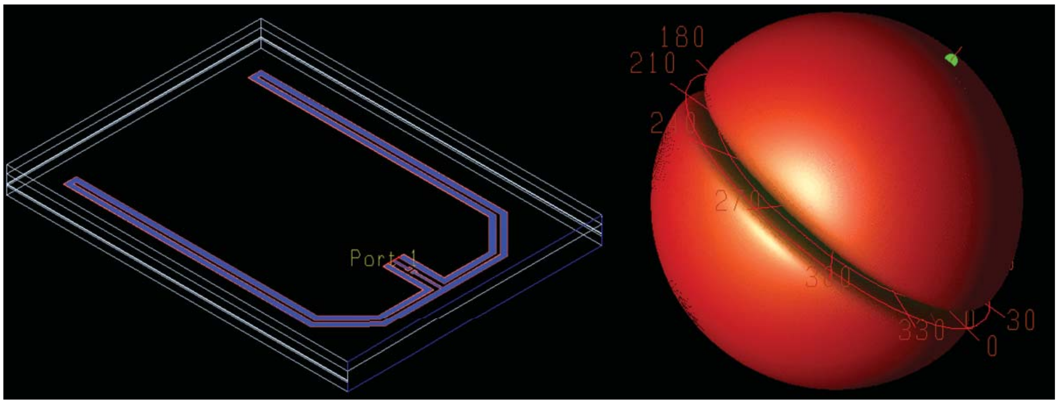


Figure 9. Half-wave dipole antenna model and radiation patterns



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When the frequency is quite low, the wavelength becomes very long, so the half-wave dipole antenna is unpracticable. In this case a short dipole antenna can be used.

The short dipole antenna is the simplest of all the antennas. It is an open circuited wire fed at its center. The word short always implies relative to a wavelength. So the absolute size of the above dipole antenna does not matter, only the size of the wire relative to the wavelength of the frequency of the operation is important. Typically, a dipole is short if its length is less than a tenth of a wavelength.

The directivity of the center fed short dipole antenna depends only on the sin of the polar angle component. It is calculated to be 1.76 dB, which is very low for realizable antennas.

The polarization of the short dipole antenna is linear, as for all dipole type antennas. When evaluated in the x-y plane, this antenna is described as vertically polarized, because the E-field is vertically oriented.

2.1.2 Monopole antenna

A monopole antenna, also called whip antenna, is an antenna consisting of one half of a dipole antenna, almost always mounted above some sort of ground plane.

The whip antenna, like a vertical dipole, has an omnidirectional radiation pattern, radiating equal radio power in all azimuthal directions (perpendicular to the antenna's axis), with the radiated power falling off with elevation angle to zero on the antenna's axis. Vertical monopole antennas are widely used for non-directional radio communication, where the direction of the transmitter (or receiver) is unknown or constantly changing, such as broadcast radios, CBs and amateur radios, and even for cellular phones. This is because they transmit (or receive) equally well in all horizontal directions.

All antennas, like any electronic component, have at least two connection points. In the case of the whip, there must be a connection to a ground, even if the ground plane area is nothing more than circuit traces and a battery. The whip and the ground plane combine to form a complete circuit. The electromagnetic field is set up between the whip and the ground plane, with current flowing through the field, therefore completing the circuit. Ideally, a ground plane should spread out at least a quarter wavelength, or more, around the base of the whip. A ground plane can also, ideally, be made smaller, but it affects the performance of the whip antenna. The ground plane area must be considered when designing an antenna.

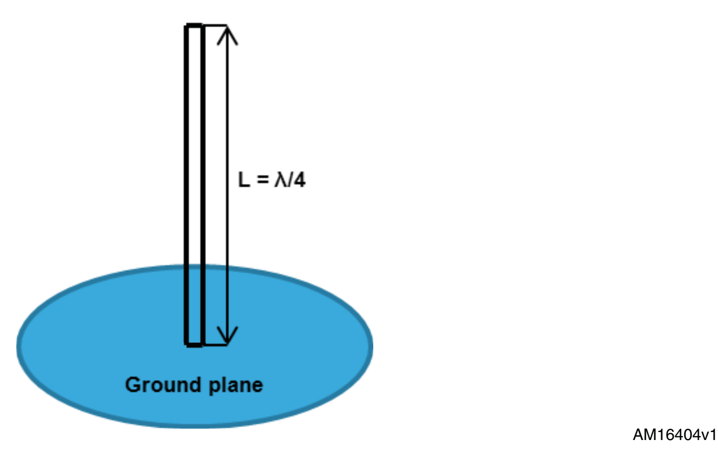
The whip antenna is normally designed as a resonant antenna. Therefore the length of the whip antenna is determined by the wavelength of the radio wave used. The most common length used is one-quarter of the wavelength, called a quarter-wave whip. Half-wave whip antennas are also common.

A quarter-wave whip antenna has a gain 3 dB (twice in linear) greater than a half-dipole if mounted above a perfect ground plane. The quarter-wave monopole antenna design and implementation is shown in *Figure 10*.

Radiation is maximum when broadside, or perpendicular to a wire, so a vertical whip is ideal communication in any direction except straight up. The radiation pattern perpendicular to the whip can be described as omnidirectional. However, the direction of peak radiation has changed from the x-y plane to an angle elevated from the plane. There is a “null”, or signal minimum, at the end of the whip.

The whip antenna polarization is vertical, even though, in the real environment, metal objects and the ground cause reflections, and may cause both horizontal and vertical polarized signal to be present.

Figure 10. Quarter-wave monopole antenna design



A simple alternative to the monopole antenna is to make it shorter than a quarter wavelength and add an inductor near the base of the whip to compensate for the resulting capacitive reactance. This type of antenna can have a performance nearly equal to that of a full size whip.

The monopole antenna, as for the dipole, can be made as a trace on a printed circuit board (PCB). This is very practical at frequencies over 800 MHz. At lower frequencies, a full size monopole may be too long. The length of the monopole is 10 or 20% shorter than the calculation, depending on the dielectric characteristics and thickness of the board.

Derivatives of the monopole are the inverted-L and inverted-F antennas, as shown in *Figure 11* and *12*.

In the inverted-L antenna, the monopole does not run perpendicularly to the ground plane over its whole length but is bent parallel to the ground plane after some distance. This helps to save space, but decreases the radiation resistance because the radiator comes closer to the ground plane. An additional matching circuit is needed to match the low feed impedance to the usual transmission line impedance of 50 Ω

If we proceed from the feed point of the inverted-L antenna to the end, we notice that the voltage increases (while the current decreases) from a maximum voltage value at the feeding point to almost zero at the end. This means that the antenna impedance has its minimum if we feed the antenna as shown in *Figure 11* and increases if we move the feeding point towards the end. The inverted-F antenna is an inverted-L antenna with a feeding tap that gives larger antenna impedance. If the antenna is tapped at the right location, no additional matching circuit is required.

Figure 11. Inverted-L antenna

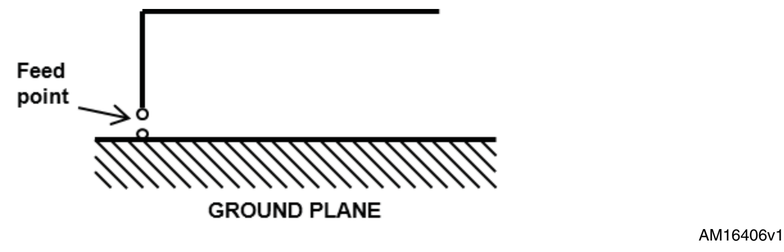
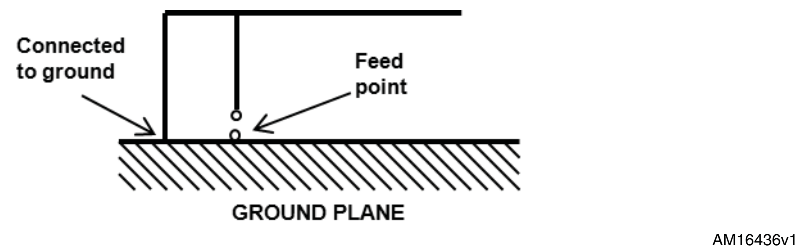


Figure 12. Inverted-F antenna



2.1.3 Loop antenna

The single-turn loop antenna is a metallic conductor bent into the shape of a closed curve, such as a circle or a square, with a gap in the conductor to form the terminals. A multi-turn loop or coil is a series connection of overlaying turns. The loop is one of the primary antenna structures.

The discussion of loop antennas is conveniently divided according to electrical size. Electrically small loops, those whose total conductor length is small compared with the wavelength in free space (less than about one-tenth of a wavelength), are the most frequently encountered in practice. For example, they are commonly used as receiving antennas with portable radios, as directional antennas for radio-wave navigation, or as probes with field-strength meters. Electrically larger loops, particularly those near resonant size (circumference of loop/wavelength ≈ 1), are used mainly as elements in directional arrays.

The small loop antenna is also known as a magnetic loop since it behaves electrically as a coil with a small but not negligible radiation resistance due to its finite size. It can be analyzed as coupled directly to the magnetic field in the near field region, which itself is coupled to an electromagnetic wave in the far field. Loop antennas with electrically small circumferences or perimeters have small radiation resistances that are usually smaller than their loss resistances. Therefore they are very poor radiators, and they are seldom employed for transmission in radio communication. When they are used in any such application, it is usually in the receiving mode, such as in portable radios and pagers, where antenna efficiency is not as important as the signal to noise ratio. The field pattern of electrically small antennas of any shape (circular, elliptical, rectangular, square, etc.) is similar to that of an infinitesimal dipole with a null perpendicular to the plane of the loop and with its maximum along the plane of the loop. As the overall length of the loop increases and its circumference approaches one free space wavelength, the maximum of the patterns shifts from the plane of the loop to the axis of the loop which is perpendicular to its plane.

The radiation resistance of the loop can be increased, and made comparable to the characteristic impedance of the practical transmission line, by increasing (electrically) its perimeter. Another way to increase the radiation resistance of the loop is to insert, within its circumferences or perimeter, a ferrite core of very high permeability which raises the magnetic field intensity and hence the radiation resistance. This form is called ferrite loop.

The loop is entirely different from a monopole, in that both ends of the antenna are terminated. In this case, the end that is opposite the transmitter (or receiver) is grounded. A capacitor is used to tune the antenna to real impedance, instead of a coil.

One advantage of a loop is that it is not easily detuned by nearby hand movements. A disadvantage of loop antennas, besides the poor gain, is the narrow bandwidth which makes tuning extremely critical.

2.1.4 Spiral antenna

Spiral antennas belong to the class of frequency independent antennas; those with a very large bandwidth. The fractional can be as high as 30:1. This means that if the lower frequency is 1 GHz, the antenna may still be in band at 30 GHz, and every frequency in between. An example of a spiral antenna is shown in *Figure 13*.

Spiral antennas are usually circularly polarized. The spiral antenna's radiation pattern typically has a peak radiation direction perpendicular to the plane of the spiral (see *Figure 14*).

Spiral antennas are widely used in the defense industry for sensing applications, where very wideband antennas that do not take up much space are needed. Spiral antenna arrays are used in military aircraft in the 1 - 18 GHz range. Other applications of spiral antenna include GPS, where it is advantageous to have right-hand circularly polarized antennas.

The best known spiral antenna is the log-periodic one. This antenna, also known as the equiangular spiral antenna, has each arm defined by the polar function:

Equation 6

$$r = R_{0e^{a\phi}}$$

where:

R_0 = constant that controls the initial radius of the spiral antenna

a = parameter that controls the rate at which the spiral antenna grows

Figure 13. Spiral antenna

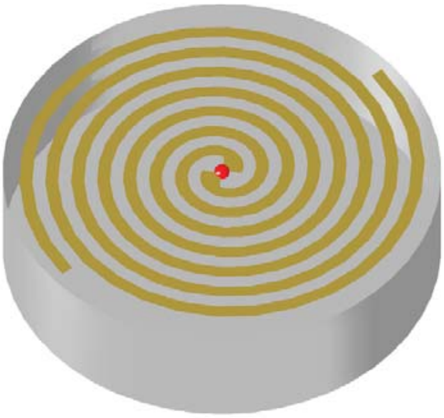
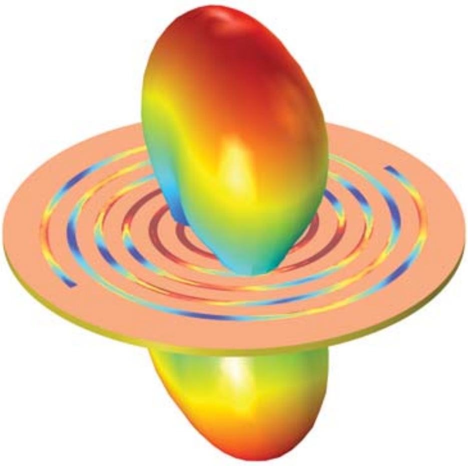


Figure 14. Spiral antenna 3D radiation pattern



The total length of the spiral (or the outer radius) determines the lowest frequency of operation for the spiral antenna. The lowest operating frequency of the spiral antenna is commonly approximated to occur when the wavelength is equal to the circumference of the spiral.

The ‘a’ parameter, called flare rate, is the rate at which the spiral grows with angle. If it is too small, the spiral is tightly wrapped around itself: in this case it behaves more like a capacitor giving poor radiation.

The feed structure determines the high end of the operating band. How tightly the spiral can be wrapped in on itself determines how small the wavelength can be that fits on the spiral and still maintains spiral antenna operation. The highest frequency in the spiral antenna's operating band occurs when the innermost radius of the spiral is equal to lambda/4.

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2.1.5 Helical antenna

A basic, simple and practical configuration of an electromagnetic radiator is that of a conducting wire wound in the form of a screw thread forming a helix. In most cases the helix is used with a ground plane.

The geometrical configuration of a helix, as shown in *Figure 15*, usually consists of N turns, diameter D and spacing S between each turn. Another important parameter is the pitch angle α which is the angle formed by a line tangent to the helix wire and a plane perpendicular to the helix axis.

Helical antennas can operate in one of two principal modes: normal mode or axial mode.

In the normal mode of operation the field radiated by the antenna is maximum in a plane normal to the helix axis and minimum along its axis. To achieve normal mode operation, the dimensions of the helix are usually small compared to the wavelength. These simple and practical antennas were primarily designed to replace very large antennas. Their reduced size is therefore most suitable to mobile and portable communication systems.

A more practical mode of operation, which can be generated with great ease, is the axial or end fire mode. In this mode of operation, there is only one major lobe and its maximum radiation intensity is along the axis of the helix, as shown in *Figure 16*. The minor lobes are at an oblique angle of the axis. To excite this mode, the diameter and spacing must be large fractions of the wavelength. Most often the antenna is used in conjunction with a ground plane, whose diameter is at least lambda/2. The helical antenna that works in axial mode produces circular polarization. In radio transmissions, circular polarization is often used where the relative orientation of the transmitting and receiving antennas cannot be easily controlled, such as animal tracking and spacecraft communications, or where the polarization of the signal may change. Since large helices are difficult to build and unwieldy to steer and aim, the design is commonly employed only at higher frequency.

Figure 15. Helical antenna implementation

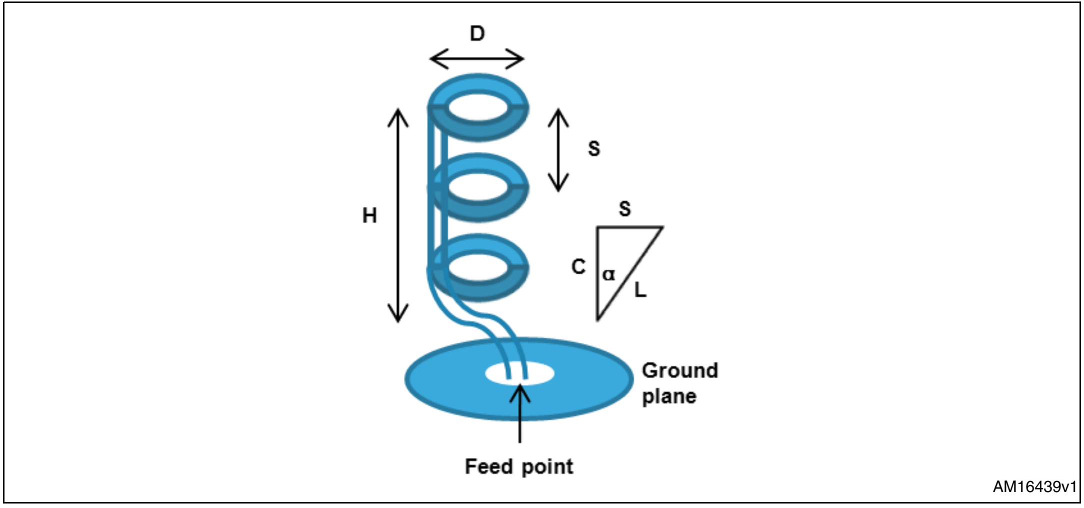
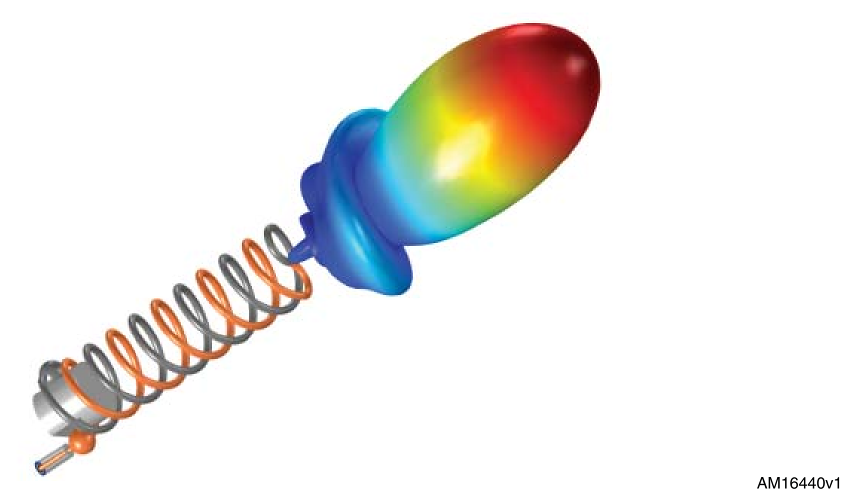


Figure 16. Helical antenna axial mode 3D radiation pattern



2.2 Microstrip patch antenna

Microstrip antennas became very popular in the 1970s primarily for space borne applications. Today they are used for government and commercial applications. These antennas consist of a metallic patch on a grounded substrate. The metallic patch can take many different configurations; however the rectangular and circular patches are the most popular because of ease of analysis and fabrication, and their attractive radiation characteristics. Microstrip antennas are low profile, conformable to planar and non-planar surfaces, simple and inexpensive to fabricate and mechanically robust when mounted on rigid surfaces. When the particular patch shape and mode are selected they are very versatile in terms of resonant frequency, polarization, pattern and impedance.

Major operational disadvantages of the microstrip antennas are their low efficiency, low power, high Q (sometimes in excess of 100), poor polarization purity, poor scan performance, spurious feed radiation and very narrow frequency bandwidth, which is typically only a fraction of a percent or at most a few percent.

An example of a microstrip antenna is shown in *Figure 17*. The patch antenna, microstrip transmission line and ground plane are made of high conductivity metal. The patch is of length L, width W, and sitting on top of a substrate of the thickness h with permittivity ε_r. Typically, the thickness h is much smaller than the wavelength of operation, but not much smaller than 0.05 of a wavelength. The length L determines the operative frequency; the width W controls the input impedance. Larger widths can also increase the bandwidth. The width also controls the radiation pattern. The directivity of patch antennas is approximately 5 - 7 dB.

The patch elements radiate primarily linearly polarized waves if conventional feeds are used with no modification. However, circular and elliptical polarizations can be obtained using various feed arrangements or slight modifications. *Figure 18* shows an example of a patch antenna designed at 5.8 GHz left-hand circular polarized used for the Italian and European toll payment systems.

Figure 17. Rectangular microstrip antenna

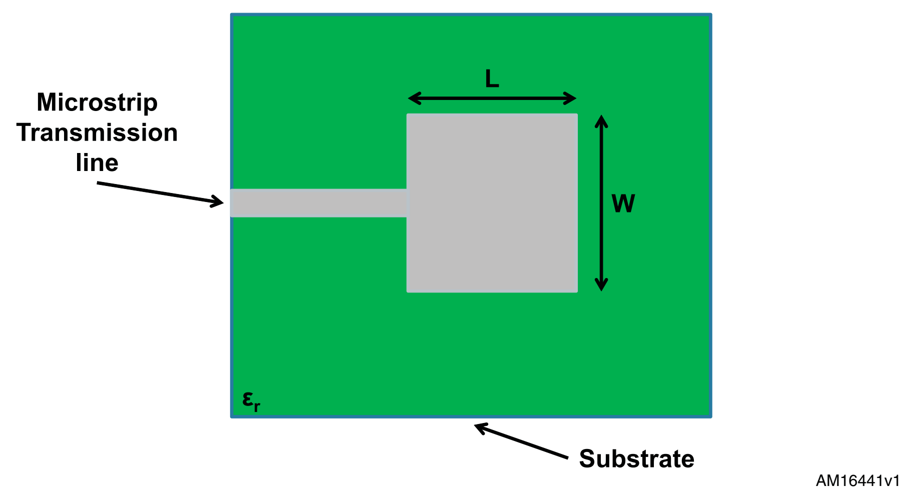
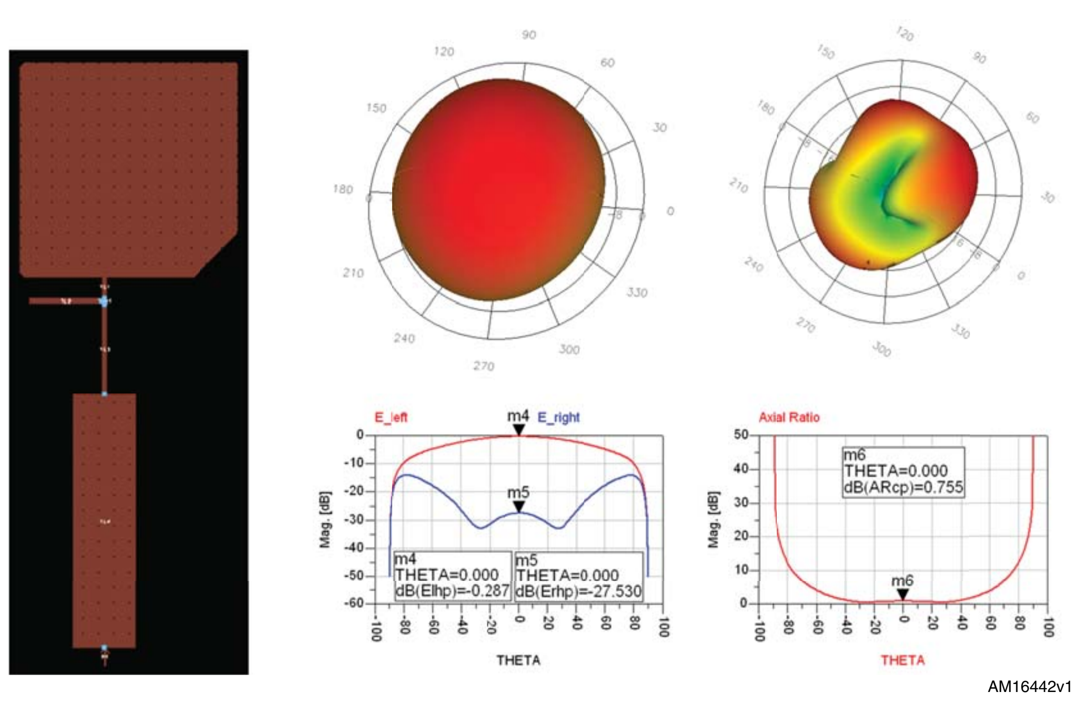


Figure 18. 5.8 GHz patch antenna implementation and characteristics



2.3 Ceramic antenna

The latest entry into the antenna field is the ceramic (chip) antenna. They are surface mount devices made of ceramic material. There are several types of ceramic antennas, each with their own characteristics.

Ceramic antennas offer some advantages: they are separate components, have small sizes and a variety of configurations are available, close proximity to other components doesn't cause as severe a detuning as with trace antennas, they are less affected by environmental factors or human operators than trace antennas, flexible tuning and testing options are possible, and design changes are more easily introduced.

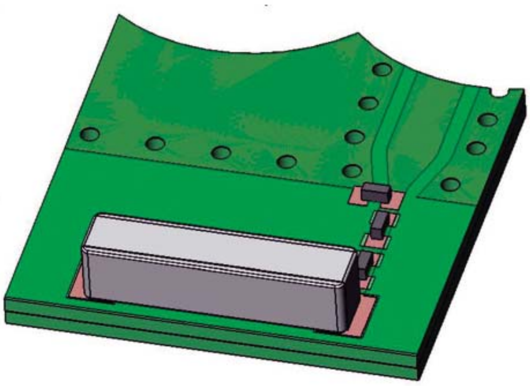
Some disadvantages are also present: the initial cost of the antenna plus logistics can be higher than the cost of others types of antennas, some level of RF expertise is needed for optimal implementation.

Ceramic antennas can be designed in both on-ground and off-ground styles, with on-ground antennas being somewhat taller. The optimal ceramic material composition for the antenna and the electrical specifications selected usually depend on the intended frequency, with an effect on the dimension. Also ceramic antennas can use matching circuits, optional ground clear areas, or a trace for coarse tuning, depending on the application.

This type of antenna can be adapted to small boards and offers flexibility for unique design layouts. The reliability and interference problems associated with being in close proximity to other components or people are greatly reduced with ceramic antennas. Incorporating a separate antenna offers the option of utilizing the full available height of the device, making it possible to have a 3D structure with a smaller PCB area.

An example of a ceramic antenna is shown in *Figure 19*.

Figure 19. Ceramic antenna



2.4 Slot antenna

A slot antenna consists of a metal surface, usually a flat plane, with a hole or slot cut into it. When the plate is driven as an antenna by a driving frequency, the slot radiates electromagnetic waves in a similar way to a dipole antenna. The shape and size of the slot, as well as the driving frequency, determine the radiation distribution pattern.

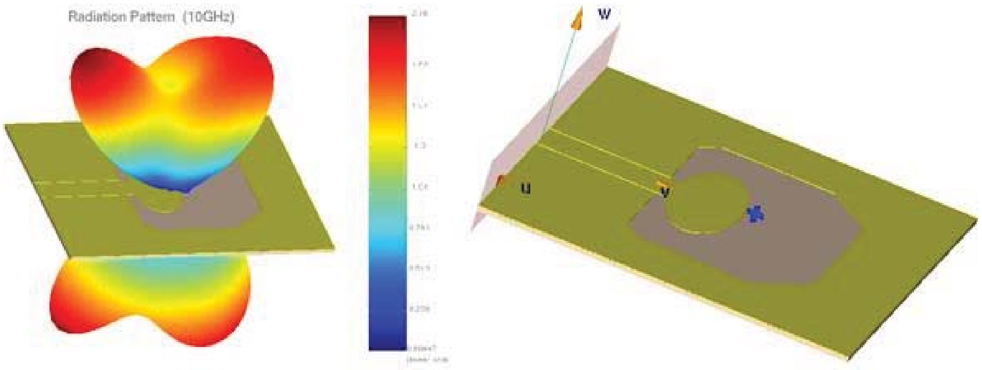
Slot antennas are typically used at UHF and microwave frequencies when greater control of the radiation pattern is required. The slot antenna is popular because it can be cut out of whatever surface it is to be mounted on, and have radiation patterns that are roughly omnidirectional (similar to a linear wire antenna). The polarization of a slot antenna is linear. The slot size, shape, and what is found inside the cavity of the cut-out antenna, offer design variables that can be used to tune performance.

Slot antennas are widely used in radar antennas, for the sector antennas, for cell phone base stations, and are often found in standard desktop microwave sources.

A slot antenna's main advantages are its size, design simplicity, robustness, and convenient adaptation to mass production using PC board technology.

Two examples of slot antenna and relative 3D radiation pattern are shown in *Figure 20*.

Figure 20. Slot antenna implementation and 3D radiation pattern



3 Antenna advantages and disadvantages

After the antenna theory, where the most important parameters of the antennas have been covered, and after the description of the main types of antennas that can be used in the sub-GHz bandwidth, a description of the main advantages and disadvantages of each antenna is shown here.

- *Dipole antenna*: this antenna is a very simple chip and presents a good gain. The main disadvantage is the large size at low frequency.
- *Whip antenna*: this antenna presents good performance with a size lower than a dipole antenna. A good ground plane is necessary to achieve good performance.
- *Loop antenna*: loop antennas are cheap and not easily detuned by nearby hand movements. They have the disadvantage of having poor gain, to be very narrowband and are difficult to tune.
- *Spiral antenna*: spiral antennas have a size lower than a whip antenna and are wideband. On the negative side, these types of antennas are difficult to feed.
- *Helical antenna*: helical antennas are very directive and have good gain. However, they have a bulky size and are easily detuned by nearby objects.
- *Microstrip antenna*: microstrip antennas have the advantage of being very cheap and have a simple and thin structure. As a negative, they are very large at low frequency.
- *Ceramic antenna*: ceramic antennas have the advantage of being separate components, have a small size and are less affected by environmental factors. The main disadvantages are the high cost, the medium performance and the matching function of the PCB size and shape of the ground plane.
- *Slot antenna*: slot antennas have the advantage of size, design simplicity, robustness and convenient adaption to mass production. The main disadvantage is the big dimension for low frequency that makes the slot antenna difficult to manage for frequencies lower than 433 MHz.

The antenna advantages and disadvantages are summarized in *Table 2*.

Table 2. Antenna types advantages and disadvantages

Antenna types	Advantage	Disadvantage
Dipole antenna	– Very cheap – Good gain	– Difficult to design for frequencies lower than 433 MHz – Large size at low frequency
Whip antenna	– Good performance	– High cost
Loop antenna	– Cheap – Not easily detuned by hand movements	– Poor gain – Very narrowband – Difficult to tune
Spiral antenna	– Lower size than whip – Wideband	– Difficult to feed
Helical antenna	– Very directive – Good gain	– Mechanical construction – Bulky size – Easily detuned by nearby objects

Table 2. Antenna types advantages and disadvantages (continued)

Antenna types	Advantage	Disadvantage
Microstrip antenna	– Low manufacturing cost – Simple and very thin structure	– Difficult to design for frequencies lower than 433 MHz – Large size at low frequency – Antenna performance and tuning affected by the PCB design
Ceramic antenna	– Separate component – Small size – Less affected by environmental factors	– High cost – Medium performance – Matching function of PCB size and shape of the ground plane – Difficult to design for frequencies lower than 433 MHz
Slot antenna	– Size – Design simplicity – Robustness	– Difficult to design for frequencies lower than 433 MHz – Large size at low frequency

4 Reference

1. C. A. Balanis, Antenna theory: analysis and design, Second Edition, John Wiley & Sons, Inc., New York, 1997.

5 Revision history

Table 3. Document revision history

Date	Revision	Changes
23-Nov-2012	1	Initial release.

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