ECE 3317
Applied Electromagnetic Waves

Prof. David R. Jackson
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Notes 21
Introduction to Antennas
Antennas

An antenna is a device that is used to transmit and/or receive an electromagnetic wave.

Note: The antenna itself can always transmit or receive, but it may be used for only one of these functions in an application.

Examples:

- Cell-phone antenna (transmit and receive)
- TV antenna in your home (receive only)
- Wireless LAN antenna (transmit and receive)
- FM radio antenna (receive only)
- Satellite dish antenna (receive only)
- AM radio broadcast tower (transmit only)
- GPS position location unit (receive only)
- GPS satellite (transmit only)
Antennas are often used for a variety of reasons:

- For communication over long distances, to have lower loss (see below)
- Where waveguiding systems (e.g., transmission lines) are impractical or inconvenient
- When it is desired to communicate with many users at once

Power loss from antenna broadcast: \( \frac{1}{r^2} \) (always better for very large \( r \))

Power loss from waveguiding system: \( e^{-2\alpha r} \)
Main properties of antennas:

- Radiation pattern
- Beamwidth and Directivity (how directional the beam is)
- Sidelobe level
- Efficiency (power radiated relative to total input power)
- Polarization (linear, CP)
- Input Impedance
- Bandwidth (the useable frequency range)
Reflector (Dish) Antenna

- Very high bandwidth
- Medium to high directivity (directivity is determined by the size)
- Linear or CP polarization (depending on how it is fed)
- Works by focusing the incoming wave to a collection (feed) point

Ideally, the dish is parabolic in shape.
- Very simple
- Moderate bandwidth
- Low directivity
- Omnidirectional in azimuth
- Most commonly fed by a twin-lead transmission line
- Linear polarization ($E_\theta$, assuming wire is along $z$ axis)
- The antenna is resonant when the length is about one-half free-space wavelength

At resonance: $Z_{in} = 73 \, [\Omega]$
The bow-tie antenna has flared dipole arms, which increases the bandwidth.
Folded Dipole Antenna

The folded dipole is a variation of the dipole antenna. It has an input impedance that is 4 times higher than that of the regular dipole antenna.

At resonance: \( Z_{in} = 292 \text{ [\Omega]} \)

Compatible with TV twin lead

\( Z_0 = 300 \text{ [\Omega]} \)
Monopole Wire Antenna

This is a variation of the dipole, using a ground plane instead of a second wire.

- Similar properties as the dipole
- Mainly used when the antenna is mounted on a conducting object or platform
- Usually fed with a coaxial cable feed

At resonance: $Z_{in} = 36.5 \ \Omega$

$h ≈ \frac{\lambda_0}{4}$
Monopole Wire Antenna (cont.)
This is a variation of the dipole, using multiples wires (with one “reflector” and one or more “directors”.

- Low bandwidth
- Moderate to high directivity
- Commonly used as a UHF TV antenna
Introduction to Antennas (cont.)

Yagi Antenna (cont.)

UHF Yagi

VHF Log-periodic

UHF Yagi
Log-Periodic Antenna

This consists of multiple dipole antennas of varying lengths, connected together.

- High bandwidth
- Moderate directivity
- Commonly used as a VHF TV antenna
Log Periodic Antenna (cont.)

Introduction to Antennas (cont.)
Typical Outdoor TV Antenna

- UHF Directors
- UHF Corner Reflector
- VHF Elements
- Dipole
- UHF Yagi
- VHF Log-periodic
Horn Antenna

It acts like a “loudspeaker” for electromagnetic waves.

- High bandwidth
- Moderate directivity
- Commonly used at microwave frequencies and above
- Often used as a feed for a reflector antenna
Arno A. Penzias and Robert W. Wilson used a large horn antenna to detect microwave signals from the “big bang” (Nobel Prize, 1978).
Horn Antenna (cont.)

This is a variety called the “hoghorn” antenna (a combination of horn+reflector).
Microstrip (Patch) Antenna

It consists of a printed “patch” of metal that is on top of a grounded dielectric substrate.

- Low bandwidth
- Low directivity (unless used in an array)
- Low-profile ($h$ can be made very small, at the expense of bandwidth)
- Can be made by etching
- Easily fed by microstrip line or coaxial cable
- Can be made conformable (mounted on a curved surface)
- Commonly used at microwave frequencies and above

$$L \approx \frac{\lambda_d}{2} = \frac{\lambda_0}{2} \sqrt{\varepsilon_r}$$
Microstrip (Patch) Antenna (cont.)
Dielectric Resonator Antenna (DRA)

It consists of a dielectric material (such as ceramic) on top of a grounded dielectric substrate.

- Moderate to large bandwidth
- Low directivity (unless used in an array)
- Commonly used at microwave frequencies and above

The dielectric resonator antenna was invented by our very own Prof. Long!
Introduction to Antennas (cont.)

Dielectric Resonator Antenna (cont.)

GPS antenna
Leaky-Wave Antenna

The wave is a “fast wave.”

\[ \beta = k_0 \sqrt{1 - \left( \frac{\pi}{k_0 a} \right)^2} < k_0 \]

This allows the wave to radiate from the slot.

Note:

\[ v_p = \frac{\omega}{\beta} > \frac{\omega}{k_0} = c \]
A narrow beam is created at angle $\theta_0$. 

$$\beta < k_0$$

$$k_z = k_0 \cos \theta_0 = \beta$$

$$\cos \theta_0 = \beta / k_0$$

A narrow beam is created at angle $\theta_0$. 
We consider here the radiation from an arbitrary antenna.

The far-field radiation acts like a plane wave going in the radial direction.

The far-field radiation acts like a plane wave going in the radial direction.
How far do we have to go to be in the far field?

Sphere of minimum diameter $D$ that encloses the antenna.

The far-field has the following form:

\[
\begin{align*}
\vec{E} &= \hat{\theta} E_\theta + \hat{\phi} E_\phi \\
\vec{H} &= \hat{\theta} H_\theta + \hat{\phi} H_\phi
\end{align*}
\]

Depending on the type of antenna, either or both polarizations may be radiated (e.g., a vertical wire antenna radiates only TM$_z$ polarization.
The far-field Poynting vector is now calculated:

\[
S = \frac{1}{2} E \times H^* \\
= \frac{1}{2} \left( \hat{\theta} E_\theta + \hat{\phi} E_\phi \right) \times \left( \hat{\theta} H_\theta + \hat{\phi} H_\phi \right) \\
= \frac{1}{2} \hat{r} \left( E_\theta H_\phi^* - E_\phi H_\theta^* \right) \\
= \frac{1}{2} \hat{r} \left( E_\theta \left( \frac{E_\theta}{\eta_0} \right)^* + E_\phi \left( \frac{E_\phi}{\eta_0} \right)^* \right) \\
= \frac{1}{2} \hat{r} \left( \left| \frac{E_\theta}{\eta_0} \right|^2 + \left| \frac{E_\phi}{\eta_0} \right|^2 \right) \\
\]

\[
\frac{E_\theta}{H_\phi} = \eta_0 \\
\frac{E_\phi}{H_\theta} = -\eta_0
\]
Hence we have

\[ S = \hat{r} \left( |E_\theta|^2 + |E_\phi|^2 \right) \left( \frac{1}{2\eta_0} \right) \]

or

\[ S = \hat{r} \left( \frac{|E|^2}{2\eta_0} \right) \]

**Note:**
In the far field, the Poynting vector is pure real (no reactive power flow).
The far field always has the following form:

\[
E(r, \theta, \phi) = \left( \frac{e^{-jk_0r}}{r} \right) E^F(\theta, \phi)
\]

\(E^F(\theta, \phi)\) = Normalized far-field electric field

In dB:

\[
\text{dB}(\theta, \phi) = 20 \log_{10} \left( \frac{|E^F(\theta, \phi)|}{|E^F(\theta_m, \phi_m)|} \right)
\]

\((\theta_m, \phi_m)\) = direction of maximum radiation
The far-field pattern is usually shown vs. the angle $\theta$ (for a fixed angle $\phi$) in polar coordinates.

$$\text{dB}(\theta, \phi) = 20 \log_{10}\left(\frac{|E^F(\theta, \phi)|}{|E^F(\theta_m, \phi_m)|}\right)$$

A “pattern cut”
The Poynting vector in the far field is

\[ S(r, \theta, \phi) = \hat{r} \left( \frac{|E_F(\theta, \phi)|^2}{2\eta_0} \right) \left( \frac{1}{r^2} \right) \]

The total power radiated is then given by

\[ P_{rad} = \int_0^{2\pi} \int_0^{\pi} (\hat{S} \cdot \hat{r}) r^2 \sin \theta \, d\theta \, d\phi = \int_0^{2\pi} \int_0^{\pi} \left( \frac{|E_F(\theta, \phi)|^2}{2\eta_0} \right) \sin \theta \, d\theta \, d\phi \]

Hence we have

\[ P_{rad} = \frac{1}{2\eta_0} \int_0^{2\pi} \int_0^{\pi} |E_F(\theta, \phi)|^2 \sin \theta \, d\theta \, d\phi \]
The directivity of the antenna in the directions \((\theta, \phi)\) is defined as

\[
D(\theta, \phi) \equiv \frac{S_r(\theta, \phi)}{P_{rad}/(4\pi r^2)} \quad r \to \infty
\]

The directivity in a particular direction is the ratio of the power density radiated in that direction to the power density that would be radiated in that direction if the antenna were an isotropic radiator (i.e., one that radiates equally in all directions).

In dB,

\[
D_{\text{dB}}(\theta, \phi) = 10 \log_{10} D(\theta, \phi)
\]

**Note:**

The directivity is sometimes referred to as the “directivity with respect to an isotropic radiator”.
The directivity is now expressed in terms of the far field pattern.

\[ D(\theta, \phi) \equiv \frac{S_r(\theta, \phi)}{P_{\text{rad}} / (4\pi r^2)} \quad r \to \infty \]

Hence we have

\[
D(\theta, \phi) = 4\pi r^2 \frac{1}{r^2} \frac{1}{2\eta_0} \int_0^{2\pi} \int_0^\pi \left| E^F(\theta, \phi) \right|^2 \sin \theta \, d\theta \, d\phi \\
\]

Therefore,

\[
D(\theta, \phi) = \frac{4\pi \left| E^F(\theta, \phi) \right|^2}{\int_0^{2\pi} \int_0^\pi \left| E^F(\theta, \phi) \right|^2 \sin \theta \, d\theta \, d\phi} 
\]
Resonant half-wavelength dipole: \[ D = 1.643 \]

Short dipole: \[ D = 1.5 \]

\[ \theta_m = \frac{\pi}{2} \]

\[ D = D_{\text{max}} = D\left(\frac{\pi}{2}, \phi\right) \]

Short dipole

\[ \overline{E^F}(\theta) = \hat{\theta} \sin \theta \]
The beamwidth measures how narrow the beam is. (The narrower the beamwidth, the higher the directivity).

HPBW = half-power beamwidth
The sidelobe level measures how strong the sidelobes are.

In this example the sidelobe level is about -13 dB
The radiation efficiency of an antenna is defined as

\[ e_r \equiv \frac{P_{\text{rad}}}{P_{\text{in}}} \]

where

- \( P_{\text{rad}} \) is the power radiated by the antenna,
- \( P_{\text{in}} \) is the power input to the antenna.

The gain of an antenna in the directions \((\theta, \phi)\) is defined as

\[ G(\theta,\phi) \equiv e_r \cdot D(\theta,\phi) \]

In dB, we have

\[ G_{\text{dB}}(\theta,\phi) = 10 \log_{10} G(\theta,\phi) \]
The gain tells us how strong the radiated power density is in a certain direction, for a given amount of input power.

Recall that

\[
D(\theta, \phi) \equiv \frac{S_r(\theta, \phi)}{P_{rad} / (4\pi r^2)} \quad r \to \infty
\]

Therefore, in the far field:

\[
S_r(\theta, \phi) = \left[ P_{rad} / (4\pi r^2) \right] D(\theta, \phi)
\]

\[
S_r(\theta, \phi) = \left[ e_r P_{in} / (4\pi r^2) \right] D(\theta, \phi)
\]

\[
S_r(\theta, \phi) = \left[ P_{in} / (4\pi r^2) \right] G(\theta, \phi)
\]
The Thévenin equivalent circuit of a wire antenna being used as a receive antenna is shown below.

\[ P_{inc} = \text{incident power density} \left[ \text{W/m}^2 \right] \]

\[ P_{d}^{inc} = \left| \frac{E_{inc}^2}{2\eta_0} \right| \left[ \text{W/m}^2 \right] \]

\[ Z_{Th} = Z_{in} \]

\[ Z_{in} = 73 [\Omega] \text{ (resonant half - wavelength dipole)} \]
The effective area determines the Thévenin voltage.

Assume an optimum conjugate-matched load:

\[ P_L = \text{power absorbed by load} \]

\[ V_{Th} \]

\[ Z_{Th} \]

\[ Z_L = Z_{Th}^* \]

\[ P_L = A_{eff} P_{d}^{inc} \]

\[ A_{eff} = \text{effective area of antenna} \]

\[ P_{d}^{inc} = \text{incident power density} \left[ \text{W/m}^2 \right] \]
We have the following general formula*

\[ A_{\text{eff}}(\theta, \phi) = G(\theta, \phi) \left( \frac{\lambda_0^2}{4\pi} \right) \]

\[ G(\theta, \phi) = \text{gain of antenna in the direction of the incident signal} \]

This assumes that the incoming signal is polarized in the optimum direction.

Effective area of a lossless resonant half-wave dipole antenna:

Assuming the incident electric field is aligned along the wire and $\theta = 90^\circ$:

$$A_{\text{eff}} \left(90^\circ, \phi\right) = G \left(90^\circ, \phi\right) \left(\frac{\lambda_0^2}{4\pi}\right)$$

$$= 1.643 \left(\frac{\lambda_0}{4\pi}\right)$$

$$= 1.643 \left(\frac{(2l)^2}{4\pi}\right) \quad (l = \lambda_0 / 2)$$

Hence

$$A_{\text{eff}} \left(90^\circ, \phi\right) = 0.5230l^2$$
Find the receive power in wireless system shown below, assuming that the receiver is connected to an optimum conjugate-matched load.

\[ f = 1 \text{ [GHz]} \quad (\lambda_0 = 29.979 \text{ [cm]}) \]

\[ P_{in} = 10 \text{ [W]} \]

\[ r = 1 \text{ [km]} \]

Assume lossless antennas \((G = D = 1.643)\)
Receive Antenna (cont.)

\[ P_L = A_{eff} P_{inc} \]

Gain of receive antenna

Gain of transmit antenna

Recall:

\[ A_{eff} \left( 90^\circ, \phi \right) = 1.643 \left( \frac{\lambda_0^2}{4\pi} \right) , \quad P_{d}^{inc} = \frac{P_{rad}}{4\pi r^2} (1.643) \]

Hence

\[ P_L = 1.643 \left( \frac{\lambda_0^2}{4\pi} \right) \left[ \frac{P_{rad}}{4\pi r^2} (1.643) \right] \]

The result is

\[ P_L = 1.54 \times 10^{-8} [W] \]
Effective area of dish antenna

\[ G(\theta, \phi) = A_{\text{eff}}(\theta, \phi) \left( \frac{4\pi}{\lambda_0^2} \right) \]

In the maximum gain direction:

\[ A_{\text{eff}} = A_{\text{phy}} e_{\text{ap}} \]

- \( A_{\text{phy}} \) = physical area of dish
- \( e_{\text{ap}} \) = aperture efficiency

The aperture efficiency is usually less than 1 (less than 100%).