RF Laboratory Manual - Antenna.

Haim Matzner, Shimshon Levy and Dafna Ackerman.

Febuary 2008.

Contents

1 Prelab Exercise

1. Define the following terms: 'radiation pattern', 'isotropic antenna', 'antenna gain', 'antenna bandwidth', 'antenna input impedance', 'antenna efficiency', 'polarization' and 'dipole antenna'.

2. For a dipole antenna which is designed for $\lambda = 30cm$ ($1\ GHz$) and has $D = 15.3cm$ (D is the largest dimension of the antenna), calculate the boundaries of the reactive and radiating near fields (R_1 and R_2). Are the electric and magnetic fields perpendicular to each other, in each region? Explain why.

3. Calculate the ratio of the power received by the receiving antenna, P_r, to the power input to the transmitting antenna, P_t, by the Friss equation for $\lambda = 30\ cm$, $R = 2\ m$ and $G_t = G_r = 2\ dB$.

4. What is a balun? and why do we need one when using a dipole antenna?

2 Background Theory

Antenna definition: Antennas are dual, metallic devices which are designed for radiating and receiving electromagnetic energy. An antenna acts as a transitional structure between the guiding device (e.g. waveguide, transmission line) and free space.

The dipole antenna which we will discuss later is shown in Figure 1.

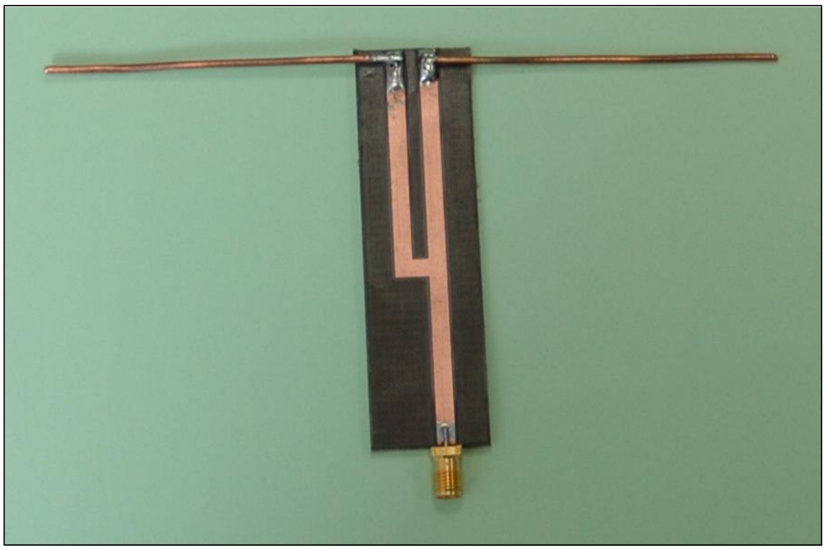

Figure 1 - The dipole antenna with integrated microstrip balun which we will use.

2.1 Near and Far Field Regions

The field patterns, associated with an antenna, change with distance and are associated with two types of energy: **radiating energy** and **reactive energy**. Hence, the space surrounding an antenna can be divided into three regions, as shown in Figure 2.

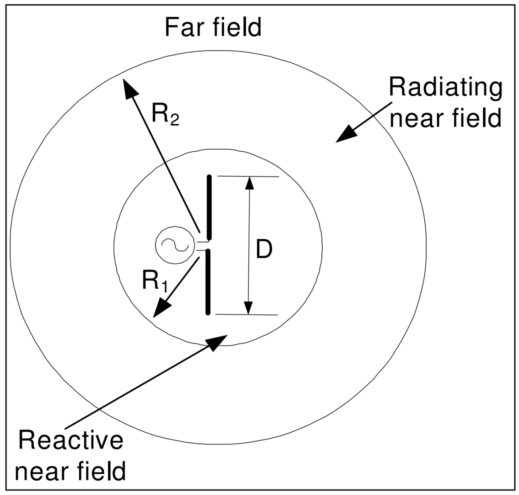

Figure 2 - Field regions around an antenna.

2.1.1 Reactive near-field region:

In this region, the reactive field dominates. The reactive energy oscillates towards and away from the antenna, thus appearing as reactance. In this region, energy is only stored and no energy is dissipated. The outermost boundary for this region is at a distance $R_1 = 0.62\sqrt{D^3/\lambda}$.

Where R_1 is the distance from the center of the antenna surface, D is the largest dimension of the antenna and λ is the wavelength.

2.1.2 Radiating Near Field

Radiating near-field region (also called Fresnel zone): This is the region which lies between the reactive near-field region and the far field region. Reactive fields are smaller in this field as compared to the reactive near-field region and the radiation fields dominate. In this region, the angular field distribution is a function of the distance from the antenna. The outermost boundary for this region is at a distance $R_2 = 2D^2/\lambda$.

Where R_2 is the distance from the center of the antenna surface.

2.1.3 Far-field region (also called Fraunhofer Zone)

The region beyond $2D^2/\lambda$ is the far field region. In this region, the reactive fields are absent and only the radiation fields exist. The angular field distribution is nearly planar and not dependent on the distance from the antenna. In this region the power density in free space varies as the inverse square of the radial distance. In this region only the wave from the antenna can be considered as TEM wave.

2.2 Radiation Pattern

The radiation pattern of an antenna is a plot of the far-field radiation properties of an antenna as a function of the spatial coordinates which are specified by the azimuth angle φ and the elevation angle θ .

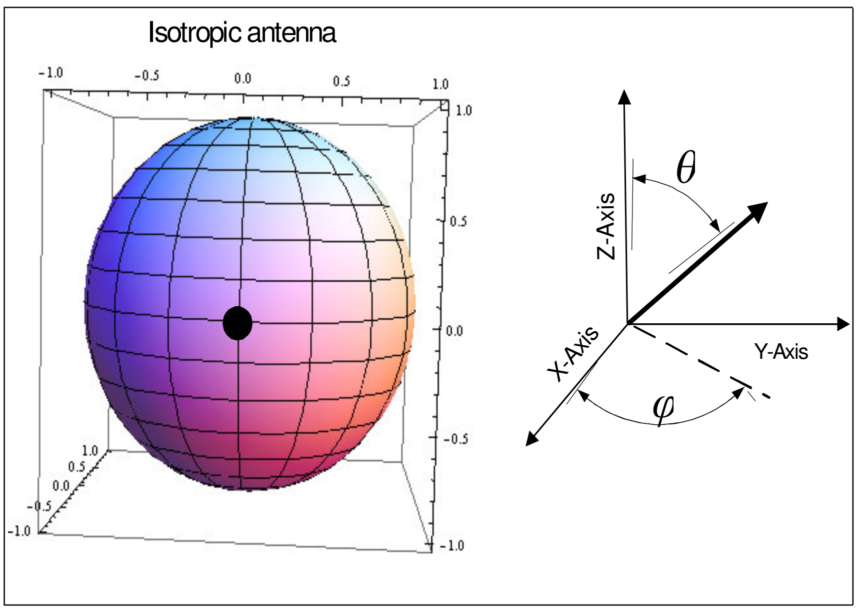

Figure 3 - Pattern of isotropic antenna, as indicated by azimuth φ and elevation θ.

More specifically it is a plot of the power radiated from an antenna per unit solid angle which is nothing but the radiation intensity. Let us consider the case of an ideal isotropic antenna . An isotropic antenna is one which radiates equally in all directions. If the total power radiated by the isotropic antenna is P_{rad} , then the power is spread over a sphere of radius r, so that the power density S (pointing vector) at this distance in any direction is given as:

$$S = \frac{P_{rad}}{Sphere\ area} = \frac{P_{rad}}{4\pi r^2} \quad \left[\frac{Watt}{m^2}\right]$$

Then the radiation intensity U_i for this isotropic antenna can be written as:

$$U_i = \frac{P_{rad}}{solid\ angle} = \frac{P_{rad}}{4\pi} \quad \left[\frac{Watt}{steradian}\right]$$

An ideal isotropic antenna is impossible to realize, in practice it is useful only for comparison purposes. A more practical type is the directional antenna which radiates more power in some directions and less power in other directions. A special case of the directional antenna is the omnidirectional antenna whose radiation pattern may be constant in one plane (e.g. H-plane) and varies in an orthogonal plane (e.g. E-plane). The radiation pattern plot of a generic directional antenna (a dipole) is shown in Figure 4.

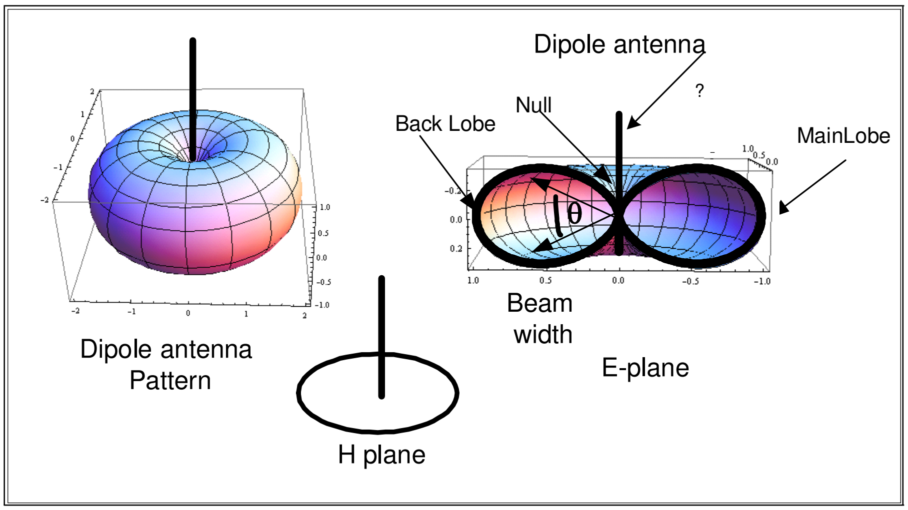

Figure 4 - Radiation patterns.

- The half power beamwidth (HPBW) can be defined as the angle enclosed by the half power points of the main lobe.
- Main Lobe: This is the radiation lobe containing the direction of maximum radiation.

- Minor Lobe: All the lobes other then the main lobe are called the minor lobes. These lobes represent the radiation in undesired directions. The level of minor lobes is usually expressed as a ratio of the power density in the lobe in question to that of the major lobe. This ratio is called as the side lobe level (expressed in decibels).
- Back Lobe: This is the minor lobe diametrically opposite the main lobe.
- Side Lobes: These are the minor lobes adjacent to the main lobe and are separated by various nulls. Side lobes are generally the largest among the minor lobes. In most wireless systems, minor lobes are undesired. Hence a good antenna design should minimize the minor lobes.

2.2.1 Directivity

The directivity of an antenna has been defined as "the ratio of the radiation intensity in a given direction (usually maximum direction) from the antenna to the radiation intensity averaged over all directions". In other words, the directivity of a non - isotropic source is equal to the ratio of its radiation intensity in a given (maximum) direction, over that of an isotropic source.

$$D_{\max} = \frac{U_{\max}}{U_i}$$

Where $D_{\max}$ is the maximum directivity,
$U_{\max}$ is the maximum radiation intensity.

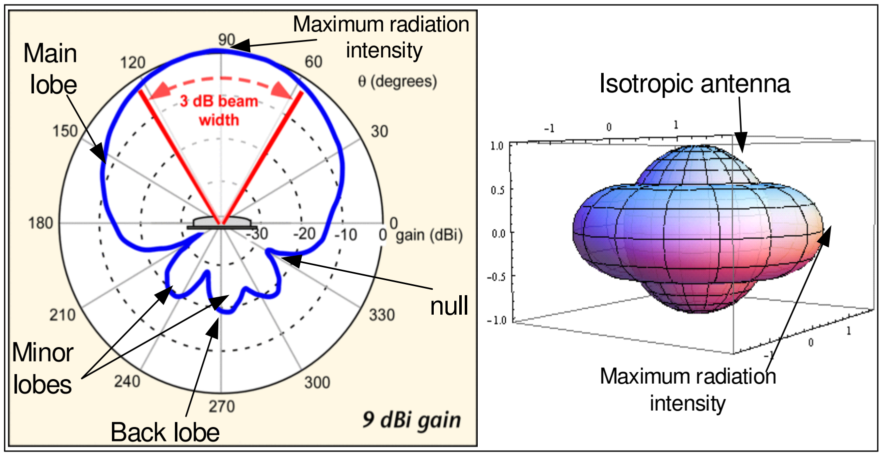

Figure 5 - Directivity of isotropic and dipole antenna.

Directivity is a dimensionless quantity, since it is the ratio of two radiation intensities. Hence, it is generally expressed in dBi. The directivity of an antenna can be easily estimated from the radiation pattern of the antenna. An antenna that has a narrow main lobe would have better directivity, then the one which has a broad main lobe, hence it is more directive.

2.2.2 Input Impedance

The input impedance of an antenna is defined as "the impedance presented by an antenna at its terminals or the ratio of the voltage to the current at the pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point". Hence the impedance of the antenna can be written as:

$$Z_{in} = R_{in} + jX_{in}$$

Where Z_{in} is the antenna impedance at the input terminal,

R_{in} is the antenna resistance at the input terminal,

X_{in} is the antenna reactance at the input terminal (X_{in} represents the power stored in the near field of the antenna).

R_{in} the resistive part, of the input impedance consists of two components:

$$R_{in} = R_{Rad} + R_{Loss}$$

R_{Rad} the radiation resistance, which is desired to be the significant part of R_{in}.

R_{Loss} loss resistance, should be kept as small as possible.

The power associated with the radiation resistance is the power actually radiated by the antenna, while the power dissipated in the loss resistance is lost due to heat in the antenna itself due to dielectric or conducting losses.

2.2.3 Antenna Efficiency

The antenna efficiency is a parameter which takes into account the amount of losses at the input terminal of the antenna and within the structure of the antenna. These losses are given as:

- Reflections because of a mismatch between the line feed and the antenna.
- Losses - Ohmic due to imperfect conductor and dielectric due to imperfect insulator (dielectric material).

Hence the total antenna efficiency can be written as:

$$\begin{aligned} \eta_t &= \eta_r \eta_c \eta_d \\ \eta_r &= \left(1 - |\Gamma|^2\right) \end{aligned}$$

Where η_t is the total antenna efficiency.

η_r is the reflection (mismatch) efficiency

η_c is the conduction efficiency.

η_d is the dielectric efficiency.

Since η_c and η_d are difficult to separate, they are lumped together to form the η_{cd} efficiency, which is given as:

$$\eta_{cd} = \eta_c \eta_d = \frac{R_{Rad}}{R_{Rad} + R_{Loss}}$$

η_{cd} is called as the antenna radiation efficiency and is defined as the ratio of the power delivered to the radiation resistance R_{Rad} , to the power delivered to R_{Rad} and losses R_{Loss}.

2.2.4 Antenna Gain

Antenna gain is a parameter which is closely related to the directivity of the antenna. We know that the directivity is how much an antenna concentrates energy in one direction in preference to radiation in other directions. Hence, if the antenna is lossless (100% efficient), than the directivity would be equal to the antenna gain.

Since most of the antennas will radiate more in some direction than in the others, the gain is the amount of power that can be achieved in one direction at the expense of the power lost in the others. It is given as:

$$G(\theta, \varphi) = \eta_{cd} \cdot D(\theta, \varphi) \quad [dBi]$$

2.2.5 Polarization

The 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 field vector". The polarization of an antenna refers to the polarization of the electric field vector of the radiated wave. In other words, the position and direction of the electric field with reference to the earth's surface or ground determines the wave polarization.

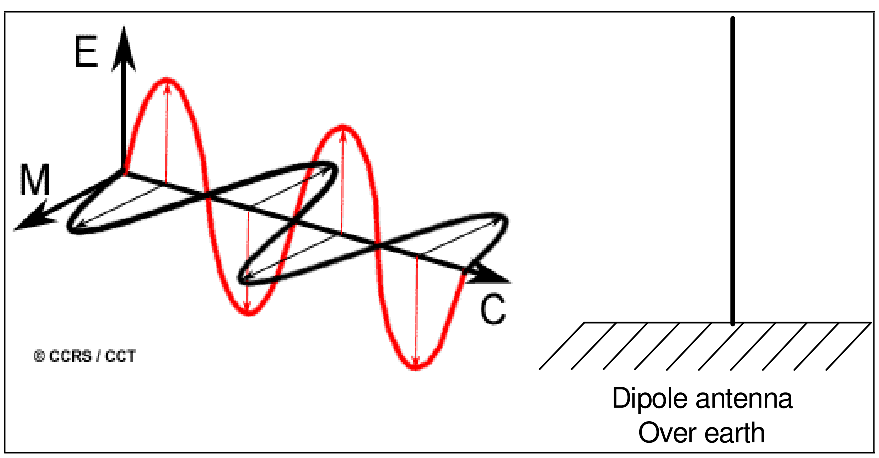

Figure 6 - Vertical linear polarization of dipole antenna. Red line electric field and black line the magnetic field.

The most common types of polarization include the linear (horizontal or vertical) and circular (right hand polarization or the left hand polarization). If the path of the electric field vector is back and forth along a line, it is said to be linearly polarized. Figure 7 shows a linearly polarized wave. In a circularly polarized wave, the electric field vector remains constant in length but rotates around in a circular path. A left hand circular polarized wave is one in which the wave rotates counterclockwise, whereas right hand circular polarized wave exhibits clockwise motion as shown in Figure 7.

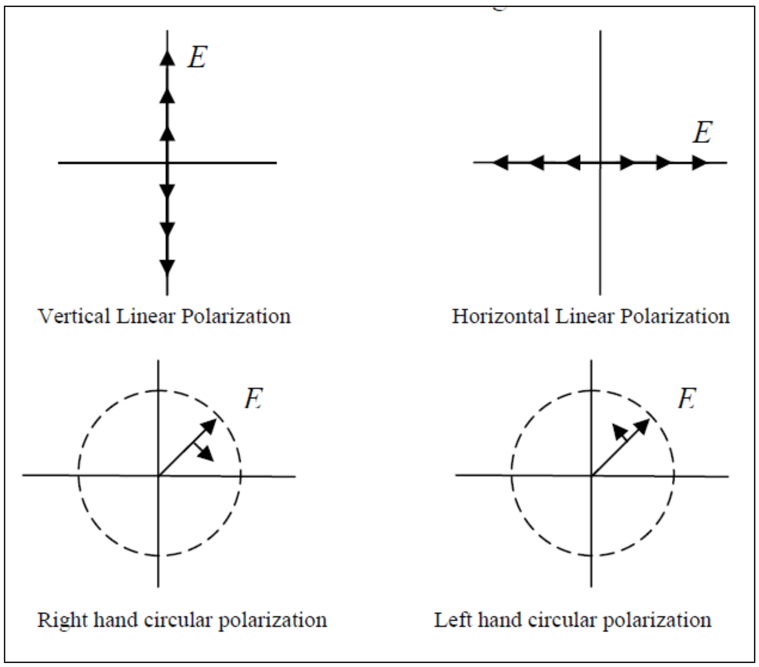

Figure 7 - Commonly used polarization schemes.

Cross Polarization In general, the polarization of the receiving antenna can be different from the polarization of the wave which the antenna received. This causes to a reduced power transfer from the wave to the antenna and it is generally an unwanted phenomenon. For the case where the polarization of the wave is perpendicular to the polarization of the receiving antenna, no power is delivered from the wave to the antenna at all, and it is called 'cross polarization'.

2.2.6 Bandwidth

The bandwidth of an antenna is defined as "the range of usable frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard". in other words, there is no unique characterization of the bandwidth and the specifications are set to meet the needs of each particular application. The reason for this qualitative definition is that all the antenna's parameters change with frequency. The bandwidth can be the range of frequencies on either side of the center frequency where the antenna characteristics, like the input SWR (equivalent return loss), are conform to a specified standard (e.g. SWR=2). For example, the bandwidth of an narrowband antenna is defined as the percentage of the frequency difference over the center frequency:

$$BW_{nar\,\mathrm{row}\,band}\ (\%) = \frac{f_U - f_L}{f_C} \times 100$$

Where f_U is the upper frequency, f_L is the lower frequency, and f_C is the center frequency of the antenna bandwidth.

2.3 Half Wave Length Dipole

The half-wave dipole is one of the most common antennas. It is a straight wire (thus linear) antenna which is fed by an AC source at its center. The length of this antenna is equal to half of its wavelength ($l = \lambda/2$ or $\beta l = \pi$), as the name itself suggests. This antenna is balanced due to its symmetry.

2.3.1 Current distribution

The current distribution along the antenna wire is known as:

$$I(z) = I_0 \cdot \sin(k(\frac{\lambda}{4} - |z|)) \quad ; \quad |z| \leq \lambda/4.$$

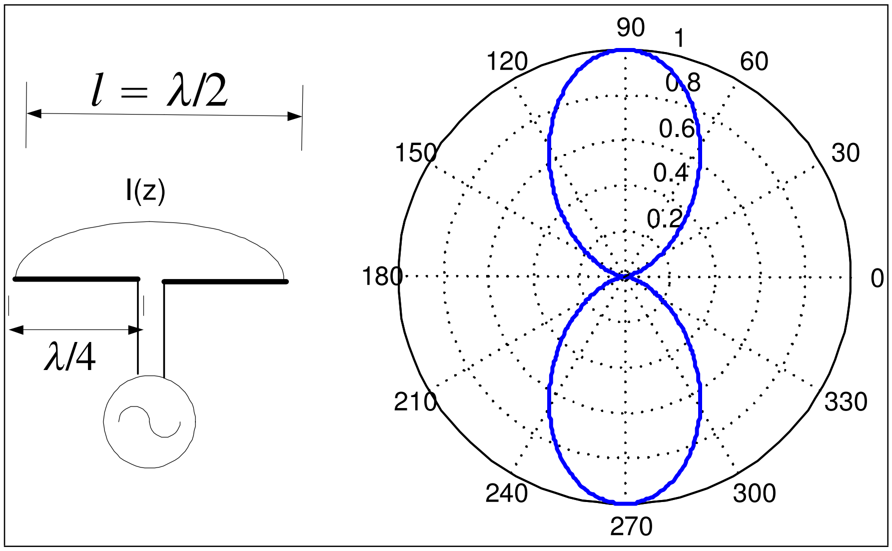

Figure 8 - Current distribution and normalized gain of half wave dipole.

2.3.2 Electric Far Field

$$E_\theta = jI_0\eta \cdot \frac{e^{-jkr}}{4\pi r} \cdot \frac{\cos\left[\frac{\pi}{2}\cos\theta\right]}{\sin\theta}$$

Where $\eta = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}$ is the space impedance.

Note that the maximum occurs at $\theta = \pi/2$.

2.3.3 Gain

The gain is:

$$\begin{aligned} g(\theta) &= C_n \frac{\cos^2\left[\frac{\pi}{2}\cos\theta\right]}{\sin^2\theta} \\ C_n &= \frac{\eta \cdot |I_0|^2}{8\pi^2} \end{aligned}$$

Note that the maximum occurs at $\theta = \pi/2$. Figure 7 (right) shows the normalized gain, assuming $C_n = 1$.

2.3.4 Directivity and Input impedance

Its Input resistance is $R_{in} = 73\Omega$. In practice, the value $R_{in} = 73\Omega$ can be matched easily to the characteristic impedance 50Ω of the feed line.

$$D_{\max} = \frac{\eta}{\pi R_{in}} = 1.64 \rightarrow D_{\max} = 2.15\ dB_i$$

Where $\eta = \sqrt{\frac{\mu}{\epsilon}} = 377\Omega$.

2.4 Friis Transmission Equation

In its simplest form, the Friis transmission equation is as follows. Given two antennas, transmit and received antenna, the ratio of power received by the receiving antenna, P_r, to the power input to the transmitting antenna, P_t, is given by:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Where G_t and G_r are the antenna gain of the transmitting and receiving antennas, respectively. λ is the wavelength and R is the distance between the antennas. The antenna gains are with respect to isotropic (and not in decibels), and the wavelength and distance units must be the same. This simple form applies only under the following ideal conditions:

- The antennas are in unobstructed free space, with no multipath.
- P_t and P_r are understood to be the available power at the transmit and received antenna terminals. There is loss introduced by both the cable running to the antennas and the connectors. Furthermore, the power at the output of the antenna will only be fully delivered into the transmission line if the antenna and transmission line are conjugate matched
- The antennas are correctly aligned and polarized.
- The bandwidth is narrow enough that a single value for the wavelength can be assumed.

The ideal conditions are almost never achieved in ordinary terrestrial communications, due to obstructions, reflections from buildings, and most importantly reflections from the ground. One situation where the equation is reasonably accurate is in satellite communications when there is negligible atmospheric absorption; another situation is in anechoic chambers specifically designed to minimize reflections.

2.5 Balanced Versus Unbalanced Transmission Line

In communications and professional audio, a balanced line or balanced signal pair is a transmission line consisting of two conductors of the same type, and equal impedance to ground and other circuits.

Transmission lines may be designed as balanced or unbalanced. Unbalanced are usually coaxial cables, while balanced are two conductors for radio frequency signals or twisted pair for lower frequencies. A balun may be used to connect the two kinds.

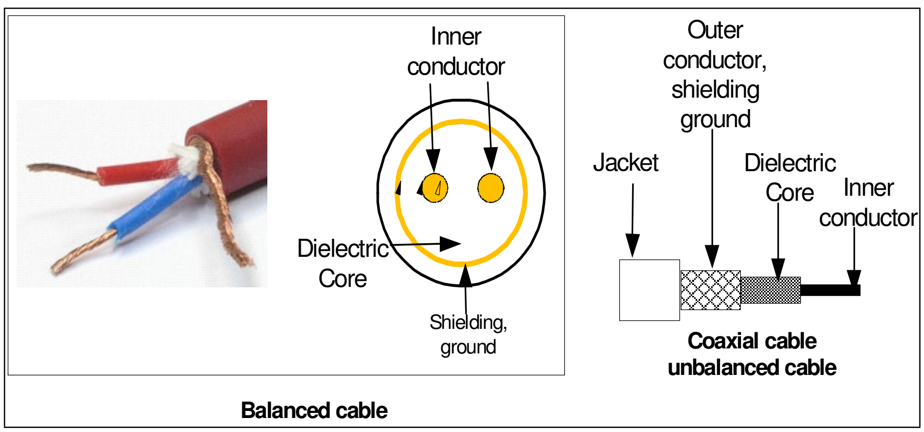

Figure 9 - Balanced and unbalanced cables structures.

Balanced lines are often operated with differential signals. External interfering sources, when present, tend to induce a common mode signal on the line.

The balanced impedances to ground minimizes differential pickup due to stray electric fields. The line is capable of being operated in such a way that when the impedances of the two conductors at all transverse planes are equal in magnitude and opposite in polarity with respect to ground, the currents in the two conductors are equal in magnitude and opposite in direction.

2.6 Antenna Balun

A balun, (balanced to unbalanced) is a type of transformer: it's used to convert an unbalanced signal to a balanced one or vice versa. Baluns isolate a transmission line and provide a balanced output. Some baluns provide impedance transformation in addition to conversion between balanced and unbalanced signal modes; others provide no impedance transformation. For 1:1 baluns (no impedance transformation), the input and output are usually both 50 ohms or 75 ohms. Impedance-transformer baluns with larger ratios are used to match high-impedance balanced antennas to low-impedance unbalanced wireless receivers, transmitters, or transceivers. In order to function at optimum efficiency, a balun must be used with loads whose impedances present little or no reactance (purely resistive). As a general rule, well-designed communications antennas present purely resistive loads of 50, 75, or 300 ohms, although a few antennas have higher resistive impedances.

Baluns can take many forms and their presence is not always obvious. They always involve some form of electromagnetic coupling.

When connecting a dipole antenna to a coaxial cable, we are actually connecting a balanced line to an unbalanced one. The inner and outer conductors of the coax are not coupled to dipole antenna in the same way, thus providing the unbalanced line. The result is a net current flow to ground on the outside part of the outer conductor. On the inner surface of the outer conductor, there is the I_2 current. At the antenna end of the coax, I_2 divides into I_3 and $I_2 - I_3$. Without a device to isolate the antenna from the coax, the outer surface of the coax's shield is a part of the antenna, thus the division in current. I_3 is radiated by the antenna. The currents flows on the coax and antenna are shown in Figure 10.

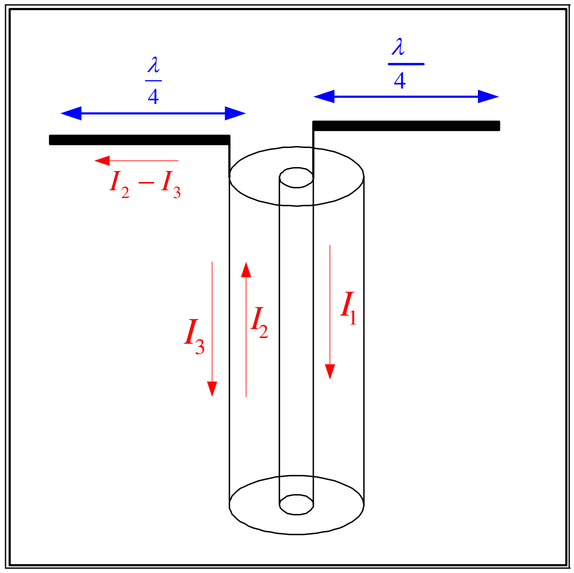

Figure 10 - A coaxial cable connected directly to a dipole antenna.

A balun substantially reduces I_3 current. It has little or no effect on I_1 and I_2 currents. With I_3 reduced to nearly zero, $I_2 \gg I_3$. That means that nearly all of the I_2 current is radiated by the antenna, and none by the coax. The antenna pattern improves and most of the RF current flowing down the outer surface of the coax's shield is eliminated.

2.6.1 $\frac{\lambda}{4}$ coaxial balun (1:1)

This type of balun requires that one end of a $\frac{\lambda}{4}$ section of a line will be connected to the outside shield of the main line while the other is connected to the dipole which is attached to the center conductor, as shown in Figure 11.

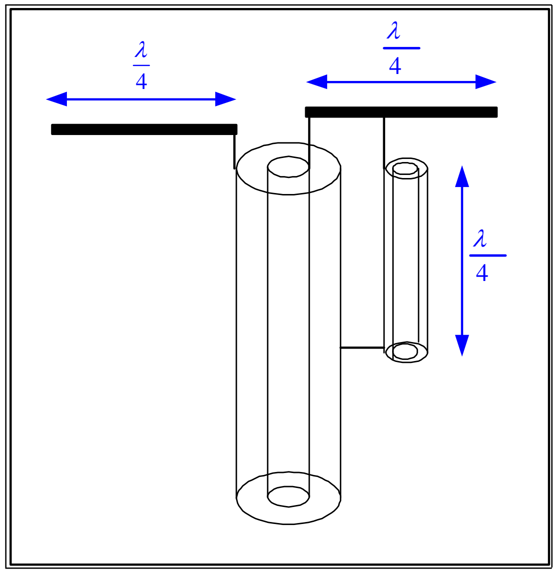

Figure 11 - A coaxial cable connected to a dipole with a balun.

The current flow on the outer shield of the main coax is canceled at the bottom end of the $\frac{\lambda}{4}$ section (where the two join together). It should be stated that the parallel auxiliary coax need not to be made $\frac{\lambda}{4}$ in length to achieve the balance. It is made $\frac{\lambda}{4}$ to prevent the upsetting of the normal operation of the antenna.

3 Experiment Procedure

3.1 Required Equipment

1. RF network analyzer.
2. Type N calibration kit HP - 85032E.
3. Terminator 50 Ω.
4. Two dipole antennas.
5. Tripod Gitzo G1348.

3.2 Return Loss, Bandwidth and Input Impedance of a Dipole Antenna

In this part of the experiment you will measure the return loss of a dipole antenna, observe its bandwidth and measure its input impedance at resonance (in its bandwidth).

1. Measure the length of the dipole antenna and calculate its resonant frequency.
2. Preform a reflection calibration on the network analyzer. Place the antenna on the tripod at horizontal polarization and connect the antenna to port 1 of the network analyzer by a coaxial cable, as indicated in Figure 1.

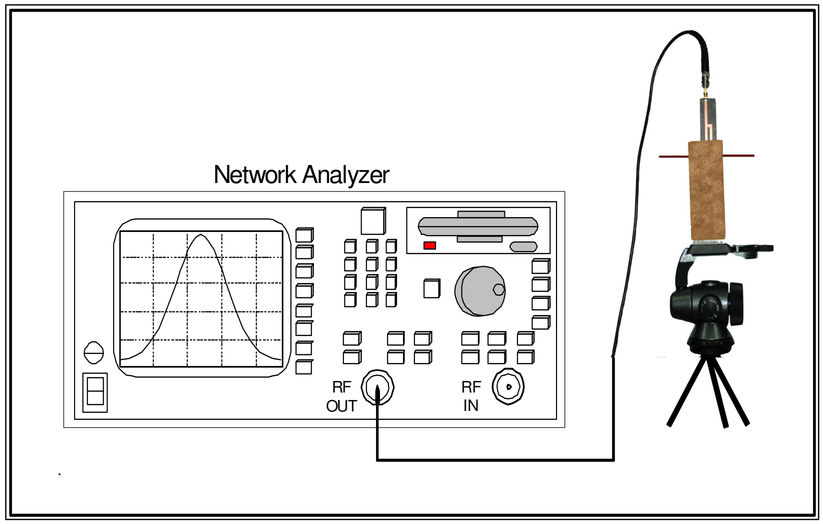

Figure 1 - Return loss, bandwidth and input impedance measurements of a dipole antenna.

3. Set the network analyzer to reflection and measure the return loss (S_{11}) of the antenna in the frequency range of 500 MHz - 1.3 GHz. **Save the data on magnetic media**.

4. Measure the bandwidth of the antenna according to the specification which indicates that S_{11} should be lower than -9.5 dB.

5. Set the network analyzer to smith chart measurement and measure the input impedance of the antenna at resonance. **Save the data on magnetic media**. What is the radiation resistance?

3.3 Antenna Pattern Cut Measurement

In this part of the experiment you will measure two main fields of the antenna; the electric and magnetic fields in open site (a place with minimum reflections).

3.3.1 E field Cut At Open Space

1. Connect the transmitting dipole antenna directly to the signal generator at horizontal polarization. Place the receiving dipole to the tripod

and connect it to a spectrum analyzer by a coaxial cable. Set the degree meter of the tripod to 0^0. The receiving dipole should be parallel to the transmitting dipole and at the same height. Figure 2 shows the system.

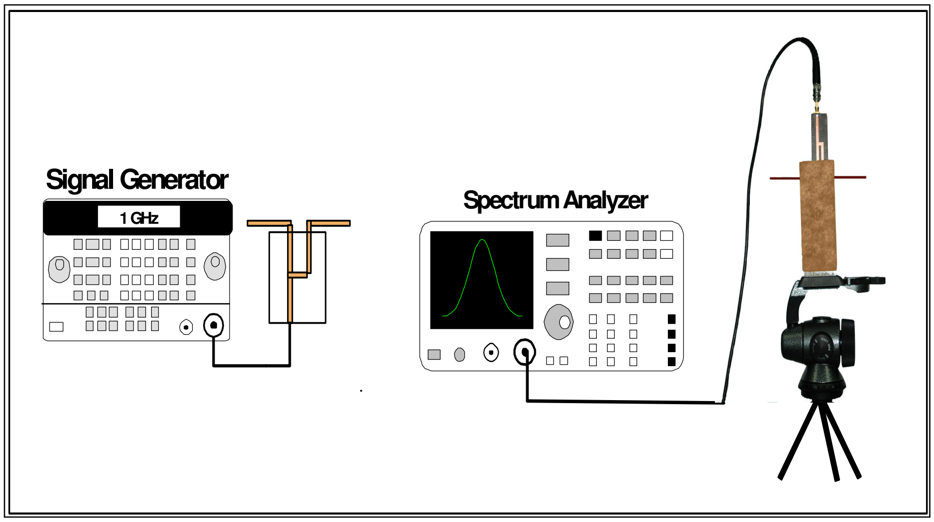

Figure 2 - Radiation patern measurement.

2. Set the signal generator to 1 GHz and an amplitude of 0 dBm. Set the spectrum analyzer to center frequency of 1 GHz, span of 50 MHz and Y axis units to Volts.

3. Move the receiving antenna to the outermost boundary of the near field region (R_2 from question 2 of the 'Prelab Exercise').

4. Move the receiving antenna 2 m away from the transmitting antenna and measure the received power at the receiving antenna and compare it to the calculated FRIIS equation (question 3 of the 'Prelab Exercise').

5. Use the degree meter of the tripod and rotate the receiving antenna, at 10° steps over the horizontal plane (E field cut), θ is from 0° to 360°. For each position measure the received power.

6. Draw the graph of the E plane of the antenna pattern in polar representation (use matlab), and find the measured beamwidth of the dipole antenna.

7. Move the receiving antenna to the outermost boundary of the near field region (at R_2) and measure the power

8. Place the transmitting dipole antenna perpendicular to the receiving antenna, according to Figure 3.

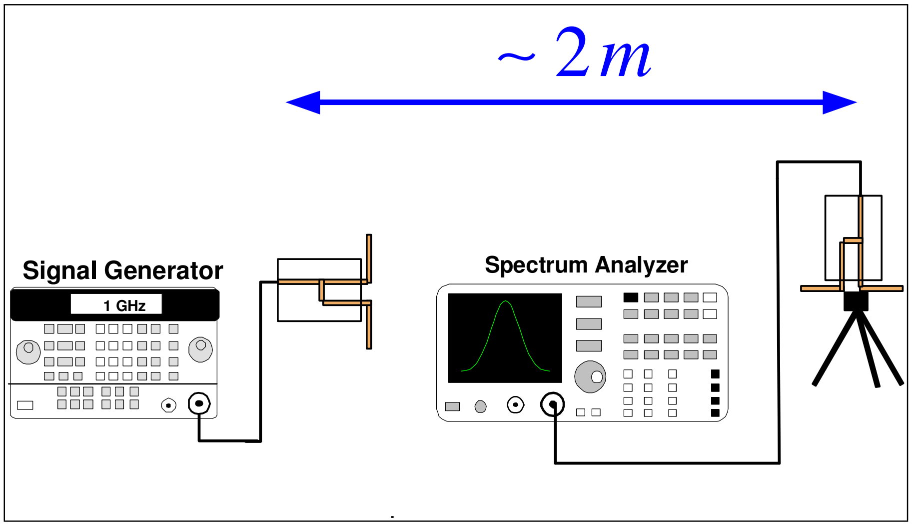

Figure 3

Measure the received power and explain why is the power has decreased?

3.3.2 H field Cut At Open Space

1. Connect the antennas at vertical polarization as shown in Figure 4.

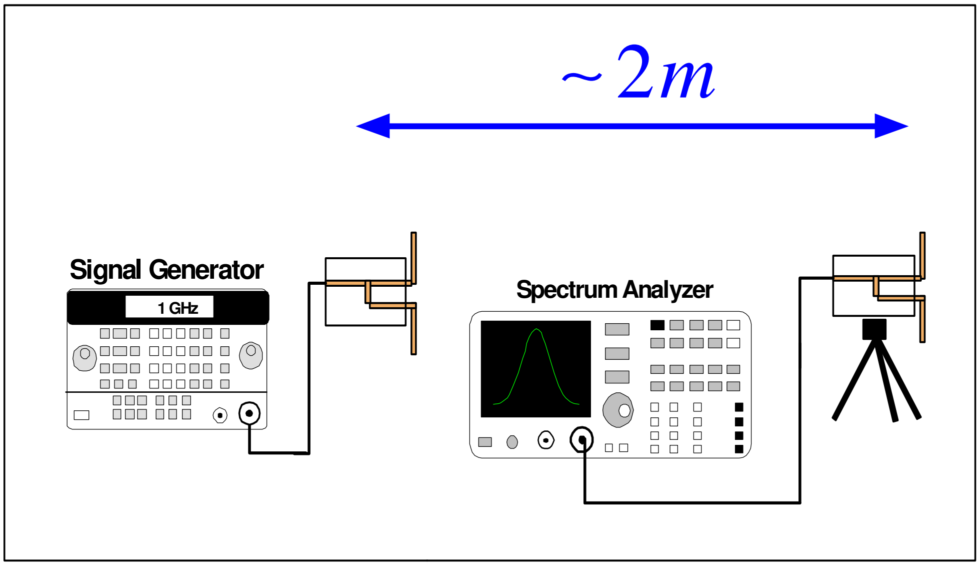

Figure 4 - H plane measurement.

2. Use the degree meter of the tripod and rotate the receiving antenna, at 10° steps over the horizontal plane (now it is the H field cut), ϕ is from 0° to 360°. For each position measure the received power.

3. Draw the graph of the H plane of the antenna pattern in polar representation (use matlab).

3.4 Final Report

1. Attach all the graphs to the report.

2. Using matlab, drew the ideal E and H planes of a dipole antenna for f = 1GHz. Specify the possible errors which could have produced the deviation from your results to the theoretical.

3. Is there a distinctive difference between the value of the average power received by the horizontal polarization to this received by the vertical polarization? Explain why.

4. A half-wavelength dipole antenna with $L = 0.15m$ ($f\ = 1GHz$) and $BW = 10\ MHz$ is transmitting to a receiving dipole antenna (with the

same length and BW as the transmitting dipole) which is 10 m away from the transmitting dipole. The transmitting dipole has an input power of 1 $Watt$ and SWR of 1.1 to its source. The two antennas have $G_t = G_r = 2\ dB$. The channel has a noise power density of $10^{-15}\ \frac{Watt}{Hz}$. Calculate:

(a) The actual transmitted power (firstly calculate Γ).

(b) The power received by the receiving dipole antenna (use Friis equation).

(c) The SNR at the receiving antenna terminals.