ANTENNA TUTORIAL

Phumzile Malindi, Department of Electrical Engineering, Walter Sisulu University, 19 Manchester Road, Chiselhurst, EAST LONDON, 5201, South Africa
pmalindi@webmail.co.za

1.INTRODUCTION

An antenna is a structure or a device that is used to couple the radio system to space; that is, it provides means for radiating or receiving radio waves. During transmission, the antenna radiates the modulated signal produced by the transmitter, in other words, the antenna converts the modulated electrical signal from the transmitter into electromagnetic waves that are propagated using space. In radio receivers, the antenna is used to intercept the electromagnetic radio waves in space and convert them into electric signal that will be further processed by the receiver to recreate the original information. Except for their different functions, transmitting and receiving antennas have identical behavior characteristic; that is, they possess a property called *reciprocity*, which makes the same antenna to be interchangeable between transmitting and receiving functions.

An antenna that radiates equally in all directions is called an *isotropic* radiator, or antenna. Isotropic antenna is a hypothetical radiator with a spherical radiation pattern, and 100 percent efficiency; that is, it does not have losses, so all the power fed to it is radiated. However, on a more practical level, all real antennas radiate better in some directions than others and can not be isotropic. Though an isotropic antenna is a hypothetical antenna, its concept is a very useful one and provides as a standard to which real antennas can be compared.

The other standard is the half-wave dipole which has in its own right a directional pattern compared to an isotropic. Unlike isotropic antenna, the half-wave dipole is a practical antenna which can be built and is therefore a more realistic basis for comparison. So it is important therefore that whenever a comparison is done it is shown clearly whether it is with reference to isotropic or half-wave dipole; for example when expressing the gain, ‘dBi’ must be used when isotropic is a reference and ‘dBd’ must be used when the gain is expressed relative to a half-wave dipole.

2.CLASSIFICATION OF ANTENNAS

There are many ways in which antennas can be classified: firstly, they can be classified according to the way they radiate; for example there are omnidirectional, sectorial and directional antennas; secondly, they can classified according to the range of frequencies of which they operate; for example, there are antennas which are classified as broadband antennas because they can operate over a wide range of frequencies; thirdly, they can be classified according to the band on which they can operate; for example you will hear people talking about LF, MF, HF, VHF or UHF antennas, and fourthly; they can be classified according to the way they are made; for example, there are wire antennas like whip, loop, helix; aperture antennas like the horn; antenna arrays like Yagi-Uda, Log-periodic; Lens antennas, etc. Antennas can also be classified as resonant and non-resonant antennas. Where resonant are those antennas in which current distribution exists as a standing wave and non-resonant antennas are those antennas in which current exists as a travelling wave.

3.FUNDAMENTAL PARAMETERS OF ANTENNAS

3.1 Polarization

Antennas radiate electromagnetic waves, which consists of an *electric field* and *magnetic field* that are at right angles with each other. These two waves oscillate in phase with each other and are perpendicular to the direction of propagation (that is, the direction of propagation is at right angle with both electrical and magnetic field).
The magnetic field always surrounds the current carrying conductor, so it is always perpendicular to it, while electric field is always parallel to the current carrying conductor. Thus, electric and magnetic field are at right angles with each other. This setup also applies after the wave has been radiated (i.e. left the antenna).

The polarization of the wave is determined by the electric field; for example, if the electric intensity vectors are vertical, the wave is said to be vertically polarized, and if they are horizontal, the wave is said to be horizontal polarized. Since the direction of the electric field is always parallel to the radiating conductor, it can be said that the direction of polarization is the same as the direction of the antenna. Thus, vertical antennas radiate *vertical polarized* waves, horizontal antennas radiate *horizontal polarized* waves and helical (helix or spiral) antennas radiate *circular polarized* waves. The energy in the circular polarized waves is divided equally between the horizontal and vertical components, thus making it possible for the circular polarized wave to be received by both horizontal and vertical polarized antennas.

On the receiver, it is important to have the antenna to be of the same orientation as the transmitting antenna (that is, both horizontal, or both vertical), and when using the helical antennas it is important to make sure that both antennas have the same thread orientation (that is, both clockwise, or both counter-clockwise), otherwise the received signal will be significantly reduced due to polarization mismatch. The loss due to polarization mismatch are referred to as *polarisation mismatch loss* and is given by

$$Polarization\ mismatch\ loss = 20\log(\cos\varphi)\ dB \qquad (1.1)$$

where φ is the misalignment angle between the two antennas. From Equation (1.1) it can be deduced that if the two antennas are 90 degrees out-of-phase the loss will be infinite. However, in real situation, though the loss is quite large, it is not infinite.

3.2 Current Distribution and Radiation Pattern

If you take current measurements along an antenna that is fed with a signal you will find different current values at different points along the length of the antenna. The graphical plot of these current values is referred to as *current distribution*. The points at which the current is zero are called *current nodes* and those where current is at maximum are called *current antinodes*, or *current loops*. The current distribution of an antenna depends mainly on its length as shown in Figure 1.

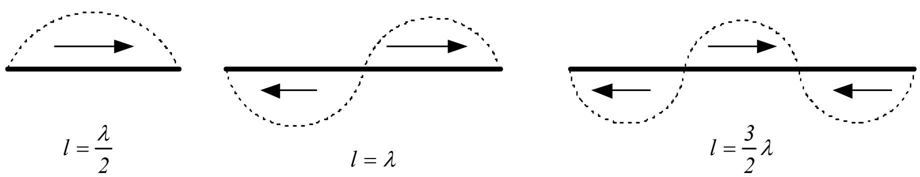


Figure 1 Current distribution of resonant dipoles

Radiation pattern of an antenna is a graphical plot of an antenna as a function of the space coordinates. It includes the plots of radiation intensity; field strength; phase and polarization. The way the antenna radiates depends upon the electrical length of the antenna. Radio antennas produce a three dimensional radiation pattern, but for the purpose of discussion only the azimuthal pattern will be considered; that is, the pattern along the azimuth plane, which is a pattern as seen from the 'bird's eye' view above the antenna. Figure 2 shows the radiation patterns of some resonant dipoles of different lengths.

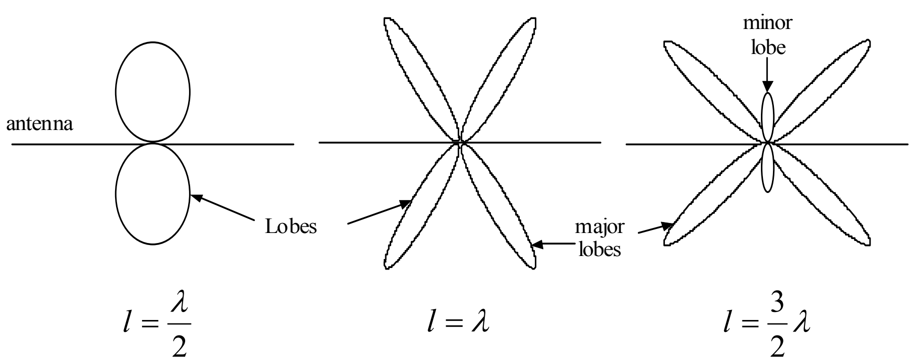


Figure 2 Radiation patterns of various resonant dipoles

When the length of the antenna is the whole wavelength, the polarity of one-half of the antenna is equal and opposite to the other half and this results in fields cancelling each other resulting in radiation at right angles from the antenna being zero. The only direction of maximum radiation that remains will be at 54^0 to the antenna. As the length of the dipole increases, the current distribution changes and more lobes appear in the radiation pattern. It can also be seen from the radiation patterns that as the length increases the direction of major lobes is brought closer and closer to the direction of dipole.

The radiation pattern of a non-resonant antenna is similar to that of a resonant antenna, except for the fact that the non-resonant is unidirectional as shown in Figure 3.

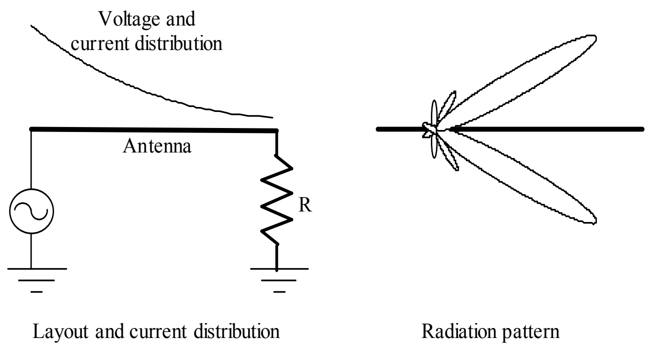


Figure 3 Resonant antenna

3.3 Antenna Gain

Except for isotropic antennas, all antennas concentrate their radiation in some direction at the expense of radiation in other directions, which makes the power density in that particular direction to be greater compared to other directions. This concentration of radiation pattern and greater power densities in some directions makes the antenna to be said to exhibit a gain, called *directive gain*, which is often expressed in decibels (dB).

Directive gain – Directive gain (in a particular direction) is defined as the ratio of the power density radiated by an antenna in a particular direction to that radiated by an isotropic antenna with both densities measured at the same distance and both antennas radiating the same power. The directive gain of an antenna increases with its length.

Directivity – Directivity is the directive gain in the direction of one major lobe of the radiation pattern; that is, directivity represents the *maximum directive gain*. When buying an antenna the figure quoted as antenna gain represents the maximum directive gain or directivity.

Power gain – Power gain is the same as directivity, except that this time the practical power is that power which must be fed to the directive antenna to develop the same field strength at the same distance in its direction of maximum radiation. Comparing the two definitions the difference is, for directivity the radiated power is considered for directive antenna whereas for power gain the power fed to the antenna is taken, thus the power gain takes into account the antenna losses and it can be written as

$$A_p = \eta D \tag{1.2}$$

where A_p = power gain,
D = directivity (maximum directive gain) and
η = antenna efficiency (= 1 for a lossless antenna)

For VHF and UHF antennas, the directivity and power gain are almost equal.

As mentioned before, there are two antenna standards: isotropic radiator and half-wave dipole, which exists side by side. Gain relative to an isotropic radiator should be designated as ‘dBi’ and the one relative to a halve-wave dipole should be also designated as ‘dBd’. Expressing the gain in decibels without reference to the standard employed can lead to a disparity of 2.15 dB in the claimed results, which is the relative gain of the two standards employed; that is, the gain of a half-wave dipole relative to the isotropic radiator.

3.4 Antenna Resistance

The impedance of an antenna Z_A is a complex quantity, which is given by

$$Z_A = R_A + jX_A \tag{1.3}$$

where R_A = antenna resistance
X_A = antenna reactance

In practice the reactive component is usually tuned so that the antenna presents a resistive load to the transmission line. The resistive part is called *antenna resistance* and it consists of two components: *radiation resistance* and *loss resistance*. Radiation resistance a virtual resistance which is due to the power the antenna converts into electromagnetic waves, while the loss resistance is due to the actual resistance of the antenna element, which dissipate power as heat.

Radiation resistance- Radiation resistance is an ac resistance, which is defined as the ratio of the power radiated by the antenna to the square of the current at a feed point. That is,

$$R_r = \frac{P}{I^2} \tag{1.4}$$

where R_r = radiation resistance

I = effective rms current at the feed point

P = total power radiated from the antenna

Antenna losses and efficiency - Power may be dissipated as the result of the antenna and ground resistance, losses in imperfect dielectric very near to antenna and eddy currents induced in the metallic objects within the induction field of an antenna. All of these are usually represented by a lumped resistance R_d, which is the total loss resistance of an antenna. If the radiation resistance is represented by R_r, the sum of the loss resistance and radiation resistance will constitute the total resistance of the antenna or the total impedance for antennas of resonant length. That is,

$$R_A = R_r + R_d \tag{1.5}$$

The antenna efficiency then becomes

$$\%\eta = \frac{R_r}{R_r + R_d} \times 100\% = \frac{R_r}{R_A} \times 100\% \tag{1.6}$$

LF and MF antennas are the least efficient because it is impractical to make them of resonant length. So to improve efficiency for these antennas the value of their radiation resistance is made so high compared to loss resistance. For short dipole that is less than half-wavelength in effective length, the radiation resistance is proportional to the length.

3.5 Effective Aperture

A receiving antenna may be thought of having an area that collects electromagnetic energy from the incident wave. This area is referred to as effective area, and is also known as effective aperture, or capture area. Effective aperture is given by

$$A_e = \frac{\lambda^2}{4\pi} D \tag{1.7}$$

where λ = wavelength

D = is directivity or maximum directive gain

The larger the effective aperture, the more effective is the antenna compared with a simple dipole.

3.6 Electrical and Physical Length of an Antenna

The velocity of a wave in a free space is the same as the speed of light ($3\times 10^{8} m/s$). Therefore, the wavelength in a free space is given by

$$\lambda = \frac{v_c}{f} = \frac{3\times 10^{8} m/s}{f} \qquad (1.8)$$

where λ = wavelength in meters
v_c = speed of light
f = frequency in Hertz

The velocity of a wave along a conductor is always slightly less than that in a free space. If we substitute the speed of light in Equation (1.8) with a slightly less value, the new wavelength (using the velocity in a conductor) will be less than that in a free space. This new wavelength represents the physical length of the antenna while the former represents the electrical length. Literature reveals that the physical length can be approximated as about 95 percent of electrical length. In dipole antennas this reduction of the length by 5% helps to eliminate the reactive component of the terminal impedance, thus making the antenna's impedance to be purely resistive at the feed point.

Example 1: A half-wave dipole is needed to transmit a 300 MHz broadcast. Determine the electrical and the optimum length of the dipole.

Solution:

For f = 300 MHz, the wavelength is

$$\lambda = \frac{v_c}{f} = \frac{3\times 10^{8}}{300\times 10^{6}} = 1m$$

The electrical length is

$$\frac{\lambda}{2} = 0.5m$$

Applying the 95 % correction factor, the actual optimum physical length of the antenna is

$$0.95\times 0.5m = 0.475m$$

3.7 Bandwidth and Beamwidth

Bandwidth **-** Bandwidth refers to the frequency range over which the operation of the antenna is satisfactory. For VHF and UHF bands the antenna bandwidths are either written on the antenna boom or colour coding is used as shown in Table 1.

Table 1: Colour coding for VHF and UHF TV antennas

Band	Channels	Colour Code
VHF	4 - 13	Blue
UHF	21 – 36	Red
UHF	37 – 52	Yellow
UHF	53 – 68	Green
UHF	21 – 68	White

Beamwidth – Beamwidth is the angular separation between the two half-power points on the power density radiation pattern and it is expressed in degrees.

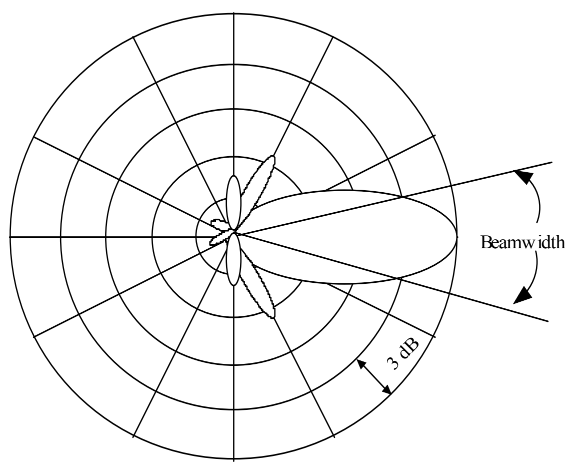


Figure 4 Beamwidth

3.8 Side Lobes and Nulls

A side lobe is a radiation lobe in any direction other than that of a major lobe. Therefore, side lobes are smaller lobes compared to the main lobe and they are commonly specified in dB down from the main lobe.

A null is a zone in an antenna radiation pattern in which the effective radiated power is at a minimum. A null often has narrow directivity angle than that of the main beam, and is useful for purpose such as suppression of interfering signals in a given direction.

3.9 Front-Back Ratio

Directional antennas' radiation patterns exhibit much greater directivity in one direction than in any other as shown in Figure 5. Where it is evident that there is more signal off the front than the back. The ratio of the maximum signal off the front (E_f) of the directional antenna to the maximum peak signal off the back (E_b) is called *front-to-back ratio* (FBR). FBR also refers to maximum gain in the most optimum direction to the gain in the direction 180^0 away from the optimum direction. FBR is usually expressed in decibels; that is,

$$FBR = 20\log\left(\frac{E_f}{E_b}\right) \quad (1.9)$$

Since FBR is the ratio of the output in the most optimum direction to the output 180^0 from the optimum direction, it can also be used to express how directive the antenna is, and the greater the FBR value, the more directive the antenna.

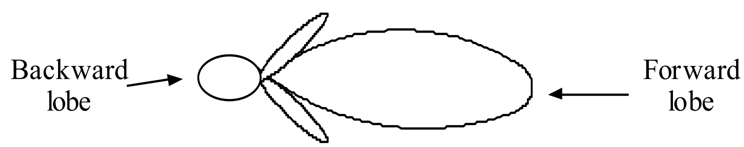


Figure 1.5 Radiation pattern of a directional antenna

3.10 Return Loss

Return loss, also called *reflection loss (RL) or mismatch loss (ML)*, of an antenna is a logarithmic ratio of the power reflected by the antenna to the total power fed into the antenna from the transmitter via the feeder line and is expressed in decibels. That is,

$$RL = ML = 10\log\left(\frac{P_R}{P_T}\right) dB \quad (1.10)$$

where P_R is the reflected power and P_T is the total power fed into the antenna. Like standing wave ratio (SWR), return loss can also be used as another way of expressing mismatch between the antenna the feeder line.
Its relationship to SWR is

$$\text{Re}\,turn\ loss = 20\log\left(\frac{SWR}{SWR-1}\right) dB \quad (1.11)$$

3.11 Resonant Frequency

The resonant frequency of an antenna is a frequency at which the input impedance is non-reactive or is purely resistive.

3.12 Antenna Impedance Matching

Since antennas are transducers that are designed for maximum radiation, they must ensure that all the energy that is generated by the transmitter is coupled into space. One of the prerequisite for ensuring this maximum power transfer is for the feeder cable (or line) to be matched to the antenna in order to prevent any reflections of power by the antenna due to impedance mismatch between the feeder line and the input impedance of the antenna. This is usually achieved by first tuning out the unwanted reactive component in the impedance of the antenna and thereafter transforming the resulting impedance to the required value. The former, which is also referred to as *antenna loading*, is necessary in order to make the antenna to have purely-resistive impedance, and is usually accomplished by using an antenna that is resonant to the frequency of the radio transmitter where possible. However, for low- and medium-frequency antennas the use of resonant effective length is sometimes impossible, thus requiring other techniques to be used to tune out the unwanted reactance.

Impedance transformation is usually accomplished by using one of the following techniques:

Delta match
Tee (or T), Gamma, and Clemens Match
Matching network
Stub
Quarter-wave match, and
Transformer match

The above-mentioned impedance matching techniques are designed to be effective for either narrow-band or broadband.

3.12.1 Delta match

Delta match is commonly used with two-wire feeder lines, where the match is obtained by gradually increasing the separation of the two wires that constitute the feeder line as it approaches the antenna. This spreading of the antenna-end of the feeder line results in its characteristic impedance being increased. Figure 1.6 below shows the delta matching technique, where the two wires on the antenna-end of the feeder line are spread from the center of the antenna to the points in the antenna where the antenna impedance equals the impedance at the output terminals of the delta section.

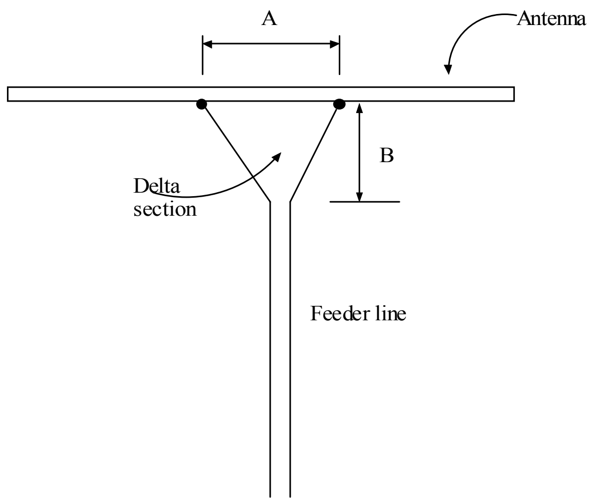


Figure 1.6 Delta match

There are two major advantages of using delta match: simplicity to construct and ability to match a wide-range of impedances. However, its major disadvantage is that the delta section becomes part of the antenna and, consequently, alters some of the characteristics of the antenna, such as radiation pattern and radiation loss. Another disadvantage is the effort needed to determine the dimensions of the delta section; that is, lengths *A* and *B* for optimum performance. In other words there is no formula for determining A and B, hence they need to be obtained experimentally.

3.12.2 Tee (or T), Gamma and Clemens match

A Tee or T match is a variation of a delta match, which is used for VHF and UHF antennas. Figure 1.7 below shows the T matching technique, where the two wires on the antenna-end of the feeder line are bent to form a T and then connected to the antenna at equidistance from the center of the antenna to the points in the antenna where the antenna impedance equals the impedance at the output terminals of the T section. However, unlike the delta match, T match does not radiate.

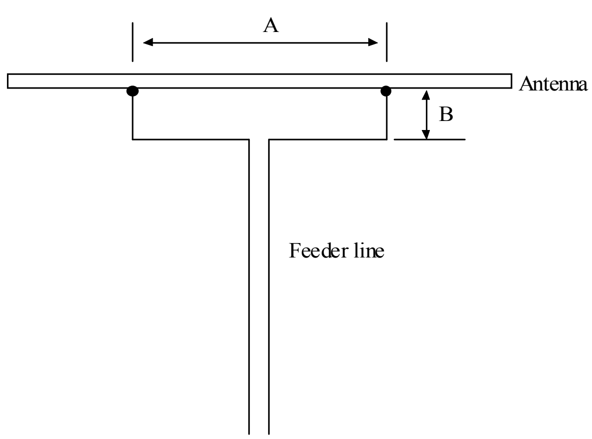


Figure 1.7 T-Match

T match is suitable for feeding closed-spaced beam antennas using low impedance twin-lead.

Gamma match is a matching technique which evolves from T match. It is used for matching unbalanced feeder line like coaxial cable. Unlike T match, where the two wires on the antenna-end of the feeder line are bent to form a T and then connected to the antenna at equidistance from the center of the antenna, here only one conductor, the inner conductor, of the feeder cable is bent and connected to a point away from the center while the outer conductor is connected to the center of the antenna. Gamma match is shown in Figure 1.8.

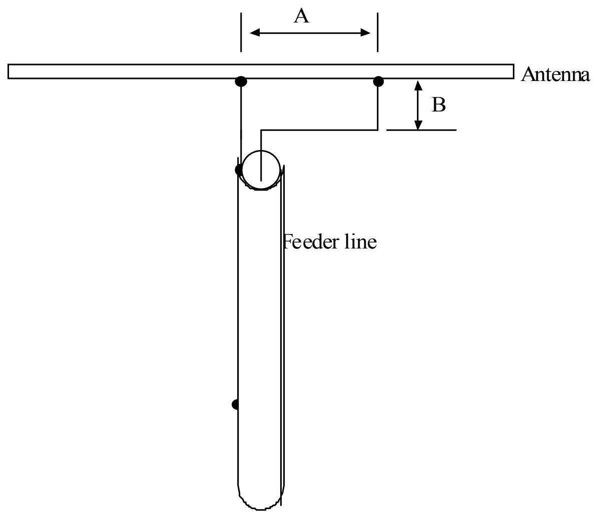


Figure 1.8 Gamma Match

As you can see the power is only fed into one-half of the radiator and the other half is being excited by induction. This unbalanced arrangement usually results in feeder radiation.

Clemens Match is an improved version of Gamma match, which incorporates the balanced-to-unbalanced transformation. The coaxial feeder cable is taken to the center point fo the antenna, bent along one side to a distance of 0.05 λ where the outer conductor is connected to the antenna, then the inner conductor is looped back to an equidistance on the other side of the center of antenna and there it is joined to the driven element via a capacitor which is formed from the cable. This formed capacitance is used to tune out the transformer reactance and also helps the tuning of the antenna. According to Bilddulph the dimensions *A*, *B*, *C*, and *S* can be derived from the electrical length *L* of the dipole as follows:

$$L = \frac{v_c}{2f} = \frac{\lambda}{2} \tag{1.12}$$

$$A = 0.95\frac{\lambda}{2} = 0.95L \tag{1.13}$$

$$B = 2 \times 0.5\lambda = 0.1\lambda = 0.2L \quad (1.14)$$

$$C = 0.039L \quad (1.15)$$

And

$$S = 0.01 \rightarrow 0.02\lambda \quad (1.16)$$

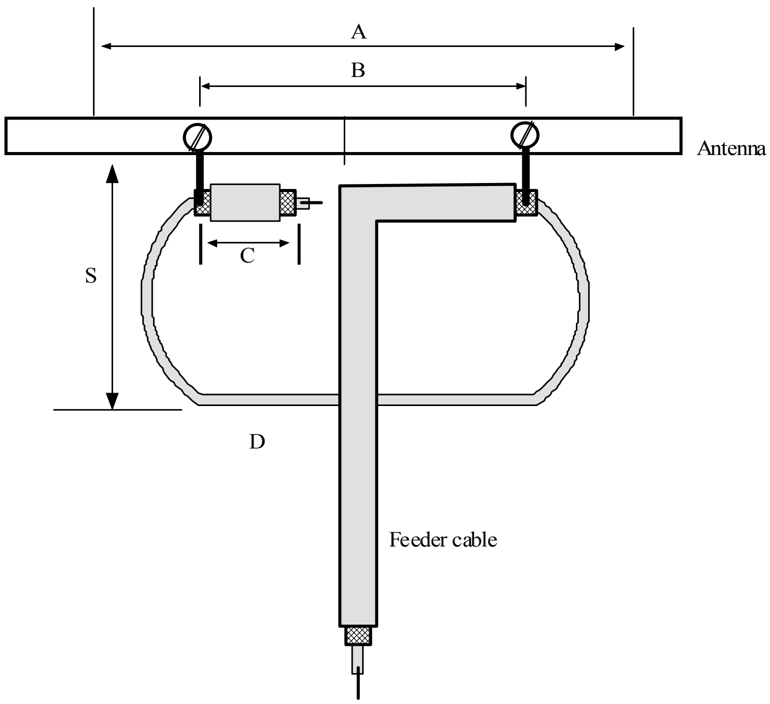


Figure 1.9 Clemens Match

The Clemens match is usually put on the underside of the driven element to prevent large birds from damaging it.

3.12.3 Matching Network

The matching network, also called *antenna tuner*, is a passive network, which is made up of capacitors and inductors. These matching networks can match any two impedance value over a relatively narrow bandwidth, and they can be used for frequencies up to 1 GHz. Matching networks come in three different configurations: L-network, T-network and pi-network as shown in Figure 1.10.

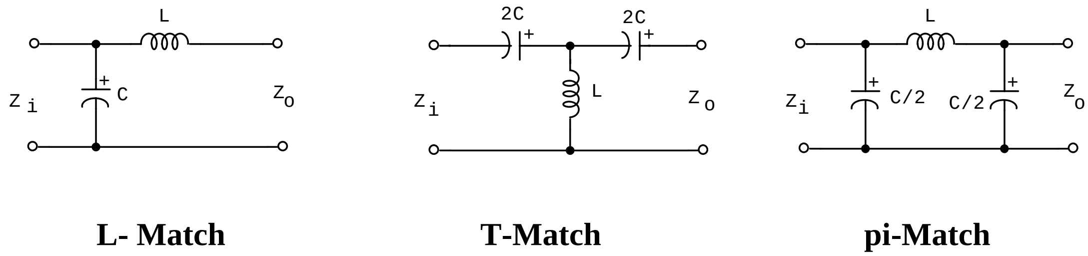


Figure 1.10 Matching Network configurations

However, the most commonly used configuration is the L-networks due to the fact that they can be easily analyzed using either circuit equations or Smith chart. Assume you have an L-network as shown in Figure 1.11 that is used to match the characteristic impedance of the feeder line (Z_o) to the input impedance of the antenna (Z_A), which are both purely resistive.

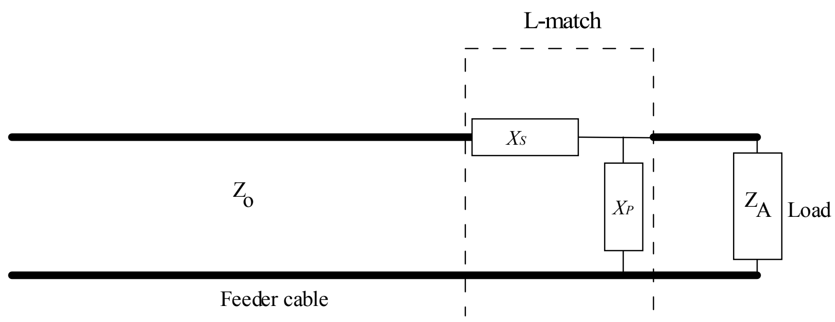


Figure 1.11 Matching L-Network

The two circuit elements: X_S and X_P may be a capacitor and inductor or inductor and capacitor, respectively. The choice of which one is an inductor and which one is a capacitor is at the discretion of the designer, but what is important is that one must be an inductor and another must be a capacitor. If we use R_o for the purely resistive characteristic impedance of the transmission line and R_L for the purely resistive load, then the analysis of the L-network is as follows:

- First the parallel combination of the load and the shunting reactance X_P are converted to its series equivalent. After this parallel-to-serial conversion, the equivalent load resistance becomes

$$R_{L_S} = \frac{R_L}{Q^2 + 1} \qquad (1.17)$$

- To match the load, the equivalent load resistance must be equal to the real part of the characteristic impedance; that is,

$$R_o = R_{L_S} \qquad (1.18a)$$

Substituting for R_{Ls} we get

$$R_o = \frac{R_L}{Q^2 + 1} \qquad (1.18b)$$

$$\therefore Q = \sqrt{\frac{R_L}{R_o} - 1} \qquad (1.19a)$$

However, the Q factor can also be expressed in terms of the reactive impedance as

$$Q = \frac{X_S}{R_o} = \frac{R_L}{X_P} \qquad (1.19b)$$

$$\therefore X_S = QR_o \qquad (1.20)$$

And

$$X_P = \frac{R_L}{Q} \qquad (1.21)$$

Since either of the reactive elements can be either a capacitor or an inductor, there will be always two possible matching networks that can provide the required match. Normally, the network that yields the smallest component values is chosen as shown in the following example.

3.12.4 Stubs

A stub is a matching device that consists of a very short or air spaced transmission line with a short or open circuit that can be used as the reactive element to provide impedance matching over a narrow-band. To minimize losses and also preserve the bandwidth of the antenna system, the lengths of the stubs is usually restricted to quarter-wavelength or less. By varying the length (*d*) between the stub and the load almost any load can be matched. The stub can either be connected in parallel or in series with the feeder line. When short-circuited line is used, the input reactance and susceptance of the stub are inductive and are given by

$$Z_s = X_{in} = jZ_o \tan\theta \qquad (1.17a)$$

$$Y_s = B_{in} = -jY_o \cot\theta \qquad (1.17b)$$

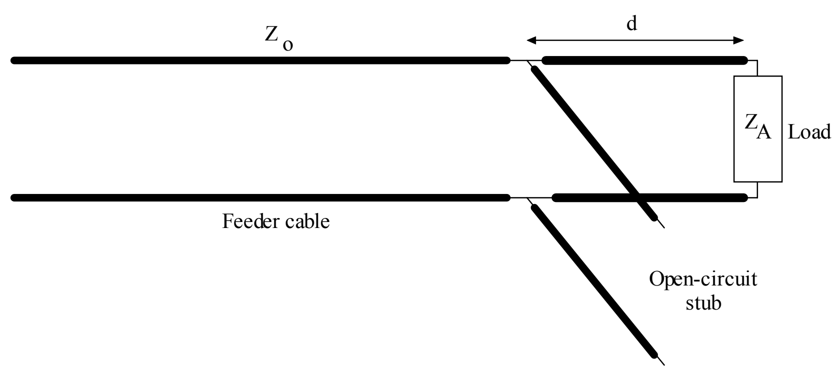
When open-circuited line is used, the input reactance and susceptance of the stub are capacitive and are given by

$$Z_{op} = X_{in} = -jZ_o \cot\theta \tag{1.18a}$$

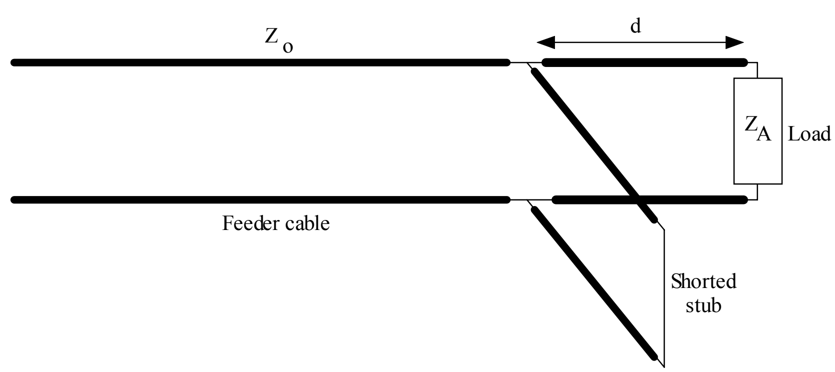
$$Y_{op} = B_{in} = jY_o \tan\theta \tag{1.18b}$$

where Z_o is the characteristic impedance of the line and θ is the electrical length of line. The stub is usually connected in parallel or series with the main feeder line towards the antenna end where the real part of the impedance or admittance of the line is equal to the characteristic impedance (Z_o) or characteristic admittance (Y_o), respectively, in order to give an equal but opposite reactance or susceptance at the input end. This is done to tune out or cancel the unwanted reactance on the feeder line.

Shunt stub



(a) Open-circuited



(b) Short-circuited

Figure 1.12 Stub Matching using parallel (or shunt) stubs

Figure 1.12 shows stub matching where the stub is connected in parallel with the main feeder line towards the antenna end to give an equal but opposite reactance at the input end. The input admittance of the stub, whether short or open circuit, is given by

$$Y_s = -jB \tag{1.19}$$

From where the stub is connected, the input admittance of the section that connects to the antenna is

$$Y_d = Y_o + jB \tag{1.20}$$

Therefore, the overall input impedance at the point where the stub is connected is

$$Y_{in} = Y_d + Y_s = Y_o + jB - jB = Y_o$$

$$\therefore Z_{in} = Z_o$$

Thus, the antenna is matched to the feeder line.

The stubs shown in Figure 1.12 are called *shunt stubs* since they are connected in parallel to the line or are shunted across the transmission line. Designs are also available for two or three shunt stubs that are placed at specified locations on the line.

Series stub

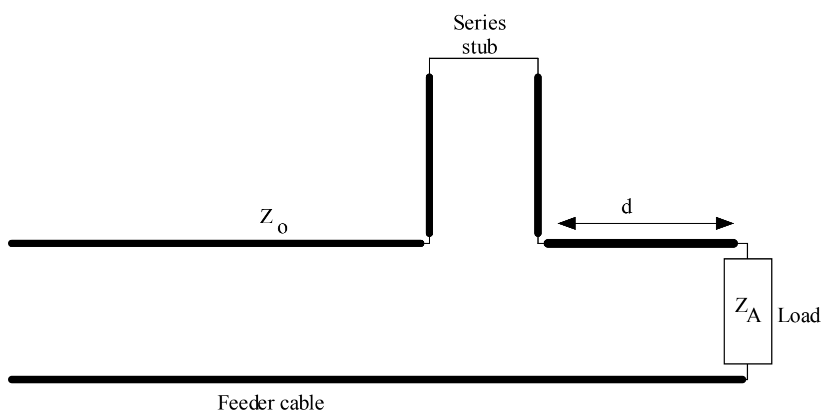


Figure 1.13 Stub Matching using a series stub

Figure 1.13 shows stub matching where the stub is connected in series with the main feeder line towards the antenna end to give an equal but opposite reactance at the input end. The input impedance of the stub, whether short or open circuit, is given by

$$Z_s = -jX \tag{1.21}$$

From where the stub is connected, the input impedance of the section that connects to the antenna is

$$Z_d = Z_o + jX \tag{1.22}$$

Therefore, the overall input impedance at the point where the stub is connected is

$$Z_{in} = Z_d + Z_s = Z_o + jX - jX = Z_o$$

Thus, the antenna is matched to the feeder line.

3.12.5 Quarter-wave Transformer Match

A quarter-wave transformer is a quarter wavelength section of transmission line that is connected in series with the main feeder line to change the impedance of the antenna to match that of the feeder cable. To accomplish this, the characteristic impedance of the quarter-wave section is different from that of the rest of the feeder cable and antenna. The quarter-wave transformer matching is shown in Figure 1.14 and its impedance, Z_Q, is given by

$$Z_Q = \sqrt{Z_A Z_o} \tag{1.23}$$

where Z_A is the antenna of impedance and Z_o is the characteristic impedance of the feeder cable.

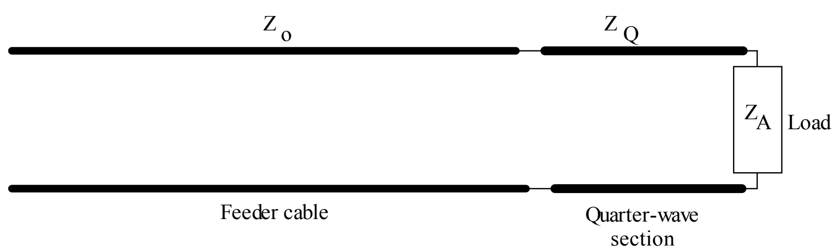


Figure 1.14 Quarter-wave transformer match

The major disadvantages of this type of matching are that it is only effective for a narrow-band, and that a transmission line of proper characteristic impedance may not be available since transmission lines are only commercially available in a limited number of characteristic impedances such as 50, 75, 95, 135, 300, and 450 ohms. However, the narrow-band matching effect can be broadened by cascading quarter-wave line sections of gradually varying characteristic impedance even though this does not yield good result over the entire broadband.

3.12.6 Transformer Match

Specially designed RF transformers can also be used to provide impedance matching between the antenna and the feeder line. A transformer is used to transform the antenna impedance as a square of the turns ratio; that is,

$$\frac{Z_s}{Z_p} = \left(\frac{N_s}{N_p}\right)^2 \tag{1.24}$$

The main advantage of transformer matching is that it can operate over a broader bandwidth. However, its disadvantages are that it does not work well with extremely large impedances, and it is also not recommended for very high frequencies.

3.12.7 Choosing the correct matching technique

According to Biddulph, the choice of the matching technique to employ depends upon the nature of the unmatched impedance and the physical details of the antenna. In some cases it is possible to modify the antenna itself to achieve the required matching, without significantly altering its characteristics as a radiating element. Examples of this include the use of wires (dipoles), the adjustment of the reflector spacing in Yagi-Uda antenna, adjustment of the separation gap (*g*) in log-periodic antenna, and using different conductor diameters for the elements of the radiator. For example, Wongpailbool discusses the modifications that can be done to the helical antenna to solve impedance mismatch, which include tapering helical windings at either one or both ends, gradually flattening the section of a helical wire near the feed point, and replacing the section of a helical wire near the feed point with a thin triangular copper strip that has the same length as that of the helical wire being substituted.

Example 2: Assume that you are required to match a 300 Ω antenna to a 75 Ω feeder line at 2 MHz.

(a) If the L-network is used determine the values of the elements required to provide the match.
(b) If transformer matching is used, determine the turns ratio of the RF transformer.
(c) If quarter-wave transformer is used, determine the impedance of the quarter-wave line section section required to provide the required match.

Solution

(a) L-network:

$$Q = \sqrt{\frac{R_L}{R_o} - 1} = \sqrt{\frac{300}{50} - 1} = 2.236$$

$$\therefore X_S = QR_o = 50 \times 2.236 = 111.803\Omega$$

$$X_P = \frac{R_L}{Q} = \frac{300}{2.236} = 134.168\Omega$$

If X_s is the capacitive reactance and X_p is the inductive reactance, then

$$C_s = \frac{1}{2\pi f X_s} = \frac{1}{2\pi \times 2M \times 111.803} = 711.765\,pF$$

And

$$L_p = \frac{X_p}{2\pi f} = \frac{134.168}{2\pi \times 2M} = 10.677\,\mu H$$

If X_s is the inductive reactance and X_p is the capacitive reactance, then

$$C_p = \frac{1}{2\pi f X_p} = \frac{1}{2\pi \times 2M \times 134.168} = 593.118\,pF$$

And

$$L_s = \frac{X_s}{2\pi f} = \frac{111.803}{2\pi \times 2M} = 8.897\,\mu H$$

In this case the *L*-network with inductor in series and capacitor in parallel with the antenna has smaller component values, thus it will be the best choice.

(b) Transformer matching:

$$\left(\frac{N_s}{N_p}\right)^2 = \frac{Z_s}{Z_p} = \frac{Z_A}{Z_o} = \frac{300}{50} = 6$$

$$\therefore \frac{N_s}{N_p} = 2.449 : 1$$

(c) Quarter-wave transformer matching:

$$Z_Q = \sqrt{Z_A Z_o} = \sqrt{300 \times 50} = 122.474\Omega$$

4. ANTENNA TYPES

4.1 Dipole and Monopole Antennas

A dipole antenna is the simplest practical antenna. It is a center-driven radiating element. The mostly commonly used versions of dipole antennas are half-wave ($\frac{\lambda}{2}$) dipoles, and folded dipoles.

Monopoles, on the other hand, are fed from one end; that is, they are end-fed instead of being center-fed like dipoles. However, for them to operate satisfactory they need to be mounted on a conductive surface which acts as a reflector to provide an image of the real antenna. The current in the image has the same direction and the phase as the real antenna which makes it to have characteristics which are almost similar to that of a dipole. The mostly commonly used version of dipole antenna is a quarter-wave ($\frac{\lambda}{4}$) dipole called a *Marconi antenna*. Theoretically, a monopole antenna has a gain of about 5.16 dBi when used on a large horizontal ground plane, but in practice finite ground planes reduces this gain to something between dipole gain of 2.16 dBi and 5.16 dBi, and simulation shows that in some cases the gain can even be less than that of a dipole if the ground plane is not that good.

Both the dipoles and the monopoles are resonant antennas that produce omnidirectional azimuth radiation patterns which make them to be useful in base stations of point-to-multipoint (P2MP) and mobile wireless communication systems.

4.1.1 Half-wave dipole

A half-wave ($\frac{\lambda}{2}$) dipole is a center-fed antenna with an electrical distance of half wavelength from one end to another end at the carrier frequency. In other words, the half-wave dipole is composed of two quarter-wave sections which are usually made with wires or hollow tubes. It was invented by Heinrich Rudolph Hertz; hence it is also referred to as a Hertz antenna. The current distribution along the dipole is zero at the ends but rises up to a maximum at the center as shown in Figure 1, while the voltage is minimum at the center and maximum at the ends. The radiation pattern of a $\frac{\lambda}{2}$ is as shown in Figure 1.15 below.

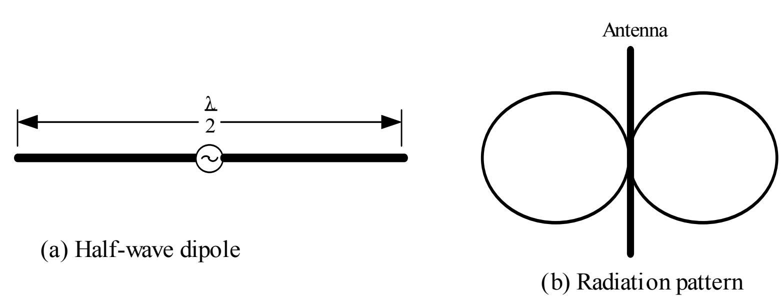


Figure 1.15 Half-wave dipole and its radiation pattern

A half-wave dipole has a maximum directive gain or directivity of 2.14 dBi (1.64) with respect to the isotropic radiator. Using Equation (1.6) the effective aperture is of a half-wave dipole is

$$A_e = \frac{\lambda^2}{4\pi} D = \frac{\lambda^2}{4\pi} \times 1.64$$

$$= 0.13\lambda^2 \quad (1.25)$$

At its electrical length the half-wave dipole has an impedance of 73 + j42.5 Ω, and at its physical length its typical input impedance is about 73 Ω at the feed point and is purely resistive.

4.1.2 Folded dipole

A folded dipole is a dipole antenna that has its radiating element folded into a λ/2 flattened loop as shown in Figure 1.16. It offers the same radiation pattern as the standard half-wave dipole discussed above. However, its input impedance is in the range of 288 Ω to about 300Ω, which is about four times that of a standard half-wave dipole. This impedance can be further increased by using a larger diameter for the antenna element. It also offers a bandwidth that is slightly broader (typically 10 % more) than that of an ordinary half-wave dipole. Folded dipoles are commonly used as the driven element in Yagi-Uda antenna arrays to help maintain a reasonably high impedance since the addition of each director lowers the array's input impedance. The use of folded dipole also broadens the band of operation of the Yagi-Uda.

Figure 1.16 Folded dipole antennas

4.1.3 Marconi antenna

A Marconi antenna is a grounded vertical quarter-wave antenna, which was invented by Guglielmo Marconi. Unlike a half-wave dipole, a Marconi antenna is a monopole resonant antenna, and therefore is end-fed. Marconi antenna needs to be mounted on an electrically conductive ground plane. This ground plane becomes part of the antenna system and it acts as a mirror to provide a mirror image of the real antenna, which is also a quarter-wave monopole. The bottom of the real antenna is joined to the top of the image antenna to form an antenna of double size, which is half-wavelength. This effective double size length makes the Marconi to have currents and voltage patterns which are similar to that of a half-wave dipole. However, half of the radiation pattern appears to lie below the ground surface as shown in Figure 1.17 (a). In reality the portion of the radiation pattern that appears to lie below ground does not exist, instead, all the power from the radiator is contained in that portion of the pattern which is above the reflective ground surface, thus, resulting in a radiation pattern which is one-half that of a vertical half-wave dipole as shown in Figure 1.17 (b).

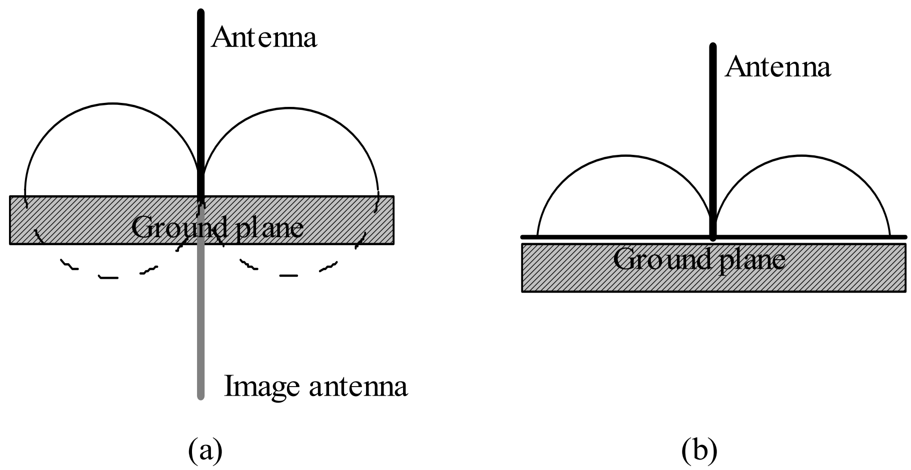


Figure 1.17 Radiation pattern of a Marconi antenna

The Marconi antenna is commonly fed by a coaxial cable, with the center conductor connected to the vertical quarter-wave antenna, which is insulated from the ground plane, and the shield (outer conductor) is connected to the ground plane. The vertical element is sometimes called a *whip* due to its motion in the wind. The Marconi antenna system structure behaves like two antennas that are fed in parallel, hence its input impedance is reduced to about 36.5 Ω, which is half that of a half-wave dipole.

If the ground plane conductivity is poor, the antenna will lose a considerable amount of power in the resistance of the ground system. In order to avoid this and keep the transmission efficiency and radiation pattern closer to the ideal situation even on poor conductive surfaces an artificial ground plane must be provided. One way of providing artificial ground is by burying a large number of radials on the ground around the base of the antenna. These radials must be equally spaced and must be of the same length as the radiating antenna; that is, they must be also quarter wavelength. These radials must be joined with a ring conductor that is connected to the outer conductor (shield) of the coax, and they must be grounded by metal spikes which are driven deeply into the subsoil.

Another way of providing artificial ground is called *counterpoise system*. It is used for antennas that are raised above the ground, perhaps on a tower, where it is not possible to bury radials around the antenna. Here the conductive artificial ground mat is derived from the supporting metal cable guy wires by cutting the guy wires immediately below the antenna to λ/4 in lengths and connecting them to the outer conductor (shield) of the coax. These λ/4 lengths portions of guy wires must be isolated from the rest of the supporting guy wires by glass insulators as shown in Figure 1.18.

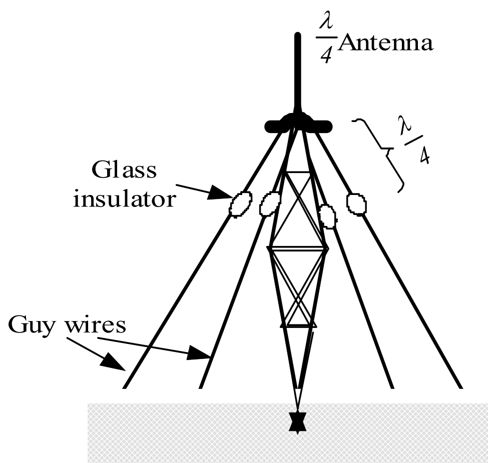


Figure 1.18 Counterpoise system

4.2 Antenna Arrays

Antenna arrays are antennas systems than consists of more than one element. These elements are placed together in the proximity so as to be within each other's induction field. The proximity of the elements to each other makes them to interact with one another to produce a radiation that is the vector sum of the individual ones. This combination of two or more elements to form an array focuses the radiated power more towards one particular direction. Thus, the antenna arrays are called directional antennas. The unidirectional radiation pattern of antenna arrays makes them to exhibit good directivity and direction gain than the antennas already discussed in the preceding sections; that is, isotropic, monopole and dipole antennas. Unlike, omnidirectional antennas, directional are used for point-to-point (P2P) wireless communication links.

In an antenna array you can either have all the elements physically or directly connected to your system (transmitter or receiver), or you can only have one element connected to your system. The former is referred to as a *driven array*, while the latter is called the *parasitic array*. A typical example of a parasitic array is a Yagi-Uda antenna, while log-periodic is an example of a driven array. In a parasitic array, the element that is directly connected to the system is referred to as a *driven element* and the one that is not directly connected to the system is called a *parasitic element*. The parasitic elements are parasitical excited; that is, they receive energy through the induction field of the driven element, rather than getting directly from the transmitter. Array elements can also be further classified into three types: active, director, and reflector. An element whose length is nearest or equal to half wavelength at the frequency of operation is called the *active element*, the element longer than the active element is called a *reflector*, and the one shorter than the active element is called a *director*.

4.2.1 Yagi-Uda antenna

The Yagi-Uda array, named after the two Japanese physicists who invented it, is a parasitic linear antenna array, which consists of one driven active element, one parasitic reflector, and one or more parasitic director(s), all supported by a central boom. Reflector is placed behind the driven element and is cut approximately 5 percent longer than the driven element. The director (or directors) is cut to approximately 5 percent shorter that the driven element and placed in front of it. The spacing between the elements of the array is from 0.15 to 0.25λ. The driven element can either be an ordinary half-wave dipole or a folded dipole as shown in Figure 1.19. However, for reasons already mentioned in Section 4.1.2, the folded dipole is the most commonly used than a standard dipole.

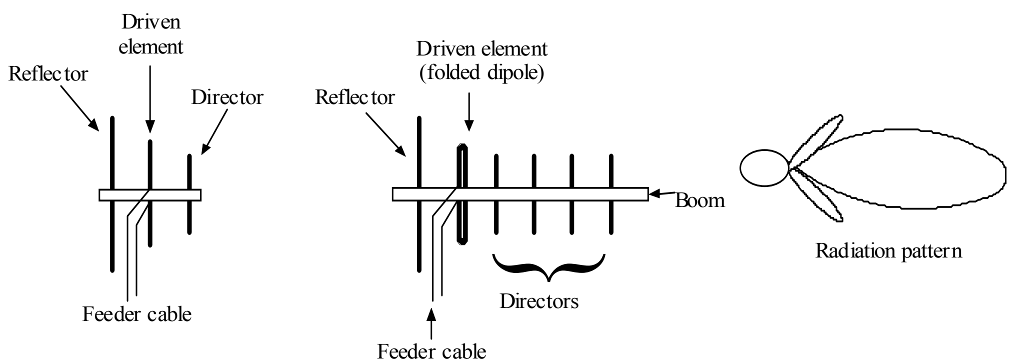


Figure 1.19 Yagi-Uda arrays and radiation pattern

The non-active elements are used to increase the directivity and the gain of the antenna. The reflector, behind the driven element, prevents radiation off the back of the array. In front the directors help focus the radiation in the forward direction. Together the reflector and directors can reduce the radiation off the back of the antenna to 25 - 30 dB below the forward radiation. As more directors are added, the forward gain increases.

Yagi-Uda can provide a high gain, depending on the number of directors, and a moderate bandwidth that is dependable on the driven element used. It is the most common antenna array in use today for TV reception and for point-to-point UHF radio links.

4.2.2 Log-Periodic Antenna

The log-periodic antenna, or log-periodic dipole array (LPDA), is a driven array which derives its name from the fact that its important characteristics are periodic with respect to the logarithm of frequency. It is a directional antenna that provides a moderate gain over an extremely wide range of frequencies. That is, log-periodic is a wide-bandwidth or broad-band antenna, which can be used for multi-band transmission and reception. It consists of an array of half-wave dipoles that are successively cross-wired as shown in Figure 1.10.

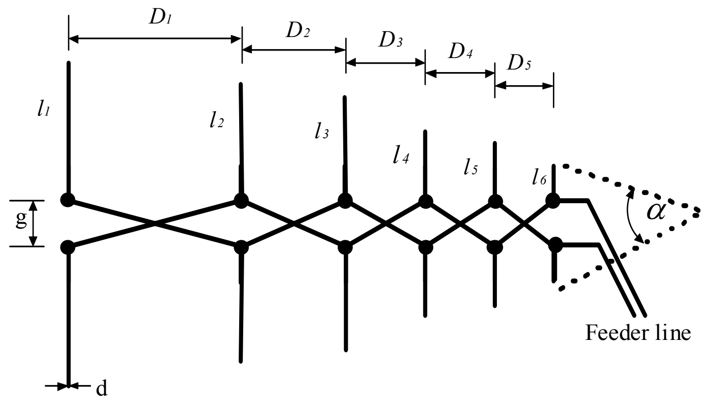


Figure 1.10 Log-periodic antennas

The longest dipole is cut for the lowest frequency and the succeeding dipoles are cut shorter and positioned closer to the one before it. The ratio of succeeding dipole lengths and the separating distances is a constant called *design ratio*, which is given by

$$\tau = \frac{l_{(n+1)}}{l_n} = \frac{D_{(n+1)}}{D_n} \tag{1.26}$$

where τ = design ratio

l = half of the length of a half-wave dipole (i.e. $l = \lambda/4$), and

D = separation distance between two successive dipoles

The angle of divergence or spread angle is given by

$$\alpha = tan^{-1}\left(\frac{l_n}{D_n}\right) \tag{1.27}$$

And the characteristic impedance of the feeder line is given by

$$Z_o = 276\, log\left(\frac{2g}{d}\right) \tag{1.28}$$

where *d* = diameter of the dipole elements, and

g = the gap or the spacing between the two *λ/4* elements that form each dipole

Though all elements in the log-periodic antenna are driven, only two are active at any given frequency. Thus leaving others to act either as directors (if they are in front of the resonant dipole), or reflectors (if they are behind the resonant dipole). The broad bandwidth is obtained because of the many dipoles, which are resonating at different frequencies.

4.3 Loop Antenna and Ferrite Rod Antenna

A loop antenna is a wire antenna made of one or more turns of wire on a frame, which can either be circular, square, or rectangular. Its size is very small. In fact its diameter is even less than λ/16; hence a wide range of frequencies may be received. Its compactness makes it to be useful for portable radio receivers. Loop antenna exhibits a sharp null along the axis of the loop, thereby producing a bidirectional toroidal or donut shaped radiation pattern as shown in Figure 1.11. However, the loop may be electrostatically shielded to improve its directional characteristic; that is, instead of providing a bidirectional pattern, it will provide a unidirectional pattern. The sensitivity of the a loop antenna is increased by increasing the number of turns. The induced voltage is given by

$$V_s = \omega BAN \tag{1.29}$$

where w = Angular frequency
B = Magnetic flux density in teslas
A = Physical loop area in m^2
N = Number of turn in the loop

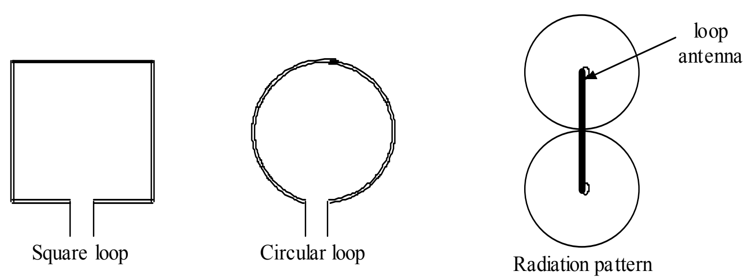


Figure 1.11 Loop antennas with their radiation pattern

Its compactness, wide bandwidth, and sharply defined radiation pattern render itself as number one choice in direction finding applications, thus outweighing the gain advantage of larger directional antennas like Yagi-Uda, log-periodic, etc.

Sometimes the turns of the loop antenna are wound around a ferrite rod. When the ferrite rod is used, the antenna is no longer called a loop antenna, but a *ferrite-rod* antenna. The ferrite is an iron based magnetic material that has a high permeability, which when inserted inside a loop antenna results in the intensification of the magnetic field inside the loop. This in turn helps to concentrate the magnetic flux, resulting in an induced voltage that is directly proportional to the number of turns. The induced voltage is given by

$$V_s = \omega BANF\mu \tag{1.30}$$

where A = Ferrite rod cross-sectional area in m^2
F = Modifying factor accounting for coil length

μ = Effective permeability of the ferrite

The placing of the ferrite rod inside the loop also increases the radiation resistance of the antenna significantly. Hence the inclusion of a ferrite rod can improve the antenna's efficiency dramatically. The radiation resistance is given by

$$R_r = 31200 \times \left(\frac{\mu NA}{\lambda} \right)^2 \tag{1.31}$$

However, though ferrite rod antennas are very convenient for portable applications, their efficiency is much less than that of larger antennas. The performance of the ferrite limits their frequency response, thus only making it to be effective up to about 1 MHz. This is mainly due to the fact that the ferrite tends to absorb some of the signal power and these losses increase with frequency. Figure 1.12 shows the ferrite rod antennas. Its directional properties are similar to those of the loop antenna, discussed above, although the null is not so quite pronounced as in the loop antenna.

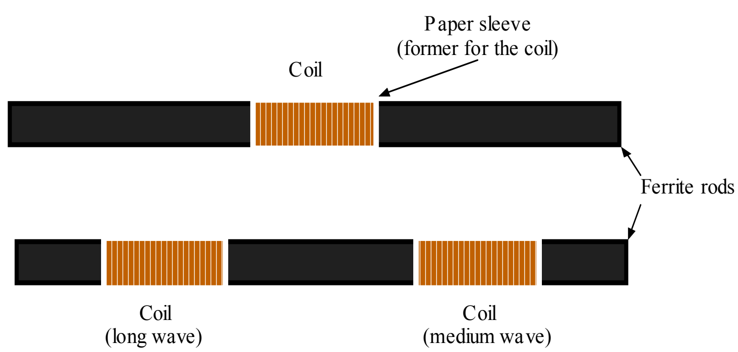


Figure 1.12 Ferrite rod antennas

The ferrite rod antennas are commonly used for portable AM broadcast receivers as well as other broadcast receivers where reception on the long, medium and short wave bands are required. It operates best only when the magnetic lines of force fall in line with the antenna; that is, when it is at right angles to the direction of the transmitter.

4.4 Helical (Helix) Antenna

A helical or helix antenna is a broadband VHF and UHF antenna which consists of a loosely wound helix that is backed by a ground plane, which is a simple screen made of chicken wire. It has two modes of radiation: normal and axial. The normal mode is due to the fact that the helix diameter is much less than one wavelength and its length is also less than a wavelength. In the normal mode the radiation is perpendicular to the axis of the helix. Axial radiation is due to the fact that waves will also travel around the turns of the helix, resulting in an end-fire mode that produces a broadband narrow beam of circular polarized waves, which is either clockwise or counter-clockwise.

The energy in the circular polarized waves is divided equally between the horizontal and vertical components. Thus making the helical antenna to be able to transmit to, or receive from, both horizontal and vertical polarized antennas. The helical antenna is used either as singly or in an array for tracking satellites. Helical antennas are also becoming popular in WiFi systems and other systems that are working in the ISM band (2.4 GHz). Figure 1.13 shows the dimensions of a helix antenna and Figure 1.14 shows

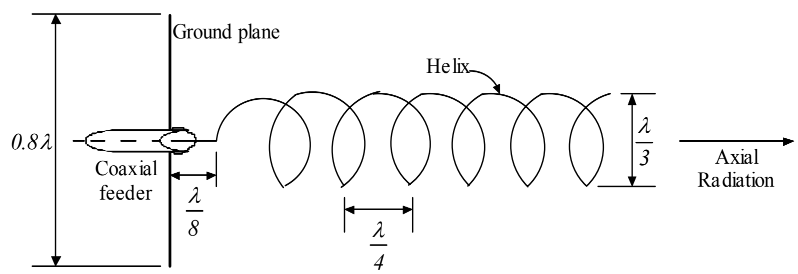


Figure 1.13 Dimensions of a helical antenna

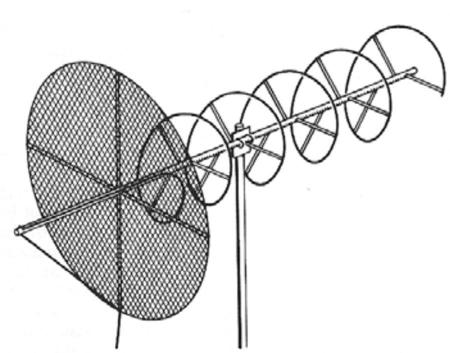


Figure 1.14 Helical Antenna

4.5 Parabolic Dish Antenna

For microwave systems, satellite communications, and radio astronomy the most commonly used antenna is a *parabolic dish antenna*. This type of an antenna is a high-gain directional antenna that is designed for UHF and SHF bands. It consists of a large parabolic or bowl-shaped reflector that is made of sheet metal, mesh wire, a plastic or a fiberglass with an embedded metal mesh material that is illuminated by a feed antenna such as dipole or a small waveguide horn that is mounted at the focal point of the parabolic reflector as shown in Figure 1.15. The feed antenna, sometimes referred to as primary antenna, is then connected to the associated RF transmitter or receiver by means of a coaxial cable or a hollow waveguide. In satellite dishes the feed antenna is called a feedhorn, and its function is to gather the wave that are reflected to the focal point by the dish and conduct them to a low-noise block down-converter (LNB). The LNB converts the waves to electrical signals and shifts the signal from the down linked C- and/or Ku-band to the L-band range.

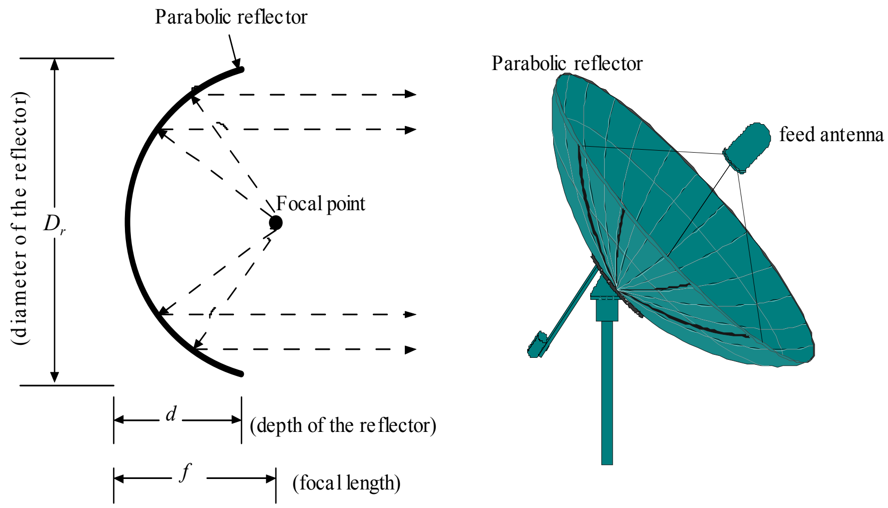


Figure 1.15 Parabolic dish antenna

The parabolic dish has a ray-collimating property, which makes the rays beamed to it, from the focal point, to be radiated parallel to each other. This property is very useful during transmission because the waves from the feed antenna that are directed towards the metal dish will be reflected as rays that are parallel to one another, thus forming a concentrated highly directive wave. The parabolic reflector also has the property of reflecting all incident rays arriving along the reflector's axis of symmetry to a common focus. This property is the one that is used during wave reception to bring all the incoming waves that are received by the dish to a focus at the focal point where the feed antenna is located. The focal point is the point where all the incoming reflected waves will converge to. The distance of the focal point from the center of the reflector is called the *focal length* and is given by

$$f = \frac{D_r^2}{16d} \qquad (1.32)$$

where D_r = diameter of the mouth of the reflector
d = depth of the reflector

The physical area of the parabolic reflector aperture with a mouth diameter D_r is given by

$$A = \frac{\pi D_r^2}{4} \qquad (1.33)$$

If you take into consideration the radiation pattern of the driven element and the effect of the angular aperture, then the effective area of the parabolic reflector aperture becomes

$$A_{eff} = AI(\theta) \qquad (1.34)$$

where $I(\theta)$ = aperture efficiency or illumination efficiency

Using Equation (1.7), the directive gain D for a parabolic antenna is

$$D = \frac{4\pi}{\lambda^2} A_{eff} \tag{1.35}$$

Substituting for A_{eff} we get

$$D = \frac{4\pi}{\lambda^2} AI(\theta) = \frac{4\pi}{\lambda^2} \times \frac{\pi D_r^{\,2}}{4} I(\theta) = I(\theta)\left(\frac{\pi D_r}{\lambda}\right)^2 \tag{1.36}$$

From the above equation it is evident that the gain of a parabolic dish antenna is primarily a function of the antenna capture area or aperture; the larger the antenna aperture, the higher the gain.

The beamwidth can be approximated by

$$\vartheta_{(-3dB)} = \frac{70\lambda}{D_r} \tag{1.37}$$

and the beamwidth between the nulls can be approximated by

$$\vartheta_{nulls} = 2\vartheta_{(-3dB)} = \frac{140\lambda}{D_r} \tag{1.38}$$

Example 2

A 3-m parabolic reflector is used to receive a 5 GHz signal. If the illumination efficiency of the antenna is 0.55 and the focal length is 0.6 m, determine the effective area, directivity, half-power Beamwidth, the Beamwidth between the nulls, and the depth of the reflector.

Solution

$$\lambda = \frac{v_c}{f} = \frac{3 \times 10^8}{10 \times 10^9} = 0.06m = 60mm$$

$$A = \frac{\pi D_r^{\,2}}{4} = \frac{\pi \times 3^2}{4} = 7.069m^2$$

The effective area: $A_{eff} = I(\theta)A = 0.55 \times 7.069 = 3.888m^2$

Directivity: $$D = \frac{4\pi}{\lambda^2} A_{eff} = \frac{4\pi}{0.06^2} \times 3.888 = 13570.706 = 41.326\,dB$$

Beamwidth: $$\vartheta_{(-3dB)} = \frac{70\lambda}{D_r} = \frac{70 \times 0.06}{3} = 1.4^0$$

Nulls Beamwidth: $$\vartheta_{nulls} = 2\vartheta_{(-3dB)} = 2 \times 1.4^0 = 2.8^0$$

Reflector depth: $$d = \frac{D_r^{\,2}}{16f} = \frac{3^2}{16 \times 0.6} = 0.938m$$

5. ACTIVE ANTENNAS

In areas where there is poor reception, an external directional antenna such as Yagi-Uda or a log-periodic is recommended. However, in some cases where the reception is very poor, the use of external antenna alone is not enough to improve reception. Hence you need to include an amplifying device in your antenna system. An antenna system with an active or amplifying element is called an *active antenna*. The amplifier is attached very closely to the antenna so as to set the signal-to-noise ratio (SNR) before the signal travels along a transmission line where it is susceptible to interference and loss. The amplifier is also act as a matching circuit to ensure a good match to the feeder. The amplifier can either be made of discrete components such as FET and BJT transistors, or integrated circuits. Some of the RF IC amplifiers are listed in Table 2 below.

Table 2 RF Amplifier ICs

Name	$BW_{3\text{-}dB}$ (MHz)	Gain (dB)	P_O (dBm)	Application/Band
ATR4251	0.15 to 110	35		AM (LW/MW/SW) and FM
MAX2611	DC to 1100	18		AM, FM, TV, Land mobile radio
MAX2240	2400 to 2500		20	Bluetooth, HomeRF, WLAN
MW4IC001N	800 to 2170	13	29.54	Cellular phones
PW210/250/ 350/410/470/510	DC to 3500	18	18.5	AM, FM, TV, DBS, RFID, Cellular, WLAN, Bluetooth

To power the active element, the power is normally supplied along the feeder coaxial cable from the power supply at the receiver end of the feeder. The inner conductor is used to carry the positive voltage while the negative of the supply is connected to the screen of the coax. This enables the supply of power to the amplifier without the need for additional wires being routed to the antenna.

6. PATH LOSS, FADING AND LINK BUDGET

As the radio signal propagates from the transmitter to the receiver it will suffer some losses. These losses can be due to the decrease of the power density with distance, absorption due to molecules in the earth's atmosphere, or signal fading. The decrease in power density with distance is called *path-loss* or *free-space attenuation*.

All radio links require the inclusion of some gain margin (excess gain) in the system gain budget to account for path losses that vary over time.

6.1 Free-space Attenuation

If the power radiated from the transmitter is P_t and the distance to the receiving antenna is d, then the power density, P_D, at the receiving antenna is

$$P_{D_r} = \frac{P_t}{4\pi d^2} \tag{1.39}$$

and the power at the receiving antenna is

$$P_r = P_{D_r} A_{er} \tag{1.40}$$

where A_{er} is the receiving antenna effective area or aperture which is given by $\frac{\lambda^2}{4\pi} D$. If we ignore the directivity, D, and the efficiency of the antenna and substitute v_c/f for lambda, then the power reaching the receiver can be represented as

$$\begin{aligned} P_r &= P_{D_r} \frac{\lambda^2}{4\pi} = \frac{P_t}{4\pi d^2} \times \frac{1}{4\pi} \times \left(\frac{v_c}{f} \right)^2 \\ &= \left(\frac{v_c}{4\pi f d} \right)^2 P_t \end{aligned} \tag{1.41}$$

The power lost between the transmitting antenna and the power appearing at the receiving antenna is called the *space attenuation*. The gain from the transmitter to the receiver is

$$G_s = \frac{P_r}{P_t} = \left(\frac{v_c}{4\pi df}\right)^2 \tag{1.50}$$

Using distance d in kilometers (km) and frequency f in MHz, the Equation (1.50) can be expressed in decibels as

$$G_s(dB) = 20\log\left(\frac{3\times10^8}{4\pi10^3 10^6}\right) + 20\log\left(\frac{1}{d_{km}}\right) + 20\log\left(\frac{1}{f_{MHz}}\right)$$

$$= -32.44 - 20\log(d_{km}) - 20\log(f_{MHz}) \;\; dB \tag{1.51}$$

The space loss L_s is the inverse of the gain G_s from the transmitter to the receiver; that is,

$$L_s = \frac{1}{G_s} = \frac{P_t}{P_r} \tag{1.52}$$

and in decibels, it can be written as

$$L_s(dB) = -G_s(dB)$$
$$= 32.44 + 20\log(d_{km}) + 20\log(f_{MHz}) \;\; dB \tag{1.53}$$

Using d in kilometers (km) and f in GHz, Equation (2.53) becomes

$$L_s(dB) = 92.44 + 20\log(d_{km}) + 20\log(f_{GHz}) \;\; dB \tag{1.54}$$

6.2 Atmospheric Absorption

Additional to the space attenuation discussed in the preceding section, the earth's atmosphere also introduces other losses, which are due to absorption by electrons, uncondensed water vapor, and molecules of various gases present in the atmosphere. Free electrons cause increasing loss at low frequencies, water vapors cause increasing loss around 21 GHz, and oxygen causes sharp peak absorption around 60HGz as shown in Figure 1.16.

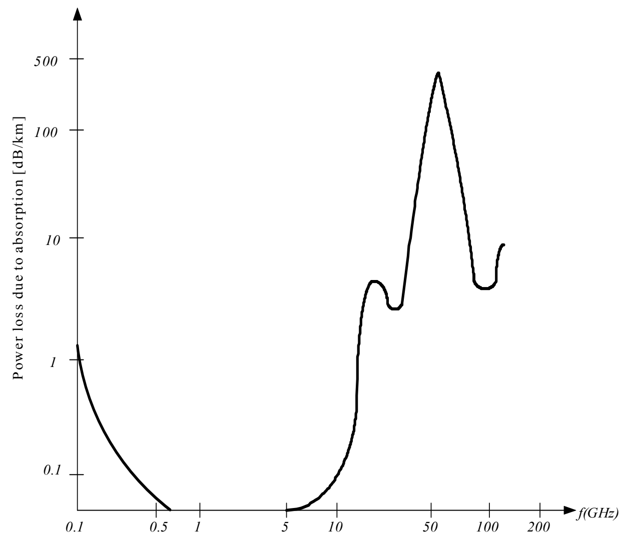


Figure 1.16 Atmospheric absorption

6.3 Fading

Some of the waves that have been radiated will go directly to the receiver, while other radiated waves will reach the receiver as a result of reflections by other objects such as buildings, mountains, and other structures. As the signal bounces off buildings, mountains and other structures it is scattered in many directions, producing multiple copies. Geometrically, the reflected waves transverse a farther distance than the direct waves as a result at the receiver they are no longer in phase with the direct wave and with each other. Since these waves are from the same source, they will interact and if they are in phase they will add, while if they are out of phase they will cancel each other.

These cancellations and additions of the received waves will result in the fluctuation of the received signal strength. This phenomenon of wave cancellation at the receiver is called *fading*. Fading may be rapid or slow, general or frequency selective. One of the major causes for fading is the interference between waves, which left the same source but arrived at the receiving antenna by different paths; that is, multipath propagation effects. Since the signal received at any instant is the vector sum of all the waves received, alternate cancellation and reinforcement will result if there is a length variation as large as a half-wavelength between any two paths. The reinforcement, which occurs when the received waves are in phase, can cause the received signal to be up by 6 dB above that received by direct path only. However, when the received waves are 180 degrees out-of-phase, the received signal may be reduced by 30 decibels or more, depending on the relative levels of the signals that are added in antiphase. For satellite systems, fading is due principally to heavy rainfall. There are three basic types of fading: Rayleigh, Rician and Multipath fading.

6.3.1 Rayleigh fading

With land mobile systems there are service areas that are created due to the multiple reflections in which the strength of the signal varies significantly as the receiver move around. In these service areas the transmitted signal reaches the receiving antenna as a result of reflection from a number of nearby objects. If the received signal is only a resultant of reflected waves and no direct wave between the transmitting antenna and the receiving antenna, then we get what is referred to as *Rayleigh fading*. The reflected signals in Rayleigh fading are delayed in time by a period that is comparable with the carrier frequency's periodic time but short compared to the periodic time of the modulating signal.

6.3.2 Rician fading

In some areas the signal getting to the receiver is a resultant of the direct wave and reflected waves from a number of nearby objects. This usually occurs when there is line of sight between the transmitting antenna and receiving antenna. In this instance the resulting type of fading is called *Rician fading*. The reflected signals in Rician fading are also delayed in time by a period that is comparable with the carrier frequency's periodic time but short compared to the periodic time of the modulating signal.

6.3.3 Multipath fading

If the reflected signals are delayed in time by a period that is long compared to the periodic time of the modulating signal, then we get *Multipath fading*.

6.4 Fade Margin and Diversity

The effects of fading can be mitigated to a certain extent by the use of *fade margin* and/or *diversity*.

6.4.1 Fade margin

Fade margin involves the adding of extra power or excess gain to the transmitting end of the link to overcome potential fading. For example, if a system needs a signal-to-noise ratio of *x*-dB, and the maximum likely fade is calculated to be *y*-dB, then the way to a received signal of x-dB is always to transmit enough power to produce a normal received signal of $(x + y)$-dB. The fade margin is normally equal to maximum expected fade. Most propagation studies call for fade margin of about 40 dB.

6.4.2 Diversity

Diversity involves the use of more than one receiving system coupled to a common network, which selects at all times the strongest signal available or combines all the signals into one. This technique, referred to as *diversity reception*, make use of the fact that although fading may be severe at some instant in time, some frequency, some point on earth or some polarization, it is extremely unlikely that the signals at different points, different frequencies or different polarization will fade simultaneously.

There are three principal versions of diversity: *frequency*, *space* and *polarization* diversity. However, there are additional two types of diversity that have since emerged: *temporal* (time) diversity and *pattern* (angle) diversity. In each case the resultant received signal can be obtained by either choosing the strongest signal or by combining all the signals into one.

6.4.2.1 Frequency diversity

The frequency diversity makes use of different carrier frequencies to transmit the same information and at the receiver the two signals are combined after demodulation has taken place. It relies on the fact that phase cancellation of a signal is frequency selective; that is, although a cancellation may be present at one frequency band, it may not at another frequency band. Since frequency diversity is more wasteful of the frequency spectrum, it is used only when other types of diversity cannot be employed, such as in restricted space where receiving antenna cannot be separated sufficiently.

6.4.2.2 Space or spatial diversity

Space diversity, which is also called *spatial* or *antenna* diversity, is obtained by using two or more receiving antennas, which are separated by a fixed number of wavelengths. This separation spacing between the receiving antennas is to make sure that they receive different combinations of wave components in a situation where multipath exists. The best signal at any instant is selected.

6.4.2.3 Polarization diversity

In polarization diversity the receiver is fed from antennas with different planes of polarization. Polarization diversity relies on the fact that as the wave bounces off some obstructions along its path it also exhibits some polarization alterations.

6.4.2.4 Temporal or time diversity

Temporal or time diversity involves lining up and comparing multiple signals that are appearing at the receiving antenna and choosing the one that matches the expected time of arrival for the desired signal. Time diversity is the technique used by CDMA systems to overcome the effects of multipath fading. Through the use of a rake receiver, individual elements or fingers can be offset in time to account for different arrival times of multipath signals.

6.4.2.5 Pattern or angle diversity

Pattern or angle diversity involves the transmission of information at two or more slightly different angles. At the receiver, angle diversity technique uses multiple antenna beams to receive multipath signals arriving at different angles.

6.5 Link Budget

Having discussed how the environment affects the transmitted signal, now its time to calculate the link budget to verify that sufficient signal will reach the receiver. In doing this we need to take into account all the gains and losses from the transmitter to the receiver. In simple terms a link budget can be written as

$$S_r(dBm) = P_t(dBm) + \sum Gains(dB) - \sum Losses(dB) \qquad (1.55)$$

Where the gains include the gain of both the transmitting and the receiving antennas, the losses account for the feeder losses, coupling losses, free-space attenuation and fade margin. Substituting for gains and losses in Equation (1.55) yields

$$\begin{aligned} S_r(dBm) = {} & P_t(dBm) - L_{Bt}(dB) - L_{ft}(dB) + G_{At}(dB) - L_S(dB) - FM(dB) \\ & - L_{Br}(dB) - Lr(dB) + G_{Ar}(dB) \end{aligned} \qquad (1.56)$$

where S_r = received signal power in dBm (or dBW)

P_t = transmitter output power in dBm (or dBW)

L_{ft} = transmit feeder losses in dB

L_{Bt} = transmit coupling losses in dB
G_{At} = transmit antenna gain in dB
L_s = free-space or path loss in dB
FM = fade margin in dB
L_{fr} = receive feeder losses in dB
L_{Br} = receive coupling losses in dB
G_{Ar} = receive antenna gain in dB

The effective power produced by the transmitter; that is, the effective radiated power by the transmitting antenna is referred to as *effective isotropic radiated power, EIRP*. EIRP in dBm (or dBW) is given by the transmitter output power plus the gain of the transmitting antenna, minus coupling losses and the transmit feeder losses. That is,

$$EIRP(dBm) = P_t(dBm) - L_{Bt}(dB) - L_{ft}(dB) + G_{At}(dB) \qquad (1.57)$$

Substituting $P_t(dBm) - L_{Bt}(dB) - L_{ft}(dB) + G_{At}(dB) = EIRP$ in Equation (1.56) we get

$$S_r(dBm) = EIRP(dBm) - L_S(dB) - FM(dB) - L_{Br}(dB) - L_{fr}(dB) + G_{Ar}(dB) \quad (1.58)$$

Figure 1.17 shows the diagram of the components in a link budget. For the system to operate satisfactory the power of the received signal S_r must be greater than or equal to the receiver sensitivity limit (RSL) or squelch, where RSL is the level of the RF signal at the receiver input that will open the receiver.

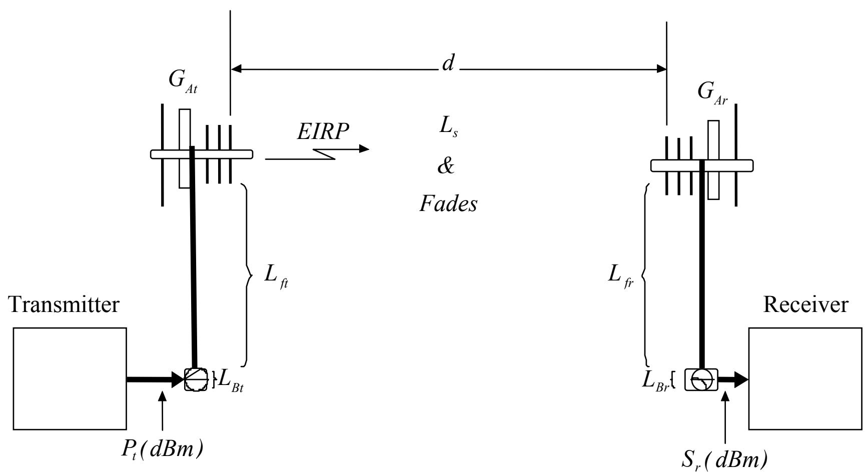


Figure 17 Components of link budget

Example 3: For the simplex communication system shown in Figure 17 above, determine the signal power received at a distance of 100 km from a 10 W transmitter, if the Yagi-Uda antennas used are having a gain of 10 dB each, the loss of the feeder cables (cable connecting the antenna to the transmitter or receiver) is 1.5 dB per cable, total coupling loss is negligible, fade margin is 35 dB, and the frequency is 470 MHz.

Solution

The total power transmitted is

$$P_T = 10W = 10\,log\left(\frac{10W}{1mW}\right) = 40dBm$$

The free space loss is

$$\begin{aligned} L_s &= 32.44 + 20\,log\left(d_{km}\right) + 20\,log\left(f_{MHz}\right) \\ &= 32.44 + 20\,log(100) + log\left(470\right) \\ &= 125.882dB \end{aligned}$$

The signal power received is

$$\begin{aligned} S_r\left(dBm\right) &= P_t\left(dBm\right) - L_{Bt}\left(dB\right) - L_{ft}\left(dB\right) + G_{At}\left(dB\right) - L_S\left(dB\right) - FM\left(dB\right) \\ &\quad - L_{Br}\left(dB\right) - L_{fr}\left(dB\right) + G_{Ar}\left(dB\right) \\ &= 40dBm - 1.5dB + 10dB - 125.882dB - 35dB - 1.5dB + 10dB \\ &= -103.882dBm \end{aligned}$$

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