Introduction to Antennas

What is an antenna?
• An antenna is a passive structure that serves as transition between a transmission line and air used to transmit and/or receive electromagnetic waves.

Types of antennas
• Can be divided into two groups
  – Wire antennas:
    • dipoles, loops, Yagi-Uda...
  – Aperture antennas:
    • parabolic, horns, microstrip antennas...

http://en.wikipedia.org/wiki/Antenna_(electronics)#Overview

Wire antennas

Yagi-Uda with reflector
Dr. S. X-Pol

Aperture antennas
- Spherical (main reflector) with Gregorian feed

Reflector and Pyramidal horn antennas

Outline
- Antenna parameters
  - Solid angle, $\Omega$, and Radiation intensity, $U$
  - Radiation pattern, $P_\theta$, sidelobes, $HPBW$
  - Far field zone, $r_f$
  - Directivity, $D$ or Gain, $G$
  - Antenna radiation impedance, $R_{rad}$
  - Effective Area, $A_e$
- All of these parameters are expressed in terms of a transmission antenna, but are identically applicable to a receiving antenna. We’ll also study:
  - Friis Transmission Equation
  - Radar Equation

Spherical coordinates
- $\phi$ = azimuth
- $\theta$ = elevation

Solid Angle
- $s = \theta = \text{arco}$
- $\theta = \text{ángulo plano}$
- $dS = \text{elemento de ángulo sólido}$
- $\text{Ángulo total} = 2\pi$ (radianes)
- $1 \text{ steradian (sr)} = (1 \text{ radian})^2$

Radiation Intensity
- Is the power density per solid angle:
  $$U = r^2 \rho_r \quad \text{[W/sr]}$$
- where
  $$\rho_r = \frac{1}{2} \text{ Re} (E \times H^*) \quad \text{[W/m}^2]\$$
is the power density also known as Poynting vector.
Total radiated power by antenna

- Can be calculated as:

\[ P_{\text{rad}} = \int U \cdot d\Omega \ [W] \]

or

\[ P_{\text{rad}} = \oint \varphi_{\text{r}} \cdot dS \ [W] \]

Total Solid Angle of an antenna

\[ \Omega_A = \int \int F_n (\theta, \phi) \cdot d\Omega \]

Is as if you changed the radiation pattern beam of an antenna into a pencil beam shape and find out what’s the equivalent solid angle occupied by this pattern.

Radiation Pattern

- Whenever we speak of radiation patterns, we normally mean we are at a distance far enough from the antenna known as the far field.

Isotropic antenna

- It’s an hypothetic antenna, i.e., it does not exist in real life, yet it’s used as a measuring bar for real antenna characteristics.

- It’s a point source that occupies a negligible space. Has no directional preference.

- Its pattern is simply a sphere so it has \[ \Omega_A = \Omega_{\text{isotropic}} = 4\pi \ [\text{steradians}] \]

Radiation Pattern

- Radiation pattern is the 3D plot of the gain, but usually the 2D horizontal and vertical cross sections of the radiation pattern are considered.

- Refers to the variation of the relative amplitude of the radiation as a function of direction.

Isotropic antenna

- Field pattern:

\[ E_{\text{rms}} (\theta, \phi) = \frac{E(\theta, \phi)}{E_{\text{rms}} (\theta, \phi)} \]

Power pattern:

\[ F_n (\theta, \phi) = \frac{U(\theta, \phi)}{U_{\text{rms}} (\theta, \phi)} \]

Where \( E \) is the radiation intensity to be defined later.

Pattern – polar plot

Note that when plotted in decibels, the power and field patterns look exactly the same.
Dipole antenna pattern

Note the radiation pattern is donut shaped.

Sidelobes

- Antennas sometimes show side lobes in the radiation pattern.
- Side lobes are peaks in gain other than the main lobe (the "beam").
- Side lobes have bad impact to the antenna quality whenever the system is being used to determine the direction of a signal, for example in RADAR systems.

Sidelobes of dipole arrays

Antenna Pattern with sidelobes

Many applications require sidelobe levels (SLL) to be below -20dB.

Gain or Directivity

An isotropic antenna and a practical antenna fed with the same power. Their patterns would compare as in the figure on the right.

Directivity and Gain

- All practical antennas radiate more than the isotropic antenna in some directions and less in others.
- Gain is inherently directional; the gain of an antenna is usually measured in the direction which it radiates best.

$$D = D_{\text{max}} (\theta, \phi) = \frac{P_{\text{max}}}{P_{\text{ave}}} = \frac{U_{\text{max}}}{U_{\text{ave}}}$$

If lossless antenna, \( G = D \)
Gain or Directivity

- Gain is measured by comparing an antenna to a model antenna, typically the isotropic antenna which radiates equally in all directions.

\[
D(\theta, \phi) = \frac{P_{\text{max}}}{P_{\text{rad}}} = \frac{\mathcal{A}(\theta, \phi)}{\mathcal{A}_{\text{isotropic}}} = \frac{4\pi^2\mathcal{A}(\theta, \phi)}{P_{\text{rad}}} = \frac{4\pi\mathcal{A}_{\text{max}}}{P_{\text{rad}}} = \Omega_{\text{isotropic}}/\Omega_{\lambda}
\]

Directivity

- For an antenna with a single main lobe pointing in the z-direction, \( \Omega_{\lambda} \) can be approximated to the product of the HPBW

\[
\Omega_{\lambda} \approx \beta_{x}\beta_{z}
\]

The Directivity:

\[
D = 4\pi\Omega_{\lambda} = \frac{4\pi}{\beta_{x}\beta_{z}}
\]

Far field

- The distance at which the fields transmitted by an antenna (spherical) can be approximated to plane waves.
- It’s defined as

\[
r_{ff} = 2D^2/\lambda
\]

\( D = \) is the largest physical dimension of the antenna
\( \lambda = \) wavelength of operation
\( r_{ff} = \) distance from the antenna to the observation point

Beamwidth, HPBW

- Is the “distance” in radians or degrees between the direction of the radiation pattern where the radiated power is half of the maximum.
- Can be found by solving \( F_{(\theta, \phi)} = 0.5 \)

\[
10\log(0.5) = -3 \text{ dB}
20\log(0.707) = -3 \text{ dB}
\text{for "pencil beam" shape;}
\text{HPBW} = 70^\circ \frac{\lambda}{D}
\]

Antenna Impedance

- An antenna is “seen” by the generator as a load with impedance \( Z_A \), connected to the line.
- The real part is the radiation resistance plus the ohmic resistance.
- Minimizing impedance differences at each interface will reduce SWR and maximize power transfer through each part of the antenna system.
- The impedance of an antenna is related to the electrical length of the antenna at the wavelength in use.
- The impedance of an antenna can be matched to the feed line and radiator by adjusting the impedance of the feed line, using the feed line as an impedance transformer.
- More commonly, the impedance is adjusted at the load (see below) with an antenna tuner, a balun, a matching transformer, matching networks composed of inductors and capacitors, or matching sections such as the gamma match.

\[
Z_A = (R_{\text{rad}} + R_I) + jX_A
\]

Antenna efficiency, \( \eta \)

- Efficiency is the ratio of power put into the antenna terminals to the power actually radiated.
- Radiation in an antenna is caused by radiation resistance which can only be measured as part of total resistance including loss resistance.

\[
P_{\text{rad}} = \eta P_i
\]

\[
G = \eta D
\]
Radiation Resistance

- The antenna is connected to a T.L., and it “sees” it as an impedance.
- The power radiated is
  \[ P_{\text{rad}} = \frac{1}{2} I^2 R_{\text{rad}} \]
- The loss power is
  \[ P_{\text{loss}} = \frac{1}{2} I^2 R_{\text{loss}} \]
- The efficiency is
  \[ \eta = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{loss}}} = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}} \]

Radar equation

- Received power by a radar is
  \[ P_r = \frac{P_i G^2 \lambda^2}{(4\pi)^2 R^4} \sigma e^{-2\tau} \]
  Where \( \sigma \) is the backscattering coefficient of the target [m²]

APPLICATIONS

- Application to several research projects: CASA, NASA-FAR, NASA-TCESS
- Show results from undergrads working in NASA and NSF projects
- Relation to Grad students

Antenna polarization

- The polarization of an antenna is the polarization of the signals it emits.
  - The ionosphere changes the polarization of signals unpredictably, so for signals which will be reflected by the ionosphere, polarization is not crucial.
  - However, for line-of-sight communications, it can make a tremendous difference in signal quality to have the transmitter and receiver using the same polarization.
  - Polarizations commonly considered are vertical, horizontal, and circular.

Antenna Bandwidth

- The bandwidth of an antenna is the range of frequencies over which it is effective, usually centered around the operating or resonant frequency.
  - The bandwidth of an antenna may be increased by several techniques, including using thicker wires, replacing wires with cages to simulate a thicker wire, tapering antenna components (like in a feed horn), and combining multiple antennas into a single assembly and allowing the natural impedance to select the correct antenna.

Effective Area

- How a Rx antenna extracts energy from incident wave and delivers it to a load?
  \[ A_e = \frac{P_{\text{rec}}}{\eta_{\text{inc}}} = \frac{\lambda^2 D}{4\pi} \]
  Above is valid for any antenna under matched-load conditions
Friis Transmission Eq.

- In any communication link, there is a transmitting antenna and a receiver with a receiver antenna.

\[ P_{\text{tx}} = \frac{G_{\text{tx}} P}{4\pi R^2} \]

\[ P_{\text{rx}} = A_{\text{rx}} P \frac{\lambda^2}{\lambda^2 + \pi^2} \]

\[ P_{\text{rec}} = \frac{G_{\text{rx}} P}{(4\pi R)^2} \]

Example

- Radar and Friis

Antenna Arrays

- Uses many antennas synchronized with each other to increase
- Pattern multiplication

Example

- Determine the direction of maximum radiation, pattern solid angle, directivity and HPBW in the y-z plane for an antenna with normalized radiation intensity given by

\[ F(\theta, \phi) = \begin{cases} 
\cos^2 \theta & \text{for } 0 \leq \theta \leq \frac{\pi}{2} \text{ and } 0 \leq \phi \leq 2\pi \\
0 & \text{elsewhere}
\end{cases} \]