EC307: Mobile Communication and Networks
Module 7: Antenna Basics

1. Introduction

An **antenna** is a device that converts electrical signals into electromagnetic (EM) waves during transmission and converts EM waves back to electrical signals during reception.

In mobile communication, antennas enable wireless links between the mobile handset and the base station.

Key Functions

- **Transmission:** Converts electrical power into electromagnetic waves.
- **Reception:** Converts electromagnetic waves back into electrical power.
- **Radiation:** Distributes power in space in a specific pattern.

Example: The antenna in a smartphone converts modulated electrical signals into RF waves that propagate through free space toward a nearby cellular base station.

2. Basic Parameters of Antennas

2.1 Radiation Pattern

The **radiation pattern** represents the variation of the power radiated by the antenna as a function of direction.

- **Main lobe:** Direction of maximum radiation.
- **Side lobes:** Smaller lobes in undesired directions.
- **Back lobe:** Radiation opposite to the main lobe.

Example: A half-wave dipole antenna exhibits a figure-eight radiation pattern in the horizontal plane.

2.2 Isotropic Radiator

A hypothetical point-source antenna that radiates uniform power density in every direction with no variation in angle. For an isotropic radiator, the power density at a distance r from the antenna is,

$$P_{DI} = \frac{P_{rad}}{4\pi r^2} = S(r)$$

2.3 Antenna Efficiency

The efficiency of an antenna determines how effectively it converts the input RF power into radiated electromagnetic power. It is defined as the ratio of radiated power to the total power delivered to the antenna.

$$\eta = \frac{P_{\text{rad}}}{P_{\text{in}}}$$

where η = antenna efficiency (0 to 1), P_{rad} = radiated power, P_{in} = input power delivered to antenna.

Radiation and Loss Resistance

An antenna can be modeled as a series combination of:

- Radiation resistance R_{rad}
- Loss resistance R_{loss}

Thus, the efficiency is:

$$\eta = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}}$$

Only R_{rad} contributes to useful radiated power, while R_{loss} represents ohmic (heat) losses.

Relation to Radiated Power

If the transmitter supplies power P_{TX}, then the radiated power is:

$$P_{\text{rad}} = \eta \, P_{\text{TX}}$$

Example 1

Given:

$$R_{\text{rad}} = 40\ \Omega, \quad R_{\text{loss}} = 10\ \Omega$$

Efficiency:

$$\eta = \frac{40}{40 + 10} = 0.8 = 80\%$$

If the transmitter feeds $P_{\text{TX}} = 50$ W:

$$P_{\text{rad}} = 0.8 \times 50 = 40 \text{ W}$$

Thus, 40 W is radiated, and 10 W is lost as heat.

Example 2

A transmitter outputs $P_{\text{TX}} = 20$ W. Antenna parameters:

$$R_{\text{rad}} = 25\ \Omega, \quad R_{\text{loss}} = 5\ \Omega$$

Efficiency:

$$\eta = \frac{25}{25+5} = \frac{25}{30} = 0.833$$

Radiated power:

$$P_{\text{rad}} = 0.833 \times 20 = 16.66\ \text{W}$$

Power density at distance $r = 10$ m for an isotropic radiator:

$$S(r) = \frac{P_{\text{rad}}}{4\pi r^2} = \frac{16.66}{4\pi(10)^2} = 0.0132\ \text{W/m}^2$$

This shows how antenna efficiency directly affects radiated field strength.

2.4 Gain (G)

The Gain of a transmitting antenna is defined as the ratio of its radiation intensity to that of an isotropic antenna.

$$G_t = \frac{P_{DA}}{P_{DI}}$$

. Thus the power desity of a real antenna at a distance r is represented as

$$P_{DA} = \frac{P_{rad}}{4\pi r^2} G_t$$

Gain is represented in decibal as

$$G_t(dB_i) = 10 \log G_t$$

Power Desity for a radiating antenna with a gain of G_t

$$S = \frac{P_{rad} G_t}{4\pi r^2}$$

Example: If $P_t = 20\,\text{W}$, $G_t = 5$, and $r = 50\,\text{m}$,

$$S = \frac{20 \times 5}{4\pi(50)^2} = 0.00318\,\text{W/m}^2$$

assuming $\eta = 1$ such that $P_{rad} = P_t$

Directivity (D)

Directivity measures how focused the radiation is compared to an isotropic radiator.

$$D = \frac{U_{\rm max}}{U_{\rm avg}} = \frac{4\pi U_{\rm max}}{P_{\rm rad}}$$

Gain includes both directivity and radiation efficiency:

$$G = \eta D$$

where η = efficiency.

Example:
If $P_{\rm rad} = 10\,\text{W}$ and $U_{\rm max} = 0.8\,\text{W/sr}$,

$$D = \frac{4\pi(0.8)}{10} = 1.005\pi \approx 3.16 \Rightarrow D_{\rm dB} = 5.0\,\text{dB}$$

Example: A power of 100 W is supplied to an antenna whose gain is 5 dBi. Find the power density at a distance of 10 km from the antenna (assume far-field, free-space).

Solution.

The power density S (power per unit area) at distance r from a transmitter with input power P_t and antenna gain G is

$$S(r) = \frac{P_t G}{4\pi r^2}.$$

Convert gain from dBi to linear scale:

$$G_{\rm (linear)} = 10^{G_{\rm (dBi)}/10} = 10^{5/10} = 10^{0.5} = \sqrt{10} \approx 3.1622776602.$$

Put the known values (use SI units):

$$P_t = 100 \text{ W}, \qquad G \approx 3.1622776602, \qquad r = 10 \text{ km} = 10{,}000 \text{ m}.$$

Compute the numerator $P_t G$:

$$P_t G = 100 \times 3.1622776602 \approx 316.2277660 \text{ W}.$$

Compute the denominator $4\pi r^2$:

$$4\pi r^2 = 4\pi(10{,}000)^2 = 4\pi \times 10^8 \approx 1.2566370614 \times 10^9.$$

Now compute S:

$$S = \frac{316.2277660}{1.2566370614 \times 10^9} \approx 2.5164606 \times 10^{-7} \text{ W/m}^2.$$

Equivalently, in logarithmic units:

$$S \approx 10\log_{10}(2.516 \times 10^{-7}) \approx -65.99 \text{ dBW/m}^2$$

or

$$S \approx -35.99 \text{ dBm/m}^2.$$

2.5 Beamwidth

The **Half Power Beam Width (HPBW)** is the angular separation between two directions where the power radiated drops to half (i.e., −3 dB) of its maximum.

$$\text{HPBW} = \theta_2 - \theta_1 \quad (\text{at } P = 0.5P_{\text{max}})$$

Example: If P_{max} occurs at $0°$, and the half-power points are at $-20°$ and $+20°$:

$$\text{HPBW} = 40°$$

2.6 Effective Aperture (A_e)

Represents the ability of an antenna to capture power from an incoming wave:

$$A_e = \frac{G_r \lambda^2}{4\pi}$$

The effective area also can be represented as,

$$A_e = \frac{P_r}{P_{DA}}$$

Thus the received power can be represnted as,

$$P_r = A_e.P_{DA} = \frac{G_r \lambda^2}{4\pi}.\frac{P_t}{4\pi r^2} = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$$

Example:
For $G = 2.686$ and $f = 900\,\text{MHz}$,

$$\lambda = \frac{3 \times 10^8}{9 \times 10^8} = 0.333\,\text{m}$$

$$A_e = \frac{2.686(0.333)^2}{4\pi} = 0.0237\,\text{m}^2$$

2.7 Bandwidth

The frequency range over which the antenna operates effectively:

$$\text{Bandwidth (\%)} = \frac{f_2 - f_1}{f_c} \times 100$$

Example:
If $f_1 = 890\,\text{MHz},\ f_2 = 960\,\text{MHz}$,

$$f_c = 925\,\text{MHz}, \quad \text{BW} = \frac{960 - 890}{925} \times 100 = 7.57\%$$

2.8 Polarization

Defines the orientation of the electric field (E) vector:

- **Linear:** E remains in one plane.
- **Circular:** E rotates in a circle (used in satellite links).
- **Elliptical:** General case combining both.

2.9 Near Field and Far Field

When an antenna radiates electromagnetic waves, the space around it can be divided into two major regions:

1. Near Field (Fresnel Region)
2. Far Field (Fraunhofer Region)

These regions determine how electromagnetic fields behave with distance.

Near Field (Fresnel Region)

The **near field** is the region close to the antenna where the electromagnetic fields do not yet behave like fully formed radiation.

Characteristics

- Field strength varies rapidly with distance.
- Electric and magnetic fields do not maintain a constant ratio (not 377 Ω).
- Contains reactive fields (stored energy).
- Wavefront is not planar.
- Strong coupling; used in NFC, RFID, inductive charging.

Near-Field Boundaries

For an antenna of maximum dimension D and wavelength λ:

- **Reactive Near Field:**

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

- **Radiating Near Field (Fresnel Region):**

$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$$

Far Field (Fraunhofer Region)

The **far field** is the region where electromagnetic waves behave as pure radiation and have stable, predictable properties.

Characteristics

- E and H fields maintain a constant ratio:

$$\frac{E}{H} = 377\ \Omega$$

- Field strength decays as $1/R$.
- Wavefront becomes planar.
- Used for antenna gain, beamwidth, and pattern measurements.
- Communication links (cellular, Wi-Fi, satellite) operate in this region.

Far-Field Boundary

$$R > \frac{2D^2}{\lambda}$$

Example 1:

Consider a patch antenna of size $D = 5$ cm operating at 2.4 GHz.

$$\lambda = \frac{3 \times 10^8}{2.4 \times 10^9} = 0.125\ \text{m}$$

The far field starts at:

$$R > \frac{2D^2}{\lambda} = \frac{2(0.05)^2}{0.125} = 0.04\ \text{m}$$

Hence, the far-field region begins at approximately **4 cm**.

Example 2:
If $D = 0.2\,\text{m}$ and $\lambda = 0.05\,\text{m}$:

$$r_{\text{far}} > \frac{2(0.2)^2}{0.05} = 1.6\,\text{m}$$

Thus, measurements should be taken beyond 1.6 m to ensure far-field conditions.

2.10 Impedance Matching

In wireless communication and RF systems, maximum power transfer occurs when the load impedance matches the source (or transmission line) impedance. If the impedances are not matched, part of the signal is reflected back, resulting in power loss and distortion. Impedance matching techniques help minimize reflections.

Transmission Line Impedance

Let

$$Z_0 = \text{characteristic impedance of the transmission line}$$

$$Z_L = \text{load impedance}$$

When a signal reaches a load that does not match the line impedance, a reflected wave is generated.

Reflection Coefficient

Reflection coefficient (Γ) is defined as the ratio of the reflected voltage wave to the incident voltage wave:

$$\Gamma = \frac{V_{\text{ref}}}{V_{\text{inc}}}$$

In terms of impedances:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Voltage Standing Wave Ratio (VSWR)

Standing waves are created on a line with reflections. VSWR (Voltage Standing Wave Ratio) is defined as:

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

Interpretation

- $\text{VSWR} = 1$ (perfect match)
- $\text{VSWR} > 1$ (mismatch)

Reflected Power

The power reflected back in terms of reflection coefficient -

$$P_r = P_{\text{inc}}|\Gamma|^2$$

Power delivered to the load:

$$P_{\text{del}} = P_{\text{inc}}(1 - |\Gamma|^2)$$

Example 1:

A line with characteristic impedance $Z_0 = 50\,\Omega$ is terminated with a load $Z_L = 100\,\Omega$.

(a) Reflection Coefficient

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{100 - 50}{100 + 50} = \frac{50}{150} = 0.333$$

(b) VSWR

$$\text{VSWR} = \frac{1 + 0.333}{1 - 0.333} = \frac{1.333}{0.667} = 2$$

(c) Power Reflected

$$P_r = |\Gamma|^2 = (0.333)^2 = 0.111$$

Thus, 11.1% of power is reflected and 88.9% is delivered.

Typical impedance = $50\,\Omega$.

3. Friis Transmission Equation

The received power between two antennas is:

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

Example 1:
$P_t = 2\,\mathrm{W}, G_t = 3, G_r = 2, f = 900\,\mathrm{MHz}, R = 100\,\mathrm{m}.$

$$\lambda = 0.333\,\mathrm{m}, \quad P_r = 2 \times 3 \times 2 \times \left(\frac{0.333}{4\pi \times 100}\right)^2 = 3.18 \times 10^{-6}\,\mathrm{W} = -25\,\mathrm{dBm}$$

Example 2:

If $R = 200\,\mathrm{m}$, power reduces by $(\frac{100}{200})^2 = 1/4$:

$$P_r = 0.795 \times 10^{-6}\,\mathrm{W} = -31\,\mathrm{dBm}$$

Hence, doubling the distance reduces received power by 6 dB.

Friis Transmission Equation in Decibel (dB)

The standard Friis transmission equation in linear form is:

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

To convert this into decibel (dB) form, each multiplicative term is transformed using:

$$10\log_{10}(xy) = 10\log_{10}(x) + 10\log_{10}(y)$$

Conversion Steps

- Transmitted and received powers:

$$P_r(\mathrm{dB}) = 10\log_{10}(P_r), \quad P_t(\mathrm{dB}) = 10\log_{10}(P_t)$$

- Antenna gains:

$$G_t(\mathrm{dBi}) = 10\log_{10}(G_t), \qquad G_r(\mathrm{dBi}) = 10\log_{10}(G_r)$$

- Propagation term:

$$10\log_{10}\left[\left(\frac{\lambda}{4\pi r}\right)^2\right] = 20\log_{10}\left(\frac{\lambda}{4\pi r}\right)$$

$$= -20\log_{10}\left(\frac{4\pi r}{\lambda}\right)$$

Final Friis Equation in dB

$$\boxed{P_r(\text{dBm}) = P_t(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - 20\log_{10}\left(\frac{4\pi r}{\lambda}\right)}$$

The term

$$FSPL(dB) = 20\log_{10}\left(\frac{4\pi r}{\lambda}\right)$$

is known as **Free-Space Path Loss**.

Thus:

$$P_r = P_t + G_t + G_r - FSPL$$

Example 3:

Consider:

$$P_t = 1 \text{ W} = 30 \text{ dBm}, \quad G_t = 5 \text{ dBi}, \quad G_r = 5 \text{ dBi}$$

$$r = 100 \text{ m}, \quad f = 2.4 \text{ GHz}, \quad \lambda = \frac{c}{f} = 0.125 \text{ m}$$

$$FSPL = 20\log_{10}\left(\frac{4\pi(100)}{0.125}\right) = 20\log_{10}(10053) \approx 80.04 \text{ dB}$$

$$P_r = 30 + 5 + 5 - 80.04 = -40.04 \text{ dBm}$$

$$\boxed{P_r \approx -40 \text{ dBm}}$$

Friis Transmission Equation (Frequency in MHz and Distance in km)

The free-space path loss (FSPL) in decibel form is normally written as:

$$FSPL(dB) = 20\log_{10}\left(\frac{4\pi r}{\lambda}\right)$$

To express the formula using *frequency in MHz* and *distance in km*, we use:

$$\lambda = \frac{c}{f} = \frac{300}{f_{\text{MHz}}} \text{ (in meters)}, \qquad r_{\text{m}} = 1000\, r_{\text{km}}$$

Substituting:

$$FSPL = 20\log_{10}\left(\frac{4\pi(1000 r_{\text{km}})}{300/f_{\text{MHz}}}\right)$$

Expanding the logarithmic terms:

$$FSPL(dB) = 20\log_{10}(4\pi) + 20\log_{10}(1000) + 20\log_{10}(f_{\text{MHz}}) + 20\log_{10}(r_{\text{km}}) - 20\log_{10}(300)$$

Evaluating constants:

$$20\log_{10}(4\pi) = 21.98, \qquad 20\log_{10}(1000) = 60, \qquad 20\log_{10}(300) = 49.54$$

Thus:

$$\boxed{FSPL(dB) = 32.44 + 20\log_{10}(f_{\text{MHz}}) + 20\log_{10}(r_{\text{km}})}$$

Friis Transmission Equation in dB

$$\boxed{P_r(\text{dBm}) = P_t(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - [32.44 + 20\log_{10}(f_{\text{MHz}}) + 20\log_{10}(r_{\text{km}})]}$$

Example 4:

Given:

$$P_t = 20\,\text{dBm}, \quad G_t = 8\,\text{dBi}, \quad G_r = 8\,\text{dBi},$$
$$f = 900\,\text{MHz}, \quad d = 2\,\text{km}$$

Compute FSPL:

$$FSPL = 32.44 + 20\log_{10}(900) + 20\log_{10}(2)$$
$$20\log_{10}(900) = 59.08, \qquad 20\log_{10}(2) = 6.02$$
$$FSPL = 32.44 + 59.08 + 6.02 = 97.54 \text{ dB}$$

Received power:

$$P_r = 20 + 8 + 8 - 97.54 = -61.54 \text{ dBm}$$

$$\boxed{P_r \approx -61.54 \text{ dBm}}$$

Example 5:

A transmitter has an output power of 150 W at a carrier frequency of 325 MHz. It is connected to a transmitting antenna having a gain of 12 dBi. A receiving antenna located 10 km away has a gain of 5 dBi. Assuming free-space propagation, calculate the power delivered to the receiver in:

- dBm
- watts

Solution

Convert Transmit Power to dBm

$$P_t(\text{dBm}) = 10\log_{10}(150 \times 10^3)$$
$$P_t = 51.7609\,\text{dBm}$$

Free Space Path Loss (FSPL)

The FSPL formula (distance in km, frequency in MHz):

$$\text{FSPL} = 20\log_{10}(d) + 20\log_{10}(f) + 32.44$$
$$\text{FSPL} = 20\log_{10}(10) + 20\log_{10}(325) + 32.44$$
$$\text{FSPL} = 20 + 50.238 + 32.44 = 102.6777\,\text{dB}$$

Received Power (Friis Transmission Equation)

$$P_r(\text{dBm}) = P_t + G_t + G_r - \text{FSPL}$$
$$P_r(\text{dBm}) = 51.7609 + 12 + 5 - 102.6777$$
$$\boxed{P_r(\text{dBm}) = -33.9168\,\text{dBm}}$$

Convert Received Power to Watts

$$P_r(\text{W}) = 10^{\frac{P_r(\text{dBm})-30}{10}}$$
$$P_r(\text{W}) = 10^{\frac{-33.9168-30}{10}}$$
$$P_r(\text{W}) = 10^{-6.39168}$$
$$\boxed{P_r = 4.058 \times 10^{-7}\,\text{W}}$$

Example 6:

A transmitter has a power output of $P_t = 10$ W at a frequency $f = 250$ MHz. It is connected by 20 m of transmission line whose loss is 3 dB/100 m to a transmitting antenna with gain $G_t = 6$ dBi. The receiving antenna is $d = 25$ km away and has a gain $G_r = 4$ dBi. There is negligible loss in the receiver feedline, but the receiver input impedance is $Z_L = 75\ \Omega$ while the antenna and line are designed for $Z_0 = 50\ \Omega$.

Assuming free-space propagation, calculate the power delivered to the receiver (in dBm and watts), accounting for transmission-line loss and mismatch.

Solution

$$P_t = 10\text{ W} = 10\log_{10}(10 \times 10^3)\text{ dBm} = 40.00\text{ dBm}.$$

Transmission-line loss

Line loss specified: 3 dB/100 m. For 20 m

$$\text{Line loss} = 3 \cdot \frac{20}{100} = 0.6\text{ dB}.$$

Power available at the transmit antenna input (after line loss):

$$P_{t,\text{ant}}(\text{dBm}) = 40.00 - 0.6 = 39.40\text{ dBm}.$$

Free-space path loss (FSPL)

Use the common FSPL formula (distance in km, frequency in MHz):

$$\text{FSPL (dB)} = 20\log_{10}(d_{\text{km}}) + 20\log_{10}(f_{\text{MHz}}) + 32.44.$$

For $d = 25$ km and $f = 250$ MHz:

$$\text{FSPL} = 20\log_{10}(25) + 20\log_{10}(250) + 32.44 \approx 108.3576 \text{ dB}.$$

Received power (Friis equation, before mismatch)

Friis (dB form):

$$P_r(\text{dBm}) = P_{t,\text{ant}}(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - \text{FSPL}.$$

Substitute values:

$$P_r(\text{dBm}) = 39.40 + 6 + 4 - 108.3576 = -58.9576 \text{ dBm}.$$

Convert to watts:

$$P_r(\text{W}) = 10^{\frac{-58.9576-30}{10}} \approx 1.2713 \times 10^{-9} \text{ W}.$$

Mismatch between 50 Ω source and 75 Ω receiver

Reflection coefficient at the load:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{75-50}{75+50} = \frac{25}{125} = 0.20.$$

Fraction of power delivered to the load:

$$\eta_{\text{mismatch}} = 1 - |\Gamma|^2 = 1 - 0.20^2 = 1 - 0.04 = 0.96.$$

Mismatch loss (positive dB value):

$$L_{\text{mismatch}} = -10\log_{10}(\eta_{\text{mismatch}}) = -10\log_{10}(0.96) \approx 0.177 \text{ dB}.$$

Power delivered to the receiver (after mismatch)

Linear:

$$P_{\text{delivered}}(\text{W}) = P_r(\text{W}) \times \eta_{\text{mismatch}} \approx 1.2713 \times 10^{-9} \times 0.96 \approx 1.2204 \times 10^{-9} \text{ W}.$$

In dBm:

$$P_{\text{delivered}}(\text{dBm}) = 10\log_{10}\big(1.2204 \times 10^{-6} \text{ mW}\big) \approx -59.1349 \text{ dBm}.$$

$$\boxed{P_{\text{delivered}} \approx 1.2204 \times 10^{-9} \text{ W} \quad (\approx -59.13 \text{ dBm})}$$