UNIT – I

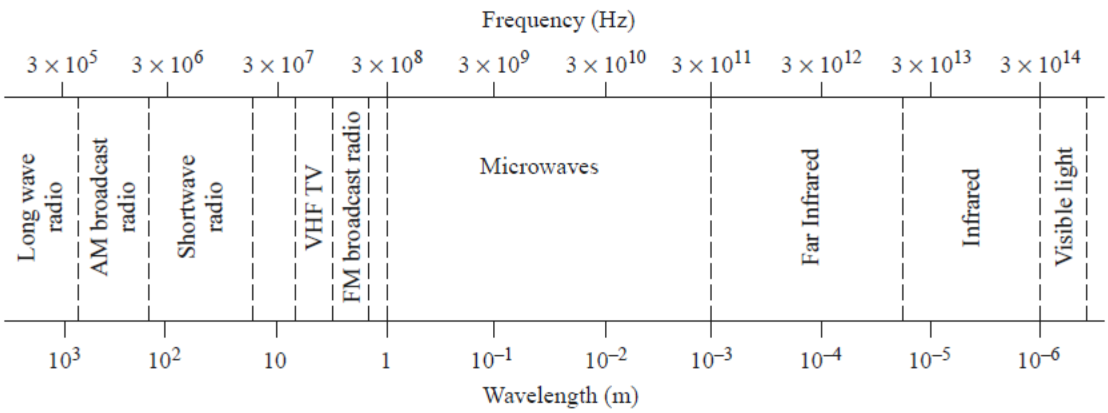
INTRODUCTION TO MICROWAVE SYSTEMS AND ANTENNAS

Microwave frequency bands, Physical concept of radiation, Near- and far-field regions, Fields and Power Radiated by an Antenna, Antenna Pattern Characteristics, Antenna Gain and Efficiency, Aperture Efficiency and Effective Area, Antenna Noise Temperature and G/T, Impedance matching, Friis transmission equation, Link budget and link margin, Noise Characterization of a microwave receiver.

1. Microwave Frequency Bands

The field of radio frequency (RF) and microwave engineering generally covers the behaviour of alternating current signals with frequencies in the range of 100 MHz. RF frequencies range from very high frequency (VHF) (30–300 MHz) to ultra-high frequency (UHF) (300–3000 MHz), while the term *microwave* is typically used for frequencies between 3 and 300 GHz, with a corresponding electrical wavelength between $\lambda = c/f = 10$ cm and $\lambda = 1$ mm, respectively.

Signals with wavelengths on the order of millimeters are often referred to as *millimeter waves.* Because of the high frequencies (and short wavelengths), standard circuit theory often cannot be used directly to solve microwave network problems. In a sense, standard circuit theory is an approximation, or special case, of the broader theory of electromagnetics as described by Maxwell's equations. This is due to the fact that, in general, the lumped circuit element approximations of circuit theory may not be valid at high RF and microwave frequencies. Microwave components often act as *distributed elements,* where the phase of the voltage or current changes significantly over the physical extent of the device because the device dimensions are on the order of the electrical wavelength. At much lower frequencies the wavelength is large enough that there is insignificant phase variation across the dimensions of a component. The other extreme of frequency can be identified as optical engineering, in which the wavelength is much shorter than the dimensions of the component. In this case Maxwell's equations can be simplified to the geometrical optics regime, and optical systems can be designed with the theory of geometrical optics.



Typical Frequencies

AM broadcast band	535–1605 kHz
Short wave radio band	3–30 MHz
FM broadcast band	88–108 MHz
VHF TV (2–4)	54–72 MHz
VHF TV (5–6)	76–88 MHz
UHF TV (7–13)	174–216 MHz
UHF TV (14–83)	470–890 MHz
US cellular telephone	824–849 MHz
	869–894 MHz
European GSM cellular	880–915 MHz
	925–960 MHz
GPS	1575.42 MHz
	1227.60 MHz
Microwave ovens	2.45 GHz
US DBS	11.7–12.5 GHz
US ISM bands	902–928 MHz
	2.400–2.484 GHz
	5.725–5.850 GHz
US UWB radio	3.1–10.6 GHz

Approximate Band Designations

Medium frequency	300 kHz–3 MHz
High frequency (HF)	3 MHz–30 MHz
Very high frequency (VHF)	30 MHz–300 MHz
Ultra high frequency (UHF)	300 MHz–3 GHz
L band	1–2 GHz
S band	2–4 GHz
C band	4–8 GHz
X band	8–12 GHz
Ku band	12–18 GHz
K band	18–26 GHz
Ka band	26–40 GHz
U band	40–60 GHz
V band	50–75 GHz
E band	60–90 GHz
W band	75–110 GHz
F band	90–140 GHz

Figure 1.1 The electromagnetic spectrum.

1.1 Applications of Microwave Engineering

- Antenna gain is proportional to the electrical size of the antenna. At higher frequencies, more antenna gain can be obtained for a given physical antenna size, and this has important consequences when implementing microwave systems.
- More bandwidth (directly related to data rate) can be realized at higher frequencies. A 1% bandwidth at 600 MHz is 6 MHz, which (with binary phase shift keying modulation) can provide a data rate of about 6 Mbps (megabits per second), while at 60 GHz a 1% bandwidth is 600 MHz, allowing a 600 Mbps data rate.
- Microwave signals travel by line of sight and are not bent by the ionosphere as are lower frequency signals. Satellite and terrestrial communication links with very high capacities are therefore possible, with frequency reuse at minimally distant locations.
- The effective reflection area (radar cross section) of a radar target is usually proportional to the target's electrical size. This fact, coupled with the frequency

characteristics of antenna gain, generally makes microwave frequencies preferred for radar systems.

- Various molecular, atomic, and nuclear resonances occur at microwave frequencies, creating a variety of unique applications in the areas of basic science, remote sensing, medical diagnostics and treatment, and heating methods.

2. Introduction to Antennas

Definition - "a usually metallic device (as a rod or wire) for radiating or receiving radio waves."

IEEE Standard Definitions of Terms for Antennas **-** "a means for radiating or receiving radio waves." In other words, the antenna is the transitional structure between free-space and a guiding device.

The guiding device or transmission line may take the form of a coaxial line or a hollow pipe (waveguide), and it is used to transport electromagnetic energy from the transmitting source to the antenna, or from the antenna to the receiver. In the former case, we have a transmitting antenna and, in the latter, a receiving antenna.

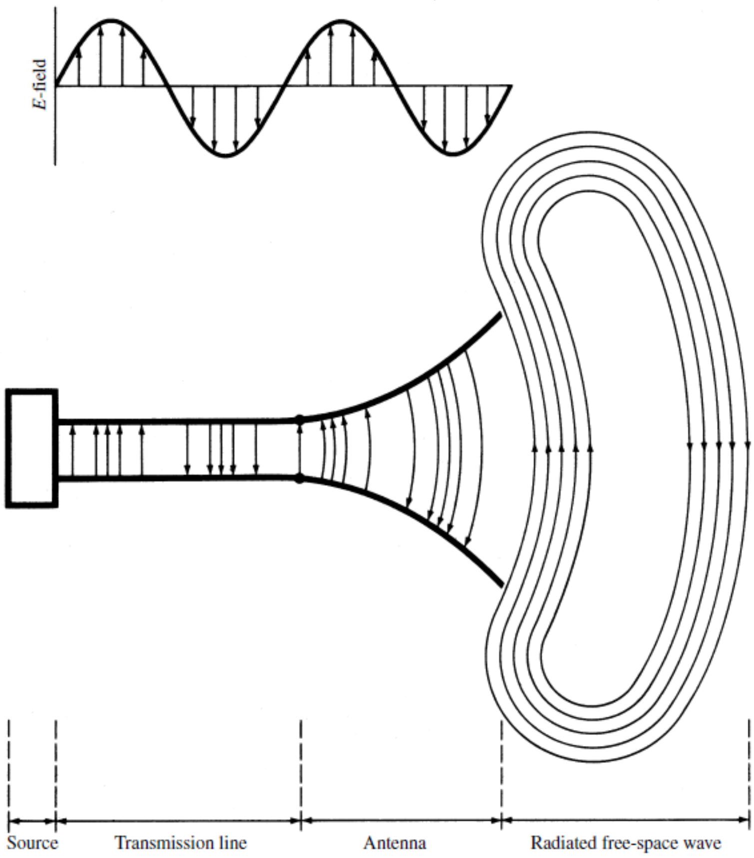


Figure 1.2 Antenna as a transition device.

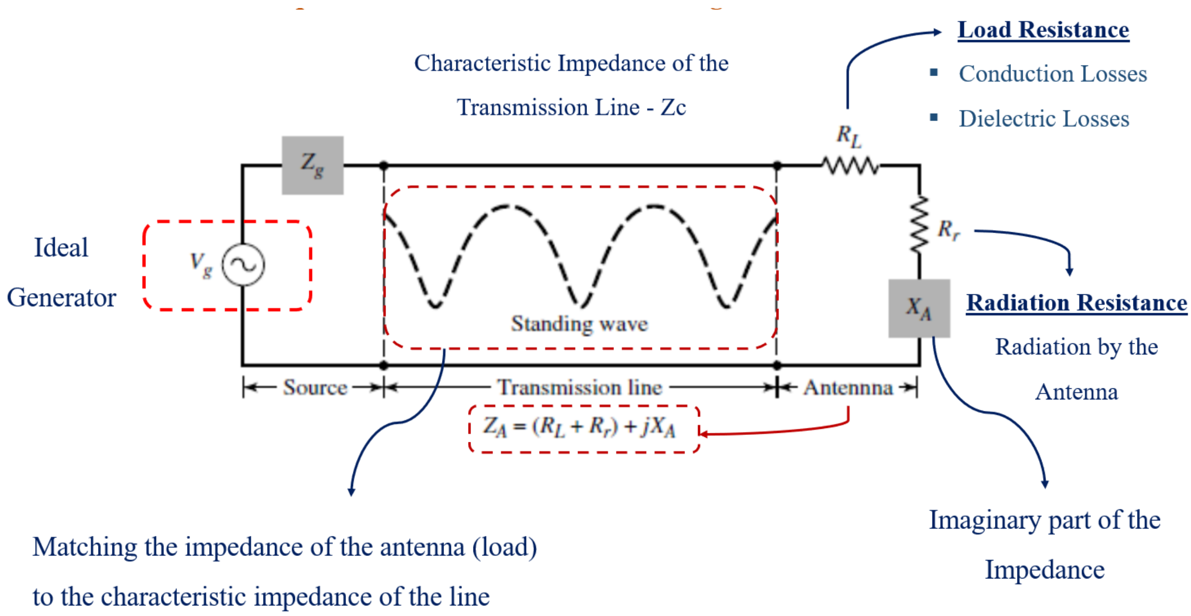


Figure 1.3 Transmission-line Thevenin equivalent of antenna in transmitting mode.

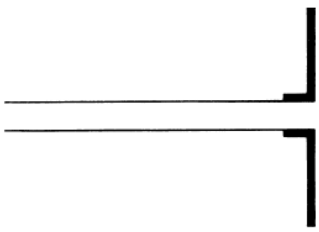
A transmission-line Thevenin equivalent of the antenna system of Figure. in the transmitting mode is shown in Figure 1.3 where the source is represented by an ideal generator, the transmission line is represented by a line with characteristic impedance Z_c, and the antenna is represented by a load Z_A [Z_A = (R_L + R_r) + jX_A] connected to the transmission line. The Thevenin and Norton circuit equivalents of the antenna. The load resistance R_L is used to represent the conduction and dielectric losses associated with the antenna structure while R_r, referred to as the ***radiation resistance***, is used to represent radiation by the antenna. The reactance X_A is used to represent the imaginary part of the impedance associated with radiation by the antenna. Under ideal conditions, energy generated by the source should be totally transferred to the radiation resistance *Rr* , which is used to represent radiation by the antenna. However, in a practical system there are conduction-dielectric losses due to the lossy nature of the transmission line and the antenna, as well as those due to reflections (mismatch) losses at the interface between the line and the antenna. Considering the internal impedance of the source and neglecting line and reflection (mismatch) losses, maximum power is delivered to the antenna under ***conjugate matching***.

The reflected waves from the interface create, along with the traveling waves from the source toward the antenna, constructive and destructive interference patterns, referred to as ***standing waves***, inside the transmission line which represent pockets of energy concentrations and storage, typical of resonant devices.

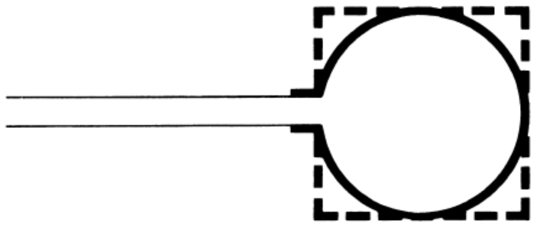
The losses due to the line, antenna, and the standing waves are undesirable. The losses due to the line can be minimized by selecting low-loss lines while those of the antenna can be decreased by reducing the loss resistance represented by *RL*. The standing waves can be reduced, and the energy storage capacity of the line minimized, by matching the impedance of the antenna (load) to the characteristic impedance of the line.

3. Types of Antennas

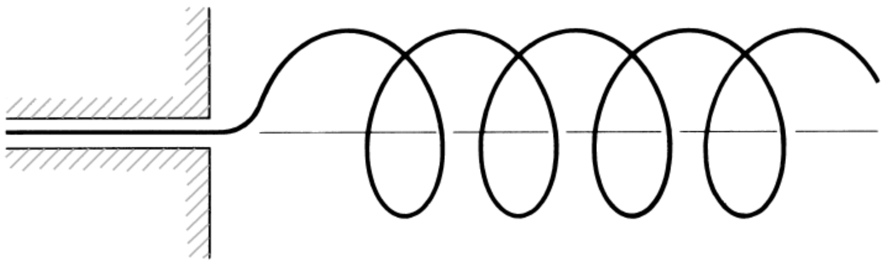
a) Wire Antennas



(a) Dipole

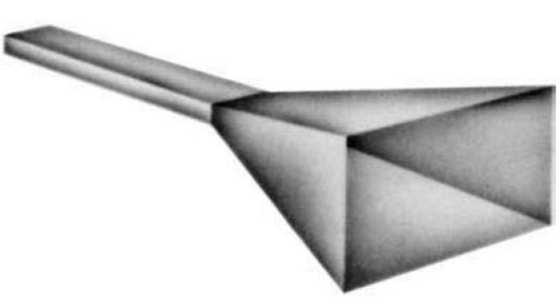


(b) Circular (square) loop



(c) Helix

b) Aperture Antennas



(a) Pyramidal horn

(b) Conical horn

Figure 1.4 Aperture antenna configurations.

c) Microstrip Antennas

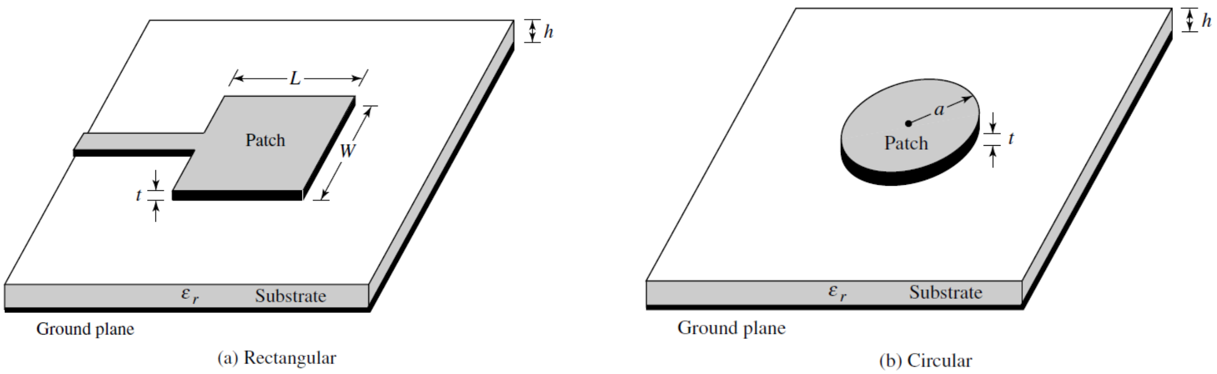


Figure 1.5 Rectangular and circular microstrip (patch) antennas

d) Array Antennas

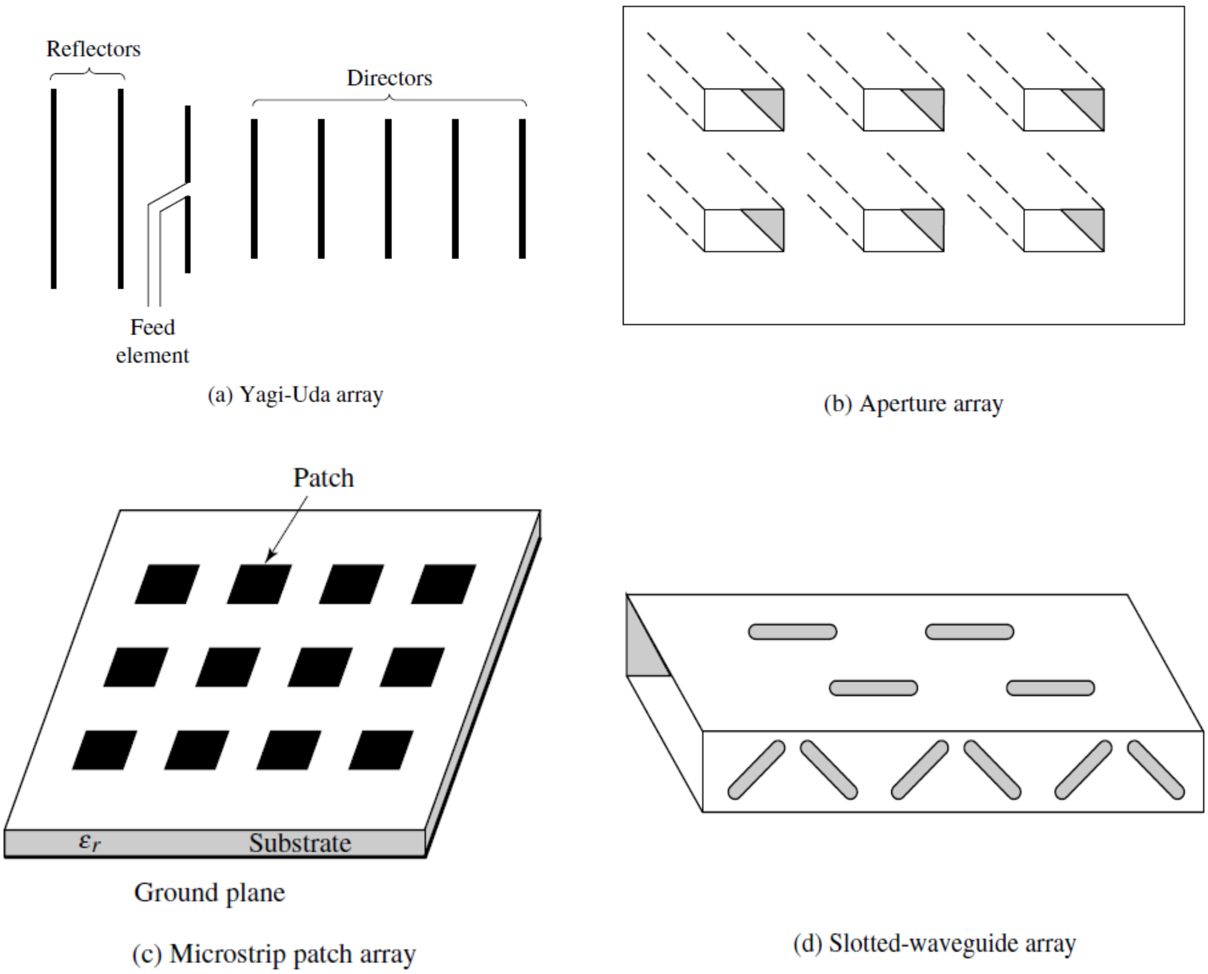


Figure 1.6 Typical wire, aperture, and microstrip array configurations.

e) Reflector Antennas

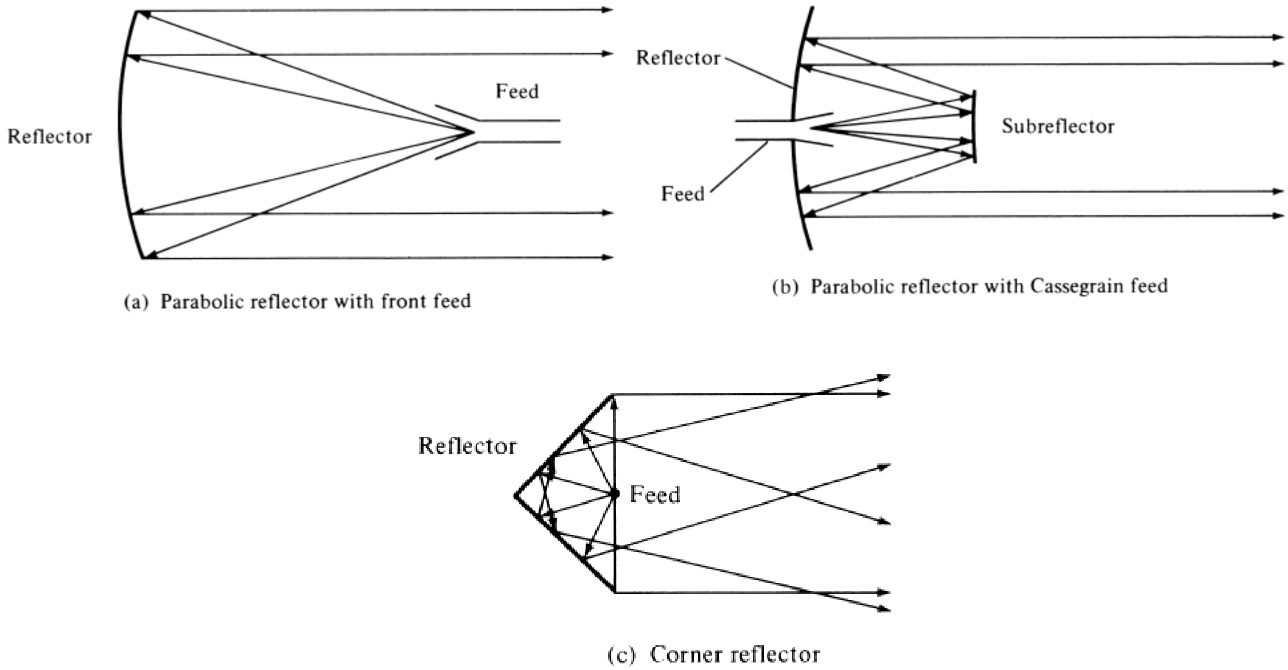


Figure 1.7 Typical reflector configurations.

f) Lens Antennas

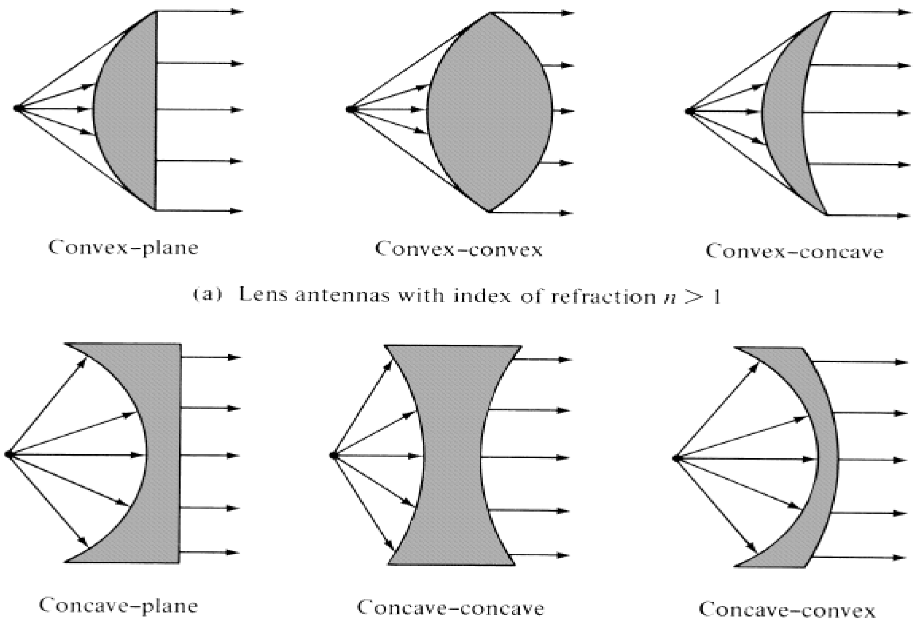


Figure 1.8 Typical lens antenna configurations

4. Physical Concept of Radiation (Radiation Mechanism)

One of the first questions that may be asked concerning antennas would be "how is radiation accomplished?"

In other words, how are the electromagnetic fields generated by the source, contained and guided within the transmission line and antenna, and finally "detached" from the antenna to form a free-space wave?

Let us first examine some basic sources of radiation

4.1 Radiation from Single Wire

Conducting wires are material whose prominent characteristic is the motion of electric charges and the creation of current flow.

The total charge Q Within volume V is moving in the z direction with a uniform velocity v_z (meters/sec). It can be shown that the current density J_z (amperes/m^2) over the cross section of the wire is given by

$$J_z = q_v v_z$$

If the wire is made of an ideal electric conductor, the current density J_s (amperes/m) resides on the surface of the wire and it is given by

$$J_s = q_s v_z$$

$$q_s - \text{surface charge density}$$

If the wire is very thin (ideally zero radius), then the current in the wire can be represented by

$$I_z = q_l v_z$$

$$q_l - \text{charge per unit length}$$

Instead of examining all three current densities, we will primarily concentrate on the very thin wire. The conclusions apply to all three. If the current is time varying, then the derivative of the current of can be written as

$$\frac{dI_z}{dt} = q_l \frac{dv_z}{dt} = q_l a_z$$

If the wire is of length l, then can be written as

$$l\frac{dI_z}{dt} = lq_l \frac{dv_z}{dt} = lq_l a_z$$

It simply states that *to create radiation, there must be a time-varying current or an acceleration (or deceleration) of charge*.

Periodic charge acceleration (or deceleration) or time-varying current is also created when charge is oscillating in a time-harmonic motion, for a $\lambda/2$ dipole. Therefore,

1. If a charge is not moving, current is not created and there is no radiation.
2. If charge is moving with a uniform velocity
    a. There is no radiation if the wire is straight, and infinite in extent.

b. There is radiation if the wire is curved, bent, discontinuous, terminated, or truncated.

3. If charge is oscillating in a time-motion, it radiates even if the wire is straight.

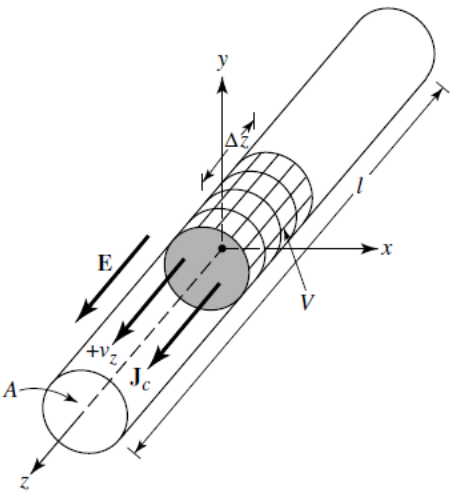


Figure 1.9 Charge uniformly distributed in a circular cross section cylinder wire.

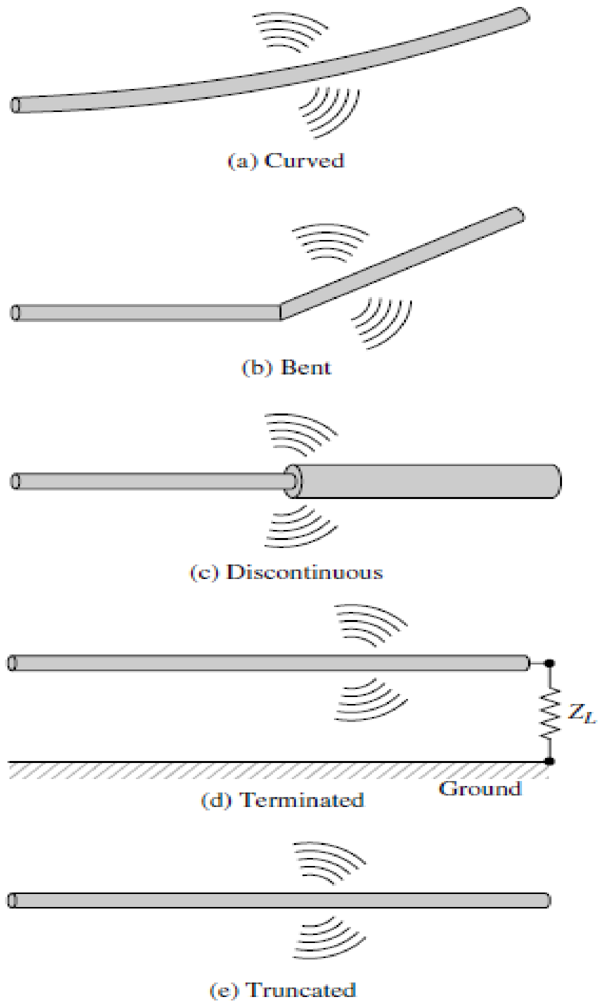
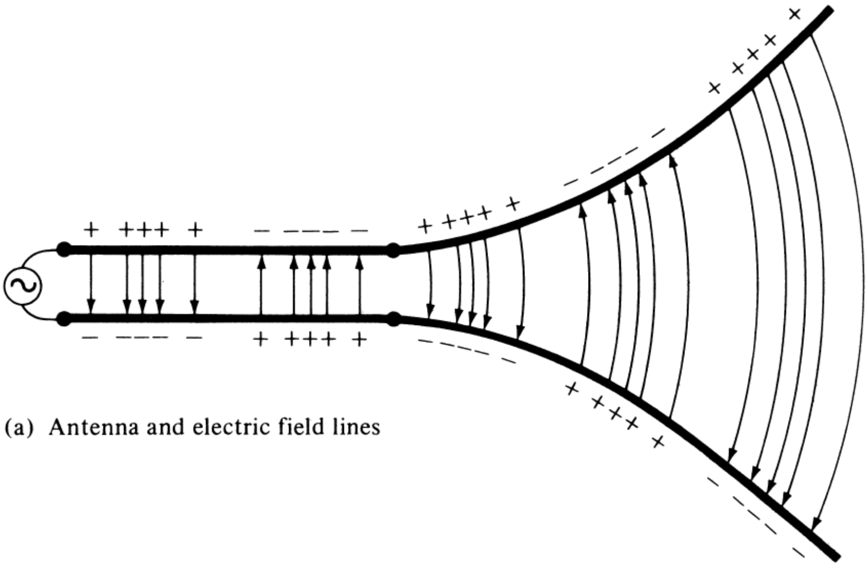


Figure 1.10 Wire configurations for radiation.

4.2 Two Wire

Let us consider a voltage source connected to a two-conductor transmission line which is connected to an antenna. Applying a voltage across the two-conductor transmission line creates an electric field between the conductors. The electric field has associated with it electric lines of force which are tangent to the electric field at each point and their strength is proportional to the electric field intensity. The electric lines of force have a tendency to act on the free electrons (easily detachable from the atoms) associated with each conductor and force them to be displaced. The movement of the charges creates a current that in turn creates a magnetic field intensity. Associated with the magnetic field intensity are magnetic lines of force which are tangent to the magnetic field.



(a) Antenna and electric field lines

Electric field lines start on positive charges and end on negative charges. They also can start on a positive charge and end at infinity, start at infinity and end on a negative charge, or form closed loops neither starting or ending on any charge. Magnetic field lines always form closed loops encircling current-carrying conductors because physically there are no magnetic charges. In some mathematical formulations, it is often convenient to introduce equivalent magnetic charges and magnetic currents to draw a parallel between solutions involving electric and magnetic sources.

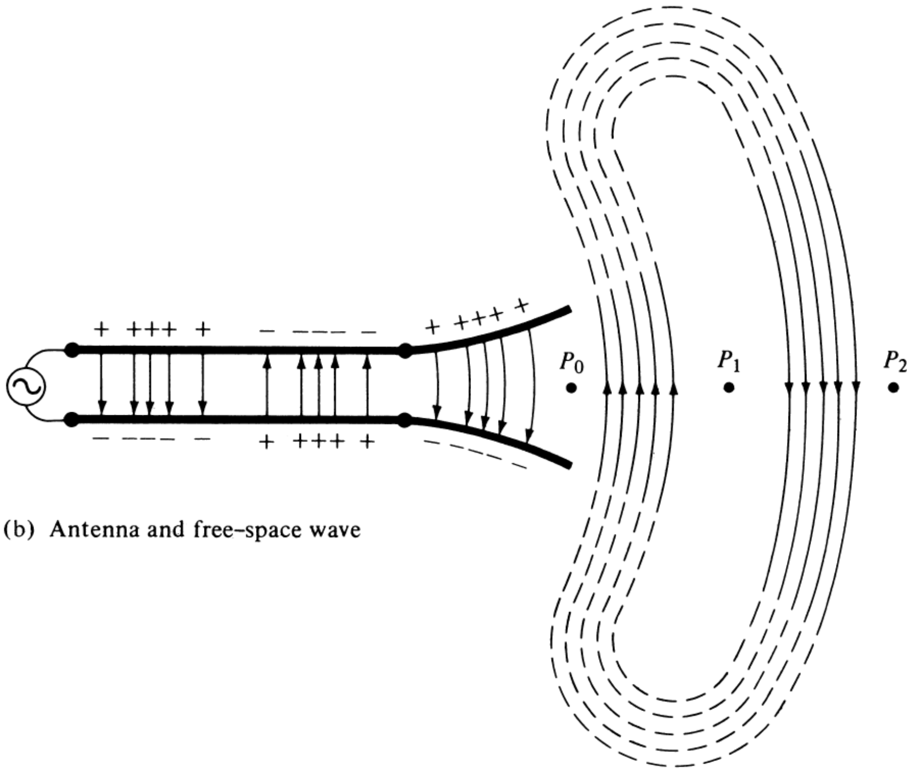


Figure 1.11 Source, transmission line, antenna, and detachment of electric field lines.

4.3 Dipole

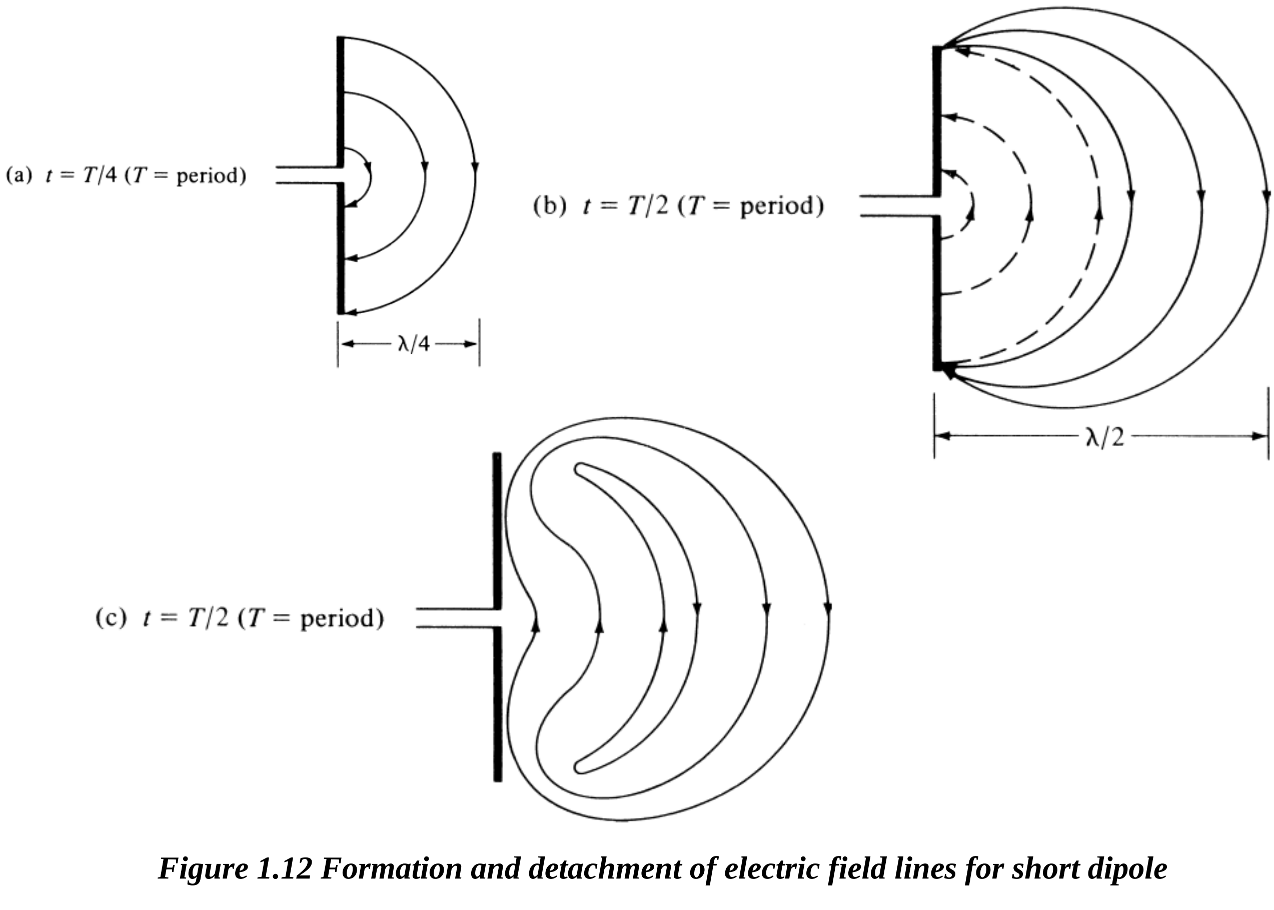


Figure 1.12 Formation and detachment of electric field lines for short dipole

5. Fundamental Parameters of Antenna

To describe the performance of an antenna, definitions of various parameters are necessary. Some of the parameters are interrelated and not all of them need be specified for complete description of the antenna performance.

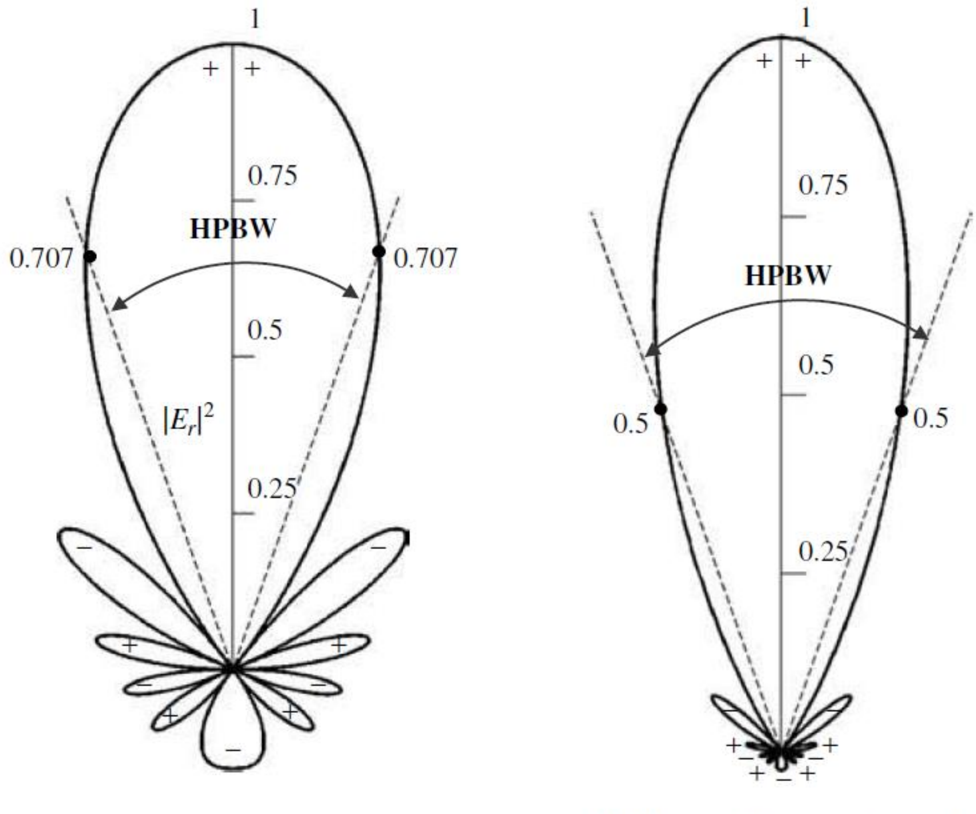
5.1 Radiation Pattern

Definition: “a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase or polarization.”

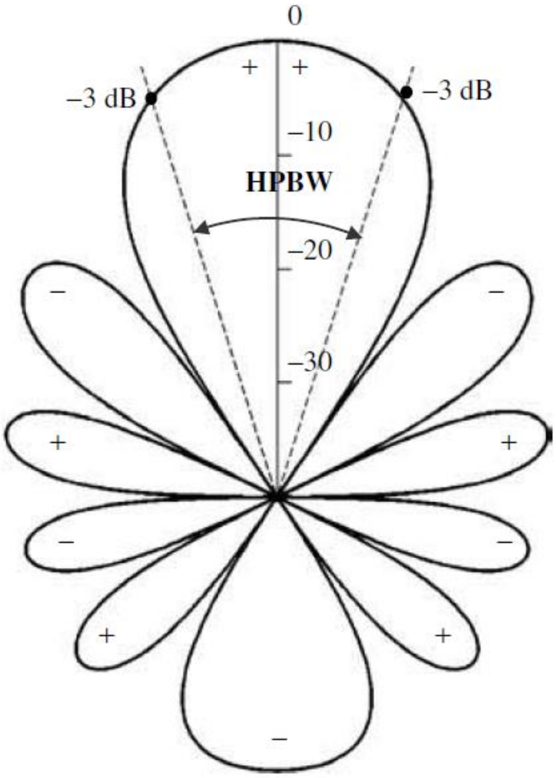
a. *field* pattern(*in linear scale*) typically represents a plot of the magnitude of the electric or magnetic field as a function of the angular space.

b. *power* pattern(*in linear scale*) typically represents a plot of the square of the magnitude of the electric or magnetic field as a function of the angular space.

c. *power* pattern(*in dB*) represents the magnitude of the electric or magnetic field, in decibels, as a function of the angular space.



(a) Field pattern (in linear scale) (b) Power pattern (in linear scale)



(c) Power pattern (in dB)

Figure 1.13 Two-dimensional normalized field pattern(linear scale), power pattern(linear scale), and power pattern(in dB)

5.1.1 Radiation Pattern Lobes

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

A ***radiation lobe*** is a "portion of the radiation pattern bounded by regions of relatively weak radiation intensity."

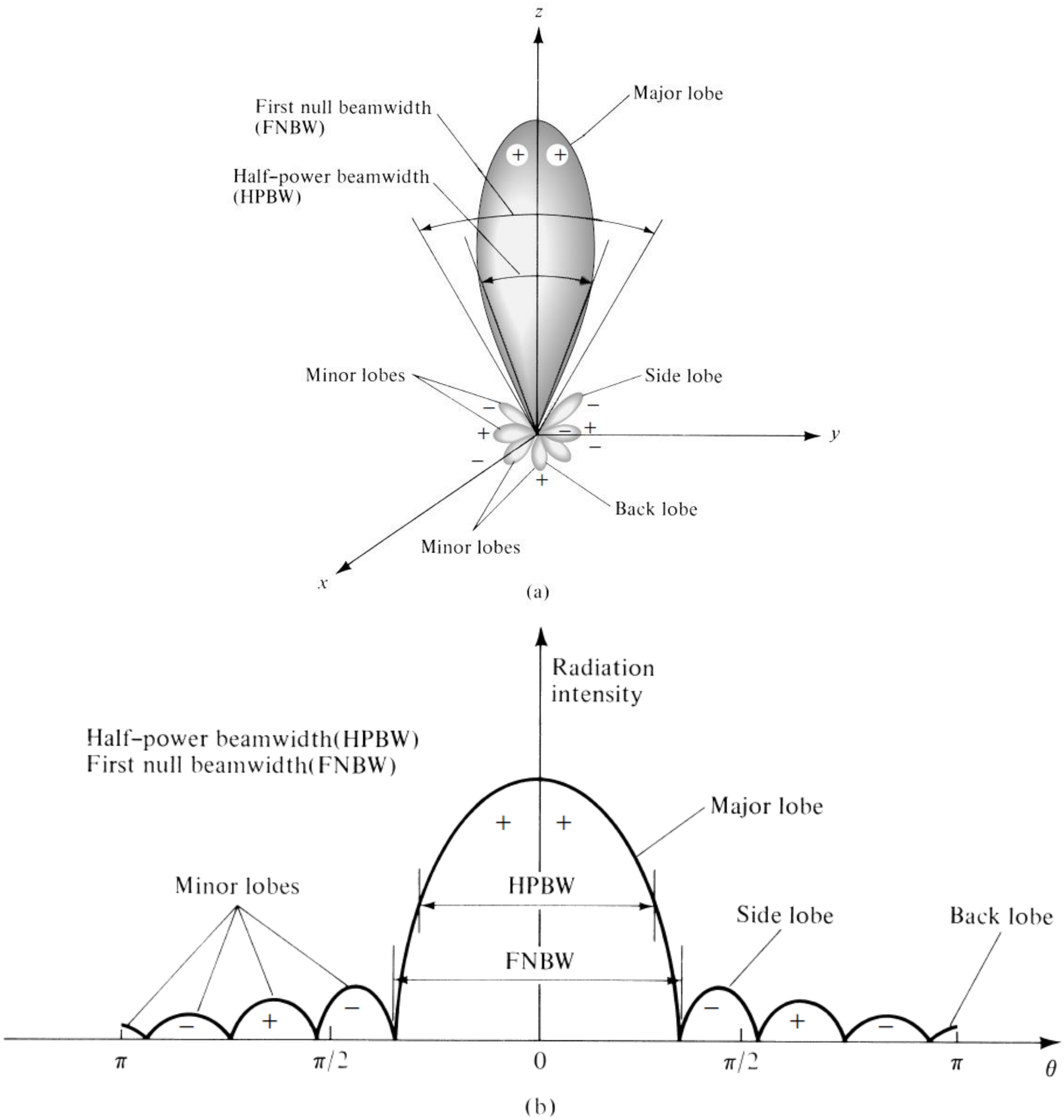


Figure 1.14 (a) Radiation lobes and beamwidths of an antenna pattern. (b) Linear plot of power pattern and its associated lobes and beamwidths.

5.1.2 Isotropic, Directional, and Omnidirectional Patterns

Isotrophic - "a hypothetical lossless antenna having equal radiation in all directions."

Directional Antenna - "having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. This term is usually applied to an antenna whose maximum directivity is significantly greater than that of a half-wave dipole."

Omnidirectional Antenna - "having an essentially nondirectional pattern in a given plane (in this case in azimuth) and a directional pattern in any orthogonal plane (in this case in elevation)."

5.1.3 Principal Patterns

E Plane - "the plane containing the electric field vector and the direction of maximum radiation,"

H Plane - "the plane containing the magnetic-field vector and the direction of maximum radiation."

5.1.4 Field Regions

The space surrounding an antenna is usually subdivided into three regions:

(a) reactive near-field

(b) radiating near-field (Fresnel)

(c) far-field (Fraunhofer) regions

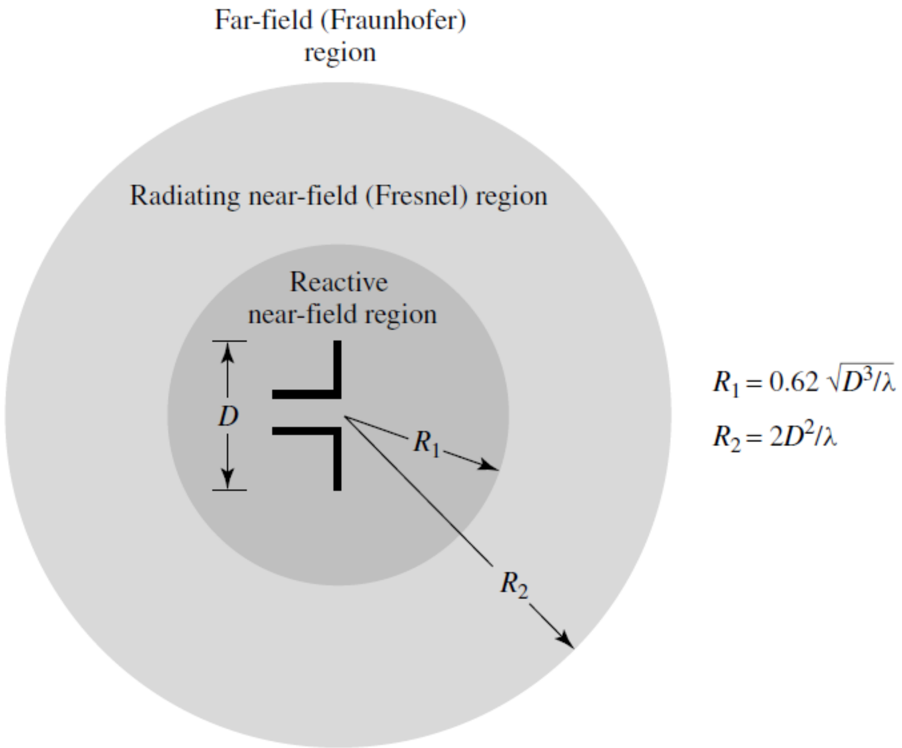


Figure 1.15 Field regions of an antenna.

Reactive near-field region: "that portion of the near-field region immediately surrounding the antenna wherein the reactive field predominates."

$$R < 0.62\sqrt{D^3/\lambda}$$

$$\lambda - Wavelength, D - Largest\ dimension\ of\ the\ Antenna$$

Radiating near-field (Fresnel) region: "that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna. If the antenna has a maximum dimension that is not large compared to the wavelength, this region may not exist. For an antenna focused at infinity, the radiating near-field region is sometimes referred to as the Fresnel region on the basis of analogy to optical terminology. If the antenna has a maximum overall dimension which is very small compared to the wavelength, this field region may not exist."

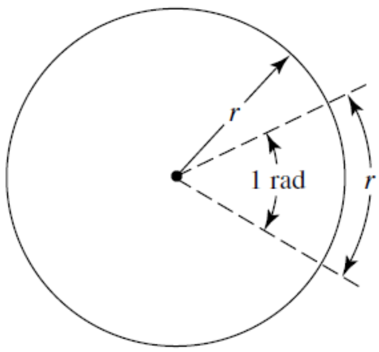
$$\text{Inner Boundary } R \geq 0.62\sqrt{D^3/\lambda}$$

$$\text{Outer Boundary } R < 2D^2/\lambda$$

Far-field (Fraunhofer) region: "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. If the antenna has a maximum∗ overall dimension D, the far-field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna, λ being the wavelength."

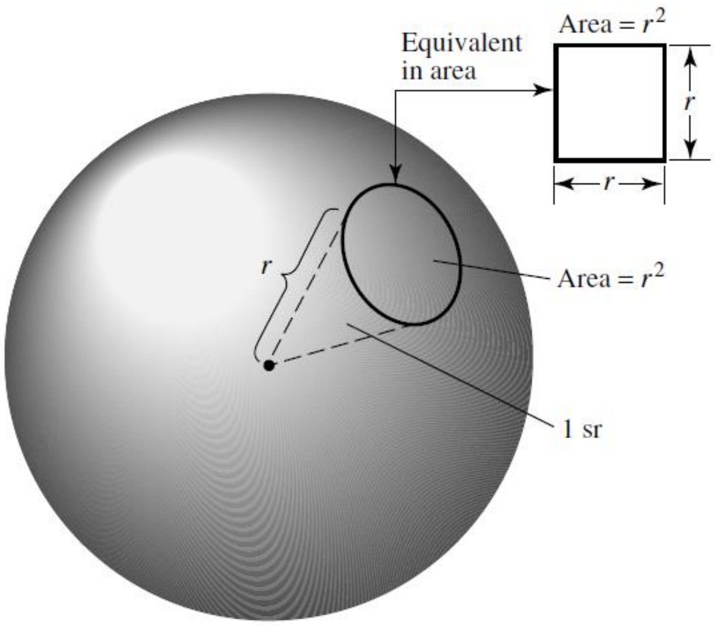
5.1.5 Radian and Steradian

One ***radian*** is defined as the plane angle with its vertex at the center of a circle of radius *r* that is subtended by an arc whose length is *r*.



(a) Radian

One ***steradian*** is defined as the solid angle with its vertex at the center of a sphere of radius *r* that is subtended by a spherical surface area equal to that of a square with each side of length *r*.



(b) Steradian

5.2 Radiation Power Density

Electromagnetic waves are used to transport information through a wireless medium or a guiding structure, from one point to the other. It is then natural to assume that power and energy are associated with electromagnetic fields. The quantity used to describe the power associated with an electromagnetic wave is the instantaneous Poynting vector defined as

$$W = E * H$$

$$W - \text{instantaneous Poynting vector } (W/m^2)$$

$$E - \text{instantaneous electric} - \text{field intensity } (V/m)$$

$$H - \text{instantaneous magnetic} - \text{field intensity } (A/m)$$

5.3 Radiation Intensity

Definition: "the power radiated from an antenna per unit solid angle."

$$U = r^2 W_{rad}$$

$$U - Radiation\ Intensity\ (\frac{W}{unit}\ solid\ angle)$$

$$W_{rad} - Radiation\ Intensity\ (\frac{W}{m^2})$$

5.4 Beamwidth

Beamwidth: "the angular separation between two identical points on opposite side of the pattern maximum."

Half-Power Beamwidth (HPBW): "In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half value of the beam."

5.5 Directivity

Definition: "the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation intensity is implied."

$$D = \frac{U}{U_o} = \frac{4\pi U}{P_{rad}}$$

If the direction is not specified, it implies the direction of maximum radiation intensity (maximum directivity) expressed as

$$D_{max} = D_o = \frac{U_{max}}{U_o} = \frac{4\pi U_{max}}{P_{rad}}$$

$$D - Directivity\ (dimensionless)$$

$$D_o - maximum\ directivity\ (dimensionless)$$

$$U - radiation\ intensity\ (\frac{W}{unit} solid\ angle)$$

$$U_{max} - maximum\ radiation\ intensity\ \left(\frac{W}{unit} solid\ angle\right)$$

$$U_o - \text{radiation intensity of isotropic source}\ (\frac{W}{unit} solid\ angle)$$

$$P_{rad} - total\ radiated\ power\ (W)$$

5.6 Antenna Efficiency

The total antenna efficiency e_o is used to consider losses at the input terminals and within the structure of the antenna. Such losses may be due

1. reflections because of the mismatch between the transmission line and the antenna
2. I^2R losses (conduction and dielectric)

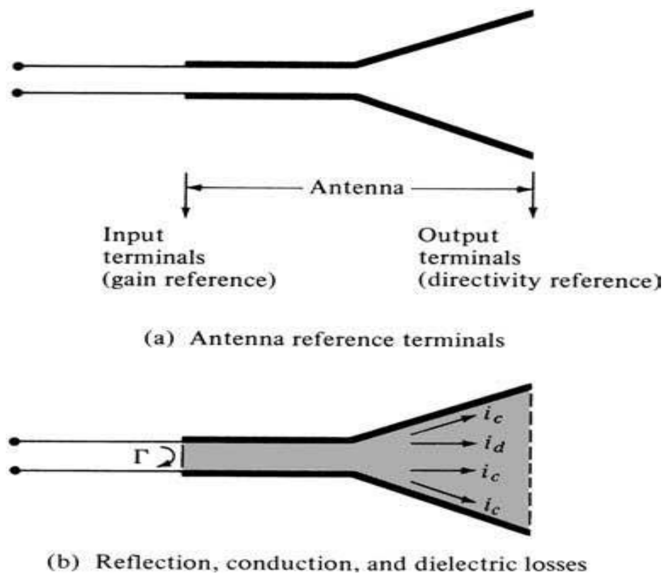


Figure 1.16 Reference terminals and losses of an antenna.

In general, the overall efficiency can be written as

$$\boldsymbol{e_0 = e_r e_c e_d}$$

Where

$$e_o - total\ efficiency\ (dimensionless)$$

$$e_r - reflection\ (mismatch) efficiency\ (dimensionless)$$

$$e_c - conduction\ efficiency\ (dimensionless)$$

$$e_d - dielectric\ efficiency\ (dimensionless)$$

$$\Gamma - Voltage\ reflection\ coefficient\ at\ the\ input\ terminals\ of\ the\ antenna$$

$$[\Gamma = (Z_{in} - Z_o)/(Z_{in} + Z_o)]$$

$$Z_{in} - Antenna\ Input\ Impedance$$

$$Z_o - Characteristic\ impedance\ of\ the\ transmission\ line$$

$$VSWR = Voltage\ Standing\ Wave\ Ratio = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

5.7 Gain

Definition: "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π."

$$Gain = 4\pi \frac{radiation\ intensity}{total\ input\ (accepted)\ power} = 4\pi \frac{U(\theta, \phi)}{P_{in}}\ (dimensionless)$$

Relative Gain

Definition: "the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction."

$$G = \frac{4\pi U(\theta, \phi)}{P_{in}(Lossless\ isotrophic\ source)}\ (dimensionless)$$

When the direction is not stated, the power gain is usually taken in the direction of maximum radiation.

5.8 Beam Efficiency

For an antenna with its major lobe directed along the *z*-axis *(θ* = 0*)*, the beam efficiency (BE) is defined by

$$BE = \frac{\text{power transmitted (received) within cone angle}}{\text{power transmitted (received) by the antenna}}\ (dimensionless)$$

5.9 Bandwidth

Definition: "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard."

5.10 Polarization

Polarization of an antenna in a given direction is defined as "the polarization of the wave transmitted (radiated) by the antenna.

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; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, *as observed along the direction of propagation*."

Polarization may be classified as

- Linear
- Circular
- Elliptical

"*Co-polarization* represents the polarization the antenna is intended to radiate (receive) while ***cross-polarization*** represents the polarization orthogonal to a specified polarization, which is usually the co-polarization."

5.10.1 Linear Polarization

A *time-harmonic wave is linearly polarized at a given point in space if the electric-field (or magnetic-field) vector at that point is always oriented along the same straight line at every instant of time*. This is accomplished if the field vector (electric or magnetic) possesses:

a. Only one component, or

b. Two orthogonal linear components that are in time phase or 180◦ (or multiples of 180◦) out-of-phase.

5.10.2 Circular Polarization

A time-harmonic wave is circularly polarized at a given point in space if the electric (or magnetic) field vector at that point traces a circle as a function of time.

The *necessary and sufficient* conditions to accomplish this are if the field vector (electric or magnetic) possesses *all* of the following:

a. The field must have two orthogonal linear components, and

b. The two components must have the same magnitude, and

c. The two components must have a time-phase difference of odd multiples of 90◦.

5.10.3 Elliptical Polarization

A time-harmonic wave is elliptically polarized if the tip of the field vector (electric or magnetic) traces an elliptical locus in space. At various instants of time the field vector changes continuously with time at such a manner as to describe an elliptical locus. It is right-hand (clockwise) elliptically polarized if the field vector rotates clockwise, and it is left-hand (counter clockwise) elliptically polarized if the field vector of the ellipse rotates counter clockwise.

A wave is elliptically polarized if it is not linearly or circularly polarized. Although linear and circular polarizations are special cases of elliptical, usually in practice elliptical polarization refers to other than linear or circular. The *necessary and sufficient* conditions to accomplish this are if the field vector (electric or magnetic) possesses *all* of the following:

a. The field must have two orthogonal linear components, and

b. The two components can be of the same or different magnitude.

c. (1) If the two components are not of the same magnitude, the time-phase difference between the two components must not be 0◦ or multiples of 180◦ (because it will then be linear). (2) If the two components are of the same magnitude, the time-phase difference between the two components must not be odd multiples of 90◦ (because it will then be circular).

6. ANTENNA NOISE TEMPERATURE AND G/T

If a receiving antenna has dissipative loss, so that its radiation efficiency η_{rad} is less than unity, the power available at the terminals of the antenna is reduced by the factor η_{rad} from that intercepted by the antenna (the definition of radiation efficiency is the ratio of output to input power). This reduction applies to received noise power, as well as received signal power, so the noise temperature of the antenna will be reduced from the brightness temperature given by the factor η_{rad}. In addition, thermal noise will be generated internally by resistive losses in the antenna, and this will increase the noise temperature of the antenna. In terms of noise power, a lossy antenna can be modelled as a lossless antenna and an attenuator having a power loss factor of $L = 1/\eta_{rad}$. The equivalent noise temperature of an attenuator, we can find the resulting noise temperature seen at the antenna terminals as

$$T_A = \frac{T_b}{L} + \frac{(L-1)}{L} T_p = \eta_{rad} T_b + (1 - \eta_{rad}) T_p$$

$$T_A - antenna\ noise\ temperature$$

is a combination of the external brightness temperature seen by the antenna and the thermal noise generated by the antenna. As with other equivalent noise temperatures, the proper interpretation of T_A is that a matched load at this temperature will produce the same available noise power as does the antenna. Note that this temperature is referenced at the output terminals of the antenna; since an antenna is not a two-port circuit element, it does not make sense to refer the equivalent noise temperature to its "input."

Reduces to $T_A = T_b$ for a lossless antenna with $\eta_{rad} = 1$. If the radiation efficiency is zero, meaning that the antenna appears as a matched load and does not see any external background noise, then the above equation reduces to $T_A = T_p$. due to the thermal noise generated by the losses. If an antenna is pointed toward a known background temperature different than T_o, then can be used to determine its radiation efficiency.

7. FRIIS TRANSMISSION EQUATION

A general radio system link is shown in Figure, where the transmit power is P_t, the transmit antenna gain is G_t, the receive antenna gain is G_r, and the received power (delivered to a matched load) is P_r. The transmit and receive antennas are separated by the distance R.

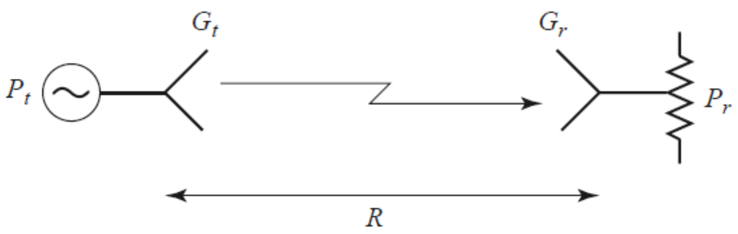


Figure 1.17 A basic radio system

The power density radiated by an isotropic antenna *(D* = 1 = 0 dB*)* at a distance *R* is given by

$$S_{avg} = \frac{P_t}{4\pi R^2}\ W/m^2$$

This result reflects the fact that we must be able to recover all of the radiated power by integrating over a sphere of radius *R* surrounding the antenna, since the power is distributed isotropically, and the area of a sphere is $4\pi R^2$. If the transmit antenna has a directivity greater than 0 dB, we can find the radiated power density by multiplying by the directivity, since directivity is defined as the ratio of the actual radiation intensity to the equivalent isotropic radiation intensity. In addition, if the transmit antenna has losses, we can include the radiation efficiency factor, which has the effect of converting directivity to gain. Thus, the general expression for the power density radiated by an arbitrary transmit antenna is

$$S_{avg} = \frac{G_t P_t}{4\pi R^2}\ W/m^2$$

If this power density is incident on the receive antenna, we can use the concept of effective aperture area, to find the received power:

$$P_r = A_e S_{avg} = \frac{G_t P_t A_e}{4\pi R^2} W.$$

Again, the possibility of losses in the receive antenna can be accounted for by using the gain (rather than the directivity) of the receive antenna. Then the result for the received power is

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

This result is known as the *Friis radio link formula*, and it addresses the fundamental question of how much power is received by a radio antenna. These include impedance mismatch at either antenna, polarization mismatch between the antennas, propagation effects leading to attenuation or depolarization, and multipath effects that may cause partial cancellation of the received field.

The Friis formula, received power is proportional to the product $P_t G_t$. These two factors—the transmit power and transmit antenna gain—characterize the transmitter, and in the main beam of the antenna the product $P_t G_t$ can be interpreted equivalently as the power radiated by an isotropic antenna with input power $P_t G_t$. Thus, this product is defined as the *effective isotropic radiated power* (EIRP):

$$\boldsymbol{EIRP}: \boldsymbol{P_t G_t W}$$

For a given frequency, range, and receiver antenna gain, the received power is proportional to the EIRP of the transmitter and can only be increased by increasing the EIRP. This can be done by increasing the transmit power, or the transmit antenna gain, or both.

8. LINK BUDGET AND LINK MARGIN

The various terms in the Friis formula of are often tabulated separately in a *link budget*, where each of the factors can be individually considered in terms of its net effect on the received power. Additional loss factors, such as line losses or impedance mismatch at the antennas, atmospheric attenuation, and polarization mismatch can also be added to the link budget. One of the terms in a link budget is the *path loss*, accounting for the free-space reduction in signal strength with distance between the transmitter and receiver. Path loss is defined (in dB) as

$$L_o(dB) = 20log\left(\frac{4\pi R}{\lambda}\right) > 0$$

Note that path loss depends on wavelength (frequency), which serves to provide a normalization for the units of distance.

With the above definition of path loss, we can write the remaining terms of the Friis formula as shown in the following link budget:

Transmit power	$\boldsymbol{P_t}$
Transmit antenna line loss	$-L_t$
Transmit antenna gain	G_t
Path loss (free-space)	$-L_o$
Atmospheric attenuation	$-L_A$
Receive antenna gain	G_r
Receive antenna line loss	$-L_r$
Receive power	$\boldsymbol{P_r}$

We have also included loss terms for atmospheric attenuation and line attenuation. Assuming that all of the above quantities are expressed in dB (or dBm, in the case of *Pt*), we can write the receive power as

$$\boldsymbol{P_r(dBm) = P_t - L_t + G_t - L_o - L_A + G_r - L_r}$$

If the transmit and/or receive antenna is not impedance matched to the transmitter/ receiver (or to their connecting lines), impedance mismatch will reduce the received power by the factor $(1 - |\Gamma|^2)$, where Γ is the appropriate reflection coefficient. The resulting impedance mismatch loss,

$$L_{imp}(dB) = -10\log(1 - |\Gamma|^2) \geq 0,$$

can be included in the link budget to account for the reduction in received power.

Another possible entry in the link budget relates to the polarization matching of the transmit and receive antennas, as maximum power transmission between transmitter and receiver requires both antennas to be polarized in the same manner. If a transmit antenna is vertically polarized, for example, maximum power will only be delivered to a vertically polarized receiving antenna, while zero power would be delivered to a horizontally polarized receive antenna, and half the available power would be delivered to a circularly polarized antenna.

In practical communications systems it is usually desired to have the received power level greater than the threshold level required for the minimum acceptable quality of service (usually expressed as the minimum carrier-to-noise ratio (CNR), or minimum SNR). This design allowance for received power is referred to as the *link margin*, and can be expressed as the difference between the design value of received power and the minimum threshold value of receive power:

$$Link\ Margin\ (dB) = LM = P_r - P_{r(min)} > 0,$$

where all quantities are in dB. Link margin should be a positive number; typical values may range from 3 to 20 dB. Having a reasonable link margin provides a level of robustness to the system to account for variables such as signal fading due to weather, movement of a mobile user, multipath propagation problems, and other unpredictable effects that can degrade system performance and quality of service. Link margin that is used to account for fading effects is sometimes referred to as *fade margin*. Satellite links operating at frequencies above 10 GHz, for example, often require fade margins of 20 dB or more to account for attenuation during heavy rain.

9. NOISE CHARACTERIZATION OF A RECEIVER

Analyze the noise characteristics of a complete antenna–transmission line– receiver front end, as shown in Figure. In this system the total noise power at the output of the receiver, *No*, will be due to contributions from the antenna pattern, the loss in the antenna, the loss in the transmission line, and the receiver components. This noise power will determine the minimum detectable signal level for the receiver and, for a given transmitter power, the maximum range of the communication link.

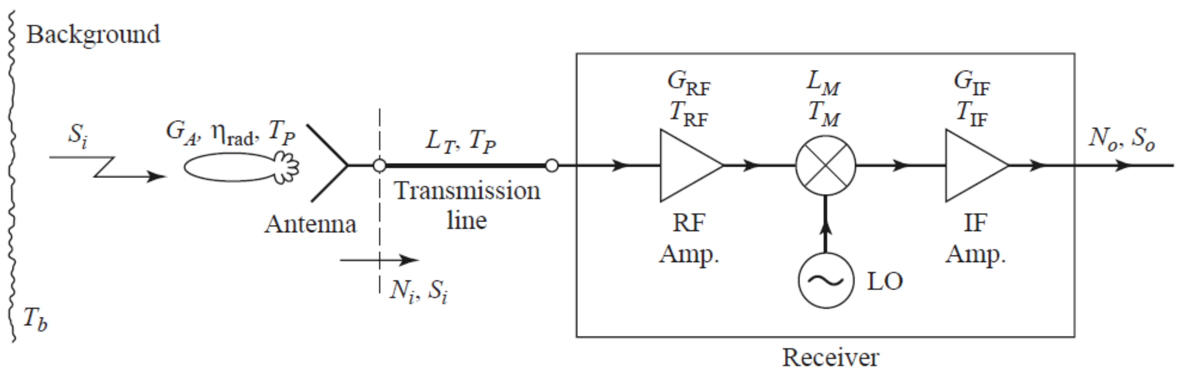


Figure 1.18 Noise analysis of a microwave receiver front end, including antenna and transmission line contributions.

The receiver components in Figure consist of an RF amplifier with gain G_{RF} and noise temperature *T*RF, a mixer with an RF-to-IF conversion loss factor *LM* and noise temperature T_M, and an IF amplifier with gain G_{IF} and noise temperature T_{IF}. The noise effects of later stages can usually be ignored since the overall noise figure is dominated by the characteristics of the first few stages. The component noise temperatures can be related to noise figures as $T = (F-1)T_o$. The equivalent noise temperature of the receiver can be found as

$$T_{REC} = T_{RF} + \frac{T_M}{G_{RF}} + \frac{T_{IF}L_M}{G_{RF}}$$

The transmission line connecting the antenna to the receiver has a loss L_T, and is at a physical temperature T_p. So from its equivalent noise temperature is

$$T_{TL} = (L_T - 1)T_p$$

We find that the noise temperature of the transmission line (TL) and receiver (REC) cascade is

$$T_{L+REC} = T_{TL} + L_T T_{REC}$$
$$= (L_T - 1)T_p + L_T T_{REC}$$

This noise temperature is defined at the antenna terminals (the input to the transmission line). The entire antenna pattern can collect noise power. If the antenna has a reasonably high gain with relatively low sidelobes, we can assume that all noise power comes via the main beam, so that the noise temperature of the antenna is given by

$$T_A = \eta_{rad}T_b + (1-\eta_{rad})T_p$$
$$\eta_{rad} - Efficiency\ of\ the\ Antenna$$
$$T_p - Physical\ Temperature$$
$$T_b - \text{equivalent brightness temperature}$$

The noise power at the antenna terminals, which is also the noise power delivered to the transmission line, is

$$N_i = kBT_A = kB\left[\eta_{rad}T_b + (1-\eta_{rad})T_p\right]$$

If S_i is the received power at the antenna terminals, then the input SNR at the antenna terminals is S_i/N_i. The output signal power is

$$S_o = \frac{S_i G_{RF} G_{IF}}{L_T L_M} = S_i G_{SYS}$$
$$G_{SYS} - System\ power\ gain.$$

The output noise power

$$N_o = (N_i + kBT_{TL+REC})G_{SYS}$$
$$= kB(T_A + T_{TL+REC})G_{SYS}$$
$$= kB\left[\eta_{rad}T_b + (1-\eta_{rad})T_p + (L_T - 1)T_p + L_T T_{REC}\right]G_{SYS}$$
$$= kBT_{SYS}G_{SYS}$$

The output SNR is

$$\frac{S_o}{N_o} = \frac{S_i}{kBT_{SYS}} = \frac{S_i}{kB\left[\eta_{rad}T_b + (1-\eta_{rad})T_p + (L_T - 1)T_p + L_T T_{REC}\right]}$$

It may be possible to improve this SNR by various signal processing techniques. Note that it may appear to be convenient to use an overall system noise figure to calculate the degradation in SNR from input to output for the above system, but one must be very careful with such an approach because noise figure is defined only for $N_i = kT_oB$, which is not the case here.