Antennas and Propagation Model

Introduction

- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception

Radiation Pattern

- A graphical representation of radiation properties of an antenna as a function of space.
- Describes how the antenna radiates energy out into space (or how it receives energy).
- Depicted as two-dimensional cross section

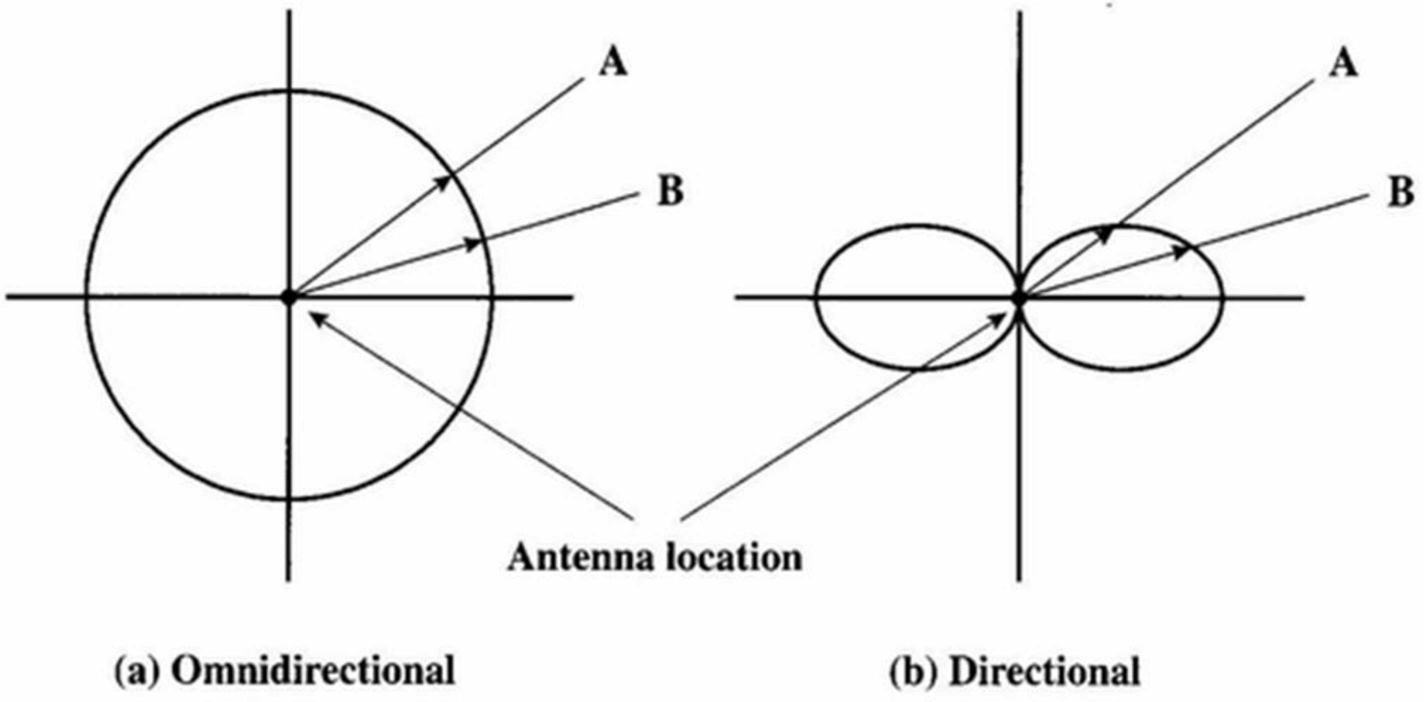
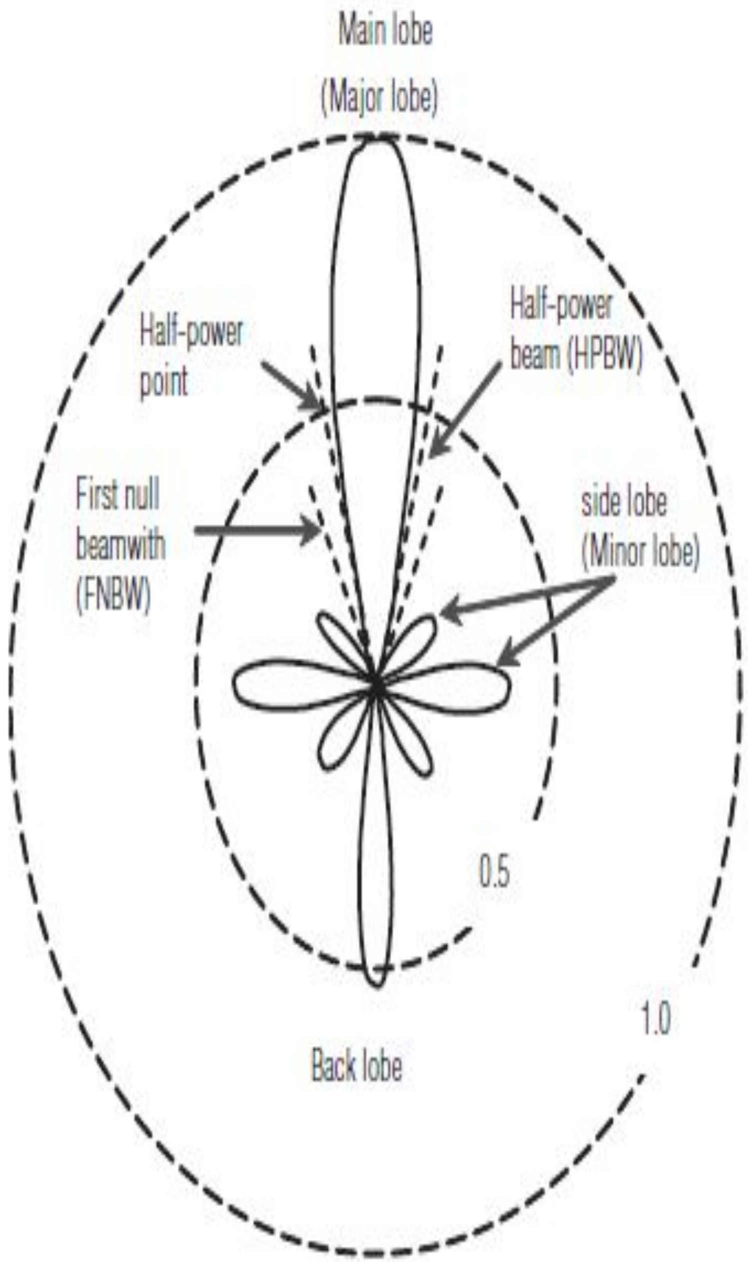


Figure 5.1 Idealized Radiation Patterns

Radiation Pattern Parameter:

- **Main lobe:** This is the radiation lobe containing the direction of maximum radiation.
- **Beamwidth:** Also referred to as the half-power (3dB) beam width. It is the angle subtended by the half power points of the main lobe.
- **Minor lobe:** All the lobes other than the main lobe are called the minor lobes. These lobes represent the radiation in undesired directions.
- **Back lobe:** This is the minor lobe diametrically opposite to the main lobe.
- **Side lobes:** These are the minor lobes adjacent to the main lobe and are separated by various nulls.

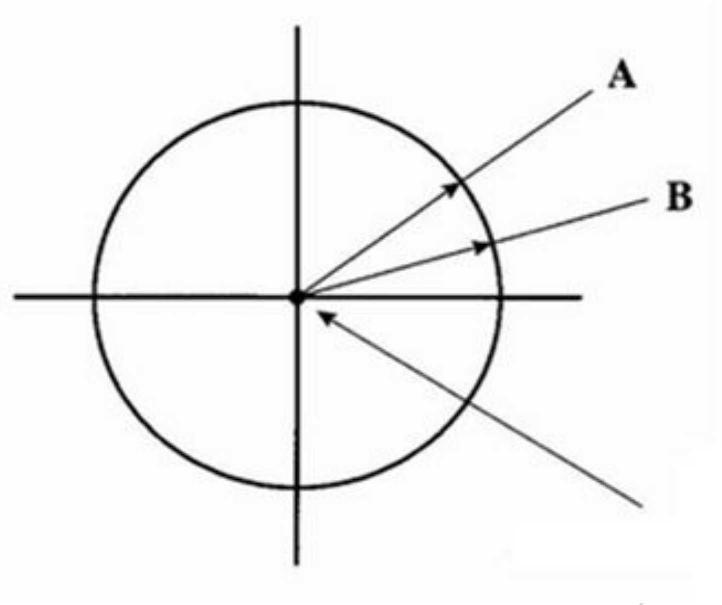


Types of Antennas

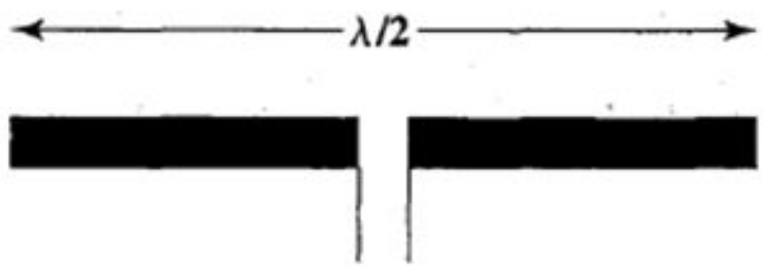
- Isotropic antenna (idealized)
  - Radiates power equally in all directions
- Dipole antennas
  - Half-wave dipole antenna (or Hertz antenna)
  - Quarter-wave vertical antenna (or Marconi antenna)
- Parabolic Reflective Antenna
- Directional Antennas
  - Signal amplitudes and phases to each antenna are adjusted to create a directional pattern
  - Very useful in modern systems

Types of Antennas

- **Isotropic antenna (idealized)**
  - Radiates power equally in all directions.
  - The pattern of radiation is sphere with the antenna at the center.
  - The distance from the antenna to each point on the radiation pattern is proportional to the power from the antenna in that direction.

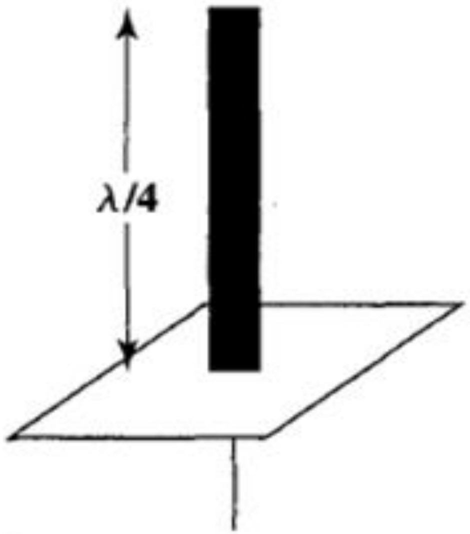


- **Dipole antennas**
  - Half-wave dipole antenna (or Hertz antenna):
    - An antenna having a physical length of ½ the wavelength λ is called a hertz antenna or a half wave dipole antenna.
    - Consists of two straight collinear conductors of equal length separated by small gap.
    - The length of the antenna is one half of the wave length of the signal that can be transmitted most efficiently



(a) Half-wave dipole

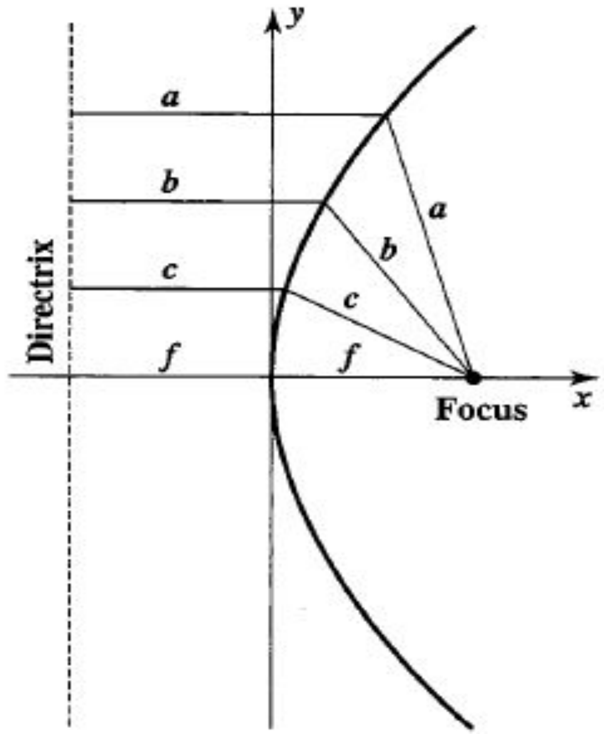
- **Dipole antennas**
  - Quarter-wave vertical antenna (or Marconi antenna) :
    - An antenna having a physical length of 1/4 the wavelength λ is called a Marconi antenna or a Quarter-wave vertical antenna.
    - A vertical quarter wave antenna is the type commonly used for automobile radios and portable radios.

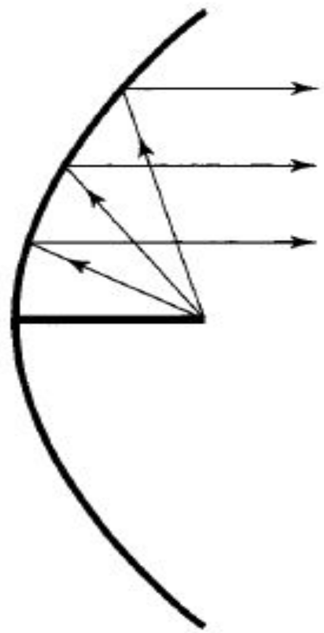


(b) Quarter-wave antenna

Parabolic Reflector Antenna

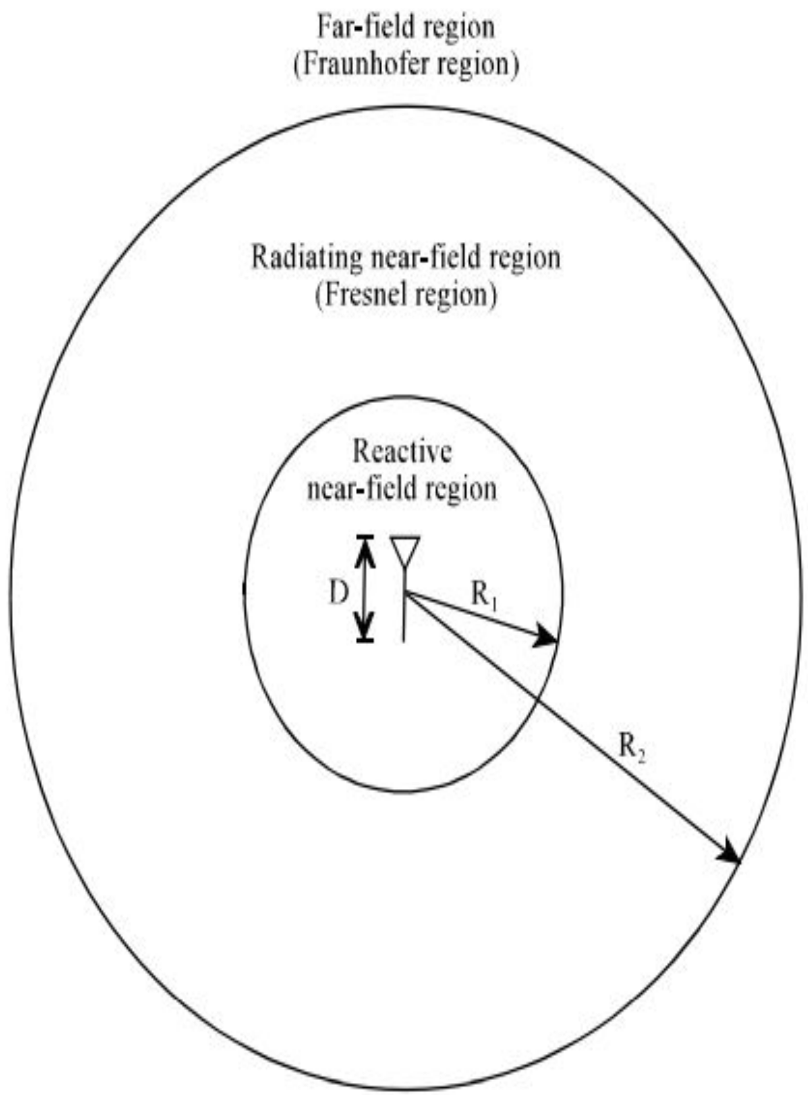
- Used in terrestrial microwave and satellite applications.
- A parabola is the locus of all points equidistant from a fixed line and a fixed point not on the line.
- The fixed point is called the focus and the fixed line is called the directrix.
- If a parabola is revolved about its axis, the surface generated is called a paraboloid.
- If a source of electromagnetic energy is placed at the focus of the paraboloid, and if the paraboloid is a reflecting surface, then the wave will bounce back in lines parallel to the axis of the paraboloid.





Antenna Field Types

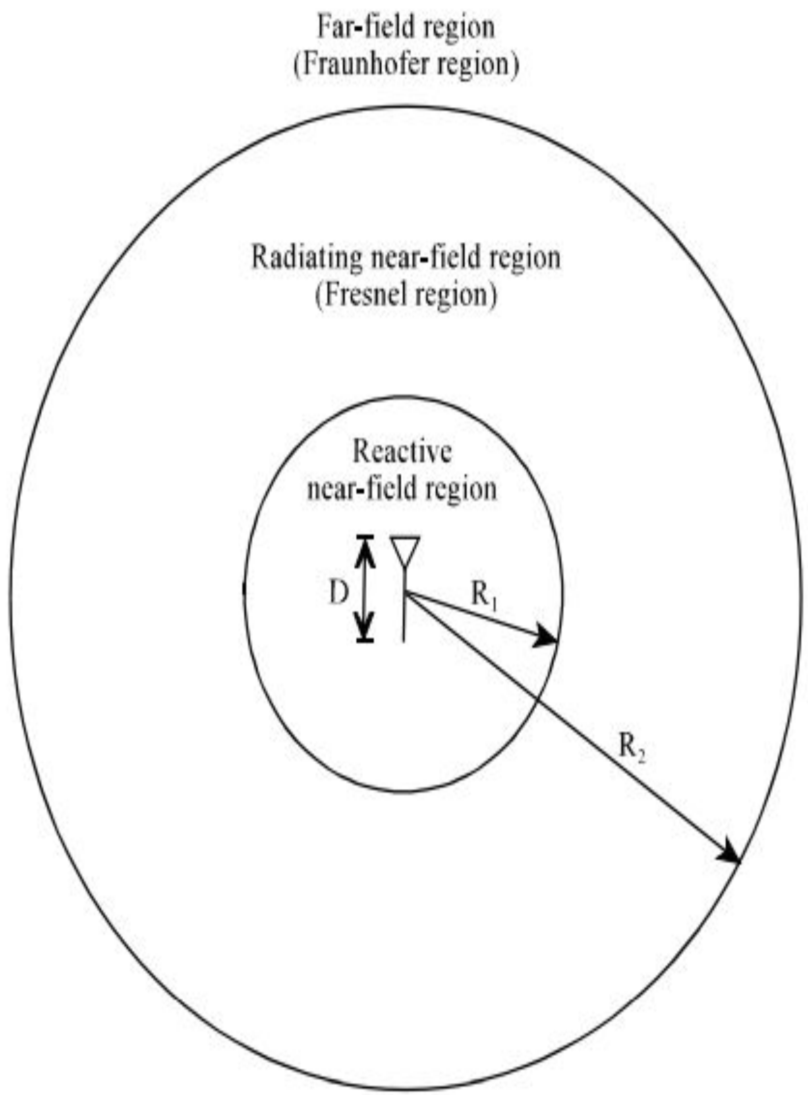
- **The fields surrounding an antenna are divided into 3 principle regions:**
  1. Reactive Near Field
  2. Radiating Near Field or Fresnel Region
  3. Far Field or Fraunhofer Region



1. Reactive Near field

- Reactive field can be characterized by standing (stationary) waves which represent stored energy.
- Close to the antenna and up to about 1 wavelength away from any radiating surface.
- The boundary of this region is commonly given as:

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



2. Radiative Near-Field (Fresnel) Region

- Radiative field can be characterized by radiating (propagating) waves which represent transmitted energy.
- This is the region where the EM fields start to transition from reactive to radiating fields.
- Since they have not completely transitioned, the shape of the radiation pattern still varies with distance.
- The region is commonly given by:

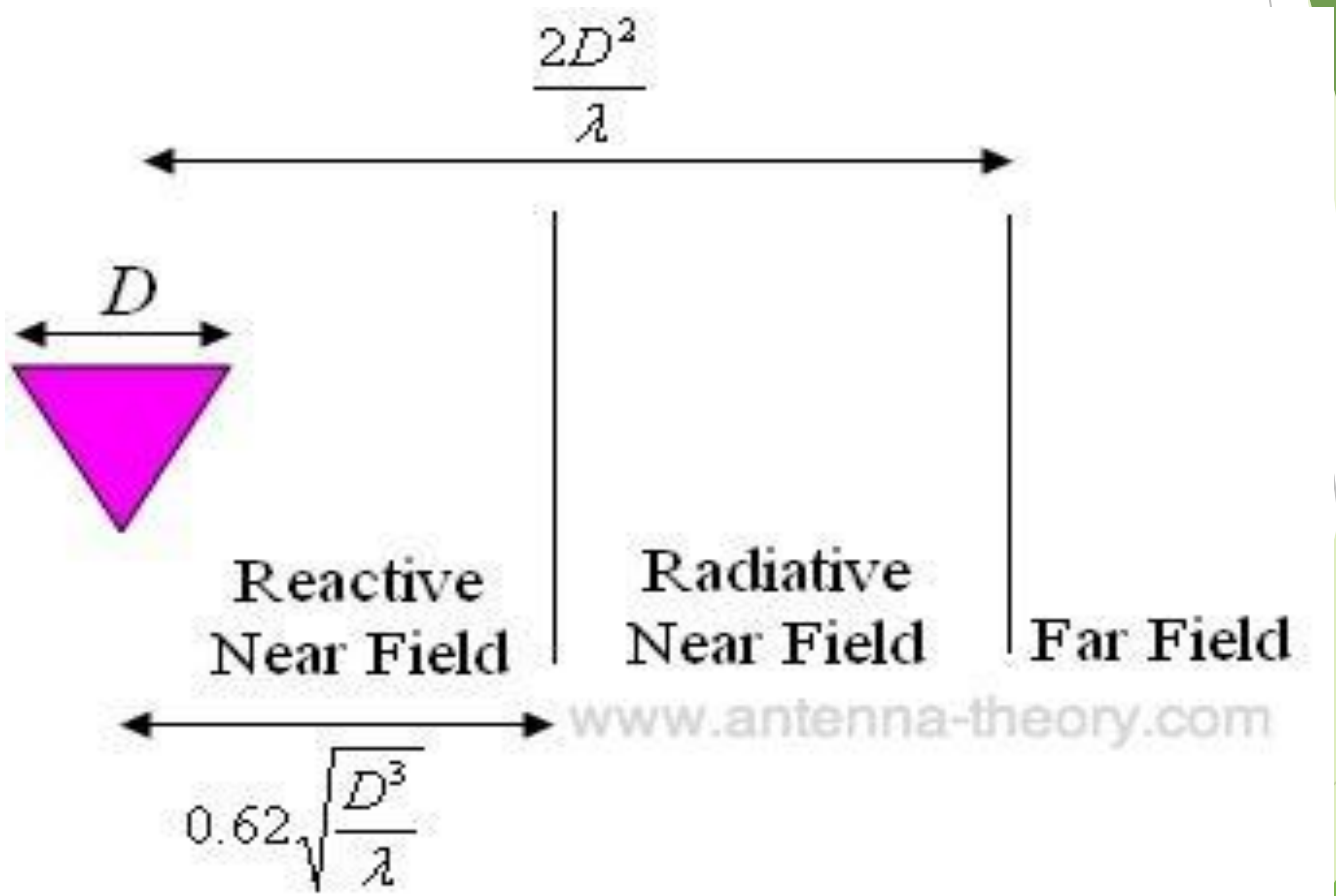
$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$$

3. Far-Field (Fraunhofer) Region

- The far field is the region far from the antenna.
- In this region, the radiation pattern does not change shape with distance.
- Antennas are usually used to transfer signals at large distances which are considered to be in the far-field region.
- One condition that must be met when making measurements in the far field region is that the distance from the antenna must be much greater than the size of the antenna and the wavelength.

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

Antenna Field Regions



Example – 1.1

- The audio power of the human voice is concentrated at about 300 Hz. a. What is the length of an antenna one-half wavelength long for sending radio at 300 Hz?

- We have, λ =c/f i.e wavelength= speed of light/frequency of wave. Actual wavelength = ($3*10^8$ m/sec) / 300Hz = 1000 Km
- So the length of an antenna which is one-half of wavelength long is λ /2 =1000 Km/2 =500 Km
- Antennas of the appropriate size for this frequency are impracticably large, so that to send voice by radio, the voice signal must be used to modulate a higher (carrier) frequency for which the natural antenna size is smaller.

Example – 1.1 cont..

- b. An alternative is to use a modulation scheme, for transmitting the voice signal by modulating a carrier frequency, so that the bandwidth of the signal is a narrow band centered on the carrier frequency.
- Suppose we would like a half-wave antenna to have a length of 1 m. What carrier frequency would we use?

- Length of a half-wave antenna λ /2=1m i.e Waveleng λ = 2m
- Therefore corresponding carrier frequency f = c/ λ = $(3*10^8$ m/sec) / (2 m) = 150 MHz.

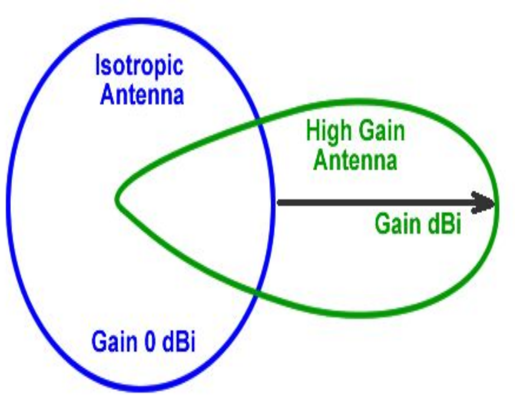
Examples

- Find the far-field distance for an antenna with maximum dimension of 1 m and operating frequency of 900 MHz.

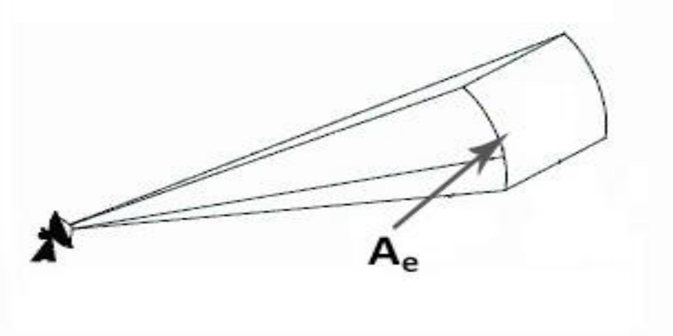
- An antenna has a diameter of 2m and frequency 16GHz. Calculate the 3 dB beamwidth for the antenna.

Antenna Gain

- Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- G = (power radiated by an antenna)/(power radiated by reference antenna)
- Example:
  - A transmitting antenna with a gain of 3 dB means that the power received far from the antenna will be 3 dB higher (twice as much) than what would be received from a lossless isotropic antenna with the same input power.



Effective Area of Antenna



- **Effective area (A_e)**
  - Related to physical size and shape of antenna
  - It is a theoretical value which is a measure of how effective an antenna is at receiving power.
  - The effective area can be calculated by knowing the gain of the receiving antenna.

- **Relationship between antenna gain and effective area**

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light (3×10^8 m/s)
  - λ = carrier wavelength

Effective Area and G for Different Types of Antennas

Type of Antenna	Effective Area A_e (m^2)	Power Gain (relative to isotropic)
Isotropic	$\lambda^2/4\pi$	1
Infinitesimal dipole or loop	$1.5\ \lambda^2/4\pi$	1.5
Half-wave dipole	$1.64\ \lambda^2/4\pi$	1.64
Horn, mouth area A	$0.81\ A$	$10\ A/\lambda^2$
Parabolic, face area A	$0.56\ A$	$7\ A/\lambda^2$
Turnstile (two crossed, perpendicular dipoles)	$1.15\ \lambda^2/4\pi$	1.15

Example –2

1. For a parabolic reflective antenna with a diameter of 2 m, operating at 12 GHz, what is the effective area and gain?

Example 5.1 For a parabolic reflective antenna with a diameter of 2 m, operating at 12 GHz, what is the effective area and the antenna gain? We have an area of $A = \pi r^2 = \pi$ and an effective area of $A_e = 0.56\pi$. The wavelength is $\lambda = c/f = (3 \times 10^8)/(12 \times 10^9) = 0.025$ m. Then

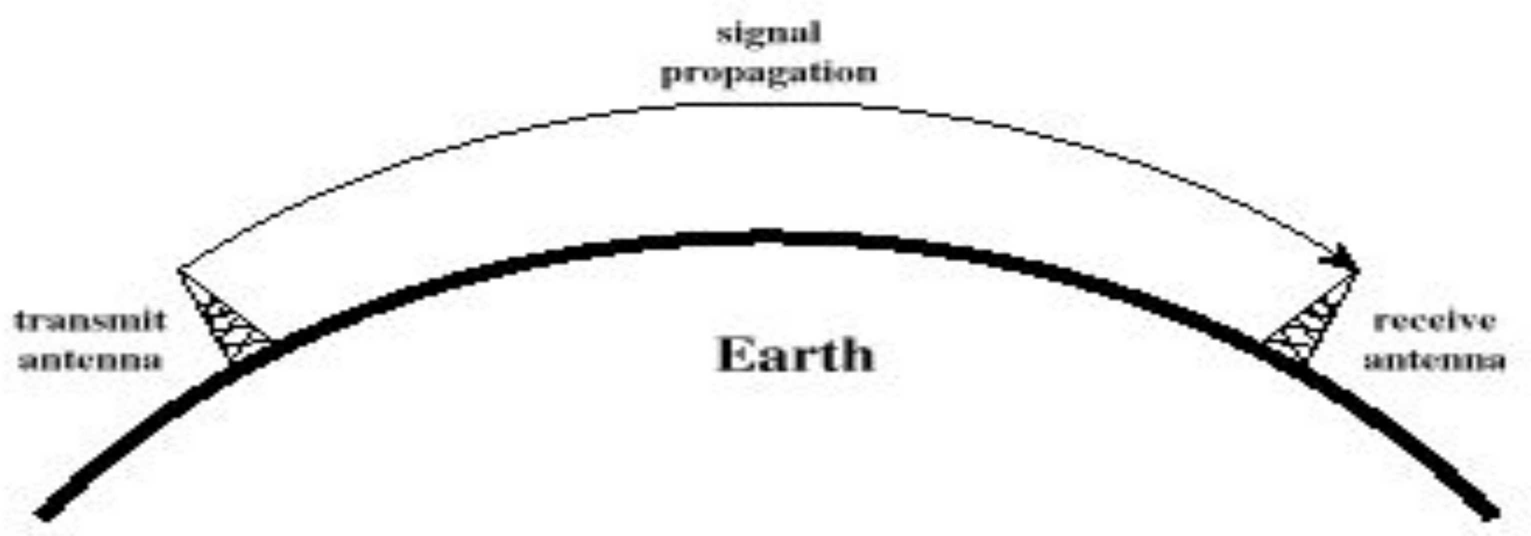
$$G = (7A)/\lambda^2 = (7 \times \pi)/(0.025)^2 = 35{,}186$$

$$G_{\pi B} = 45.46 \text{ dB}$$

Propagation Modes

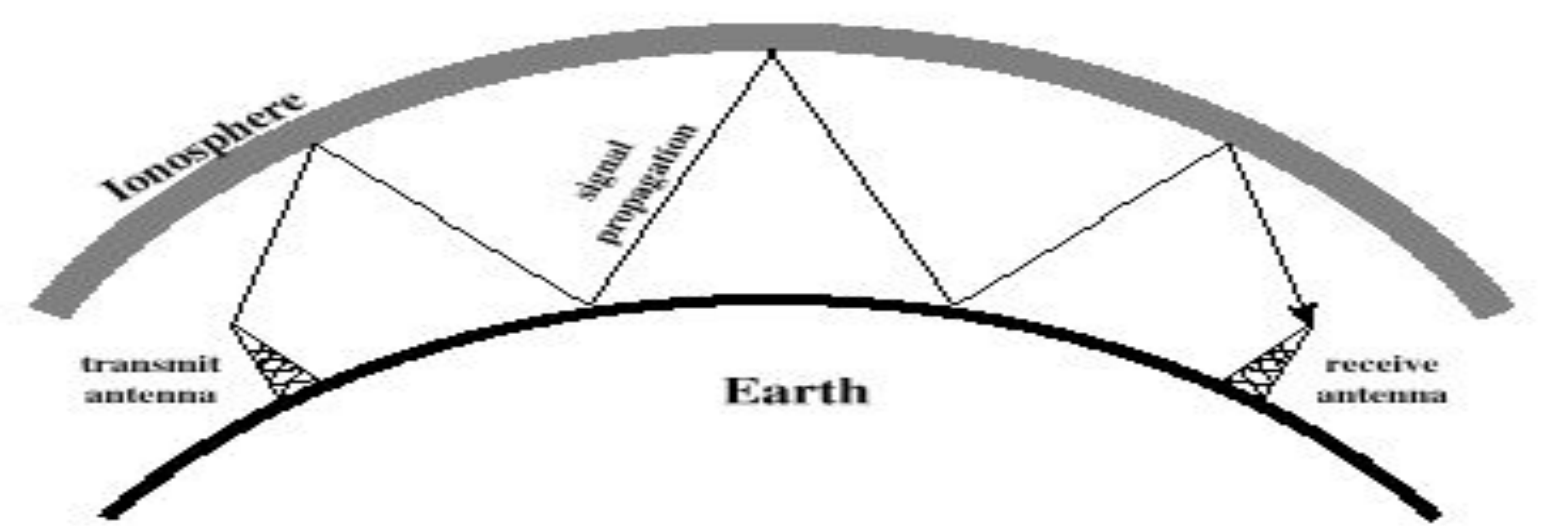
- Wave propagation is any of the ways in which waves travel.
  - Ground Wave (GW) Propagation: < 3MHz
  - Sky Wave (SW) Propagation: 3MHz to 30MHz
  - Effective Line-of-Sight (LOS) Propagation: > 30MHz

Ground Wave Propagation



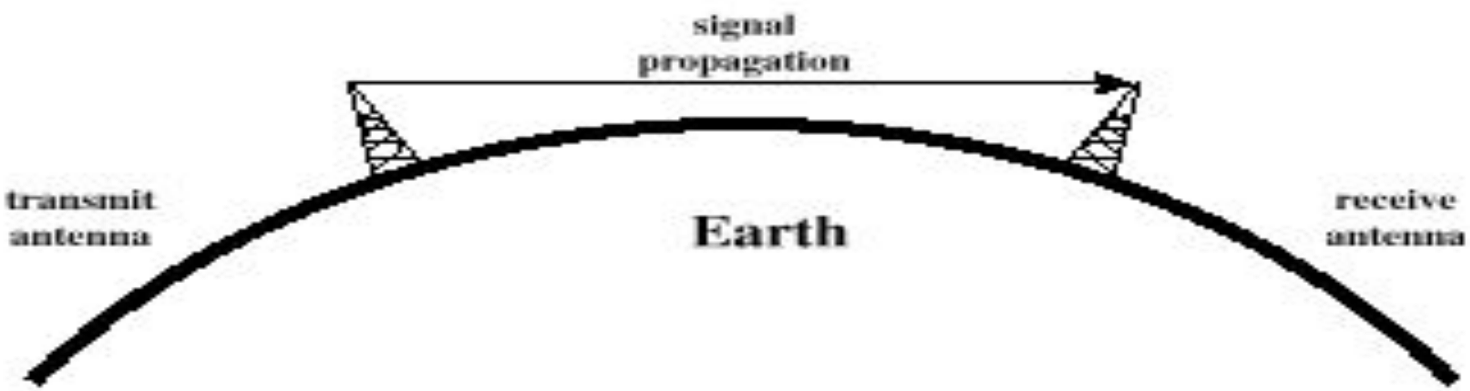
- Follows contour of the earth.
- Can propagate considerable distances.
- Frequency bands: ELF, VF, VLF, LF, MF.
- Spectrum range: 30Hz ~ 3MHz, e.g. AM radio.

Sky Wave Propagation



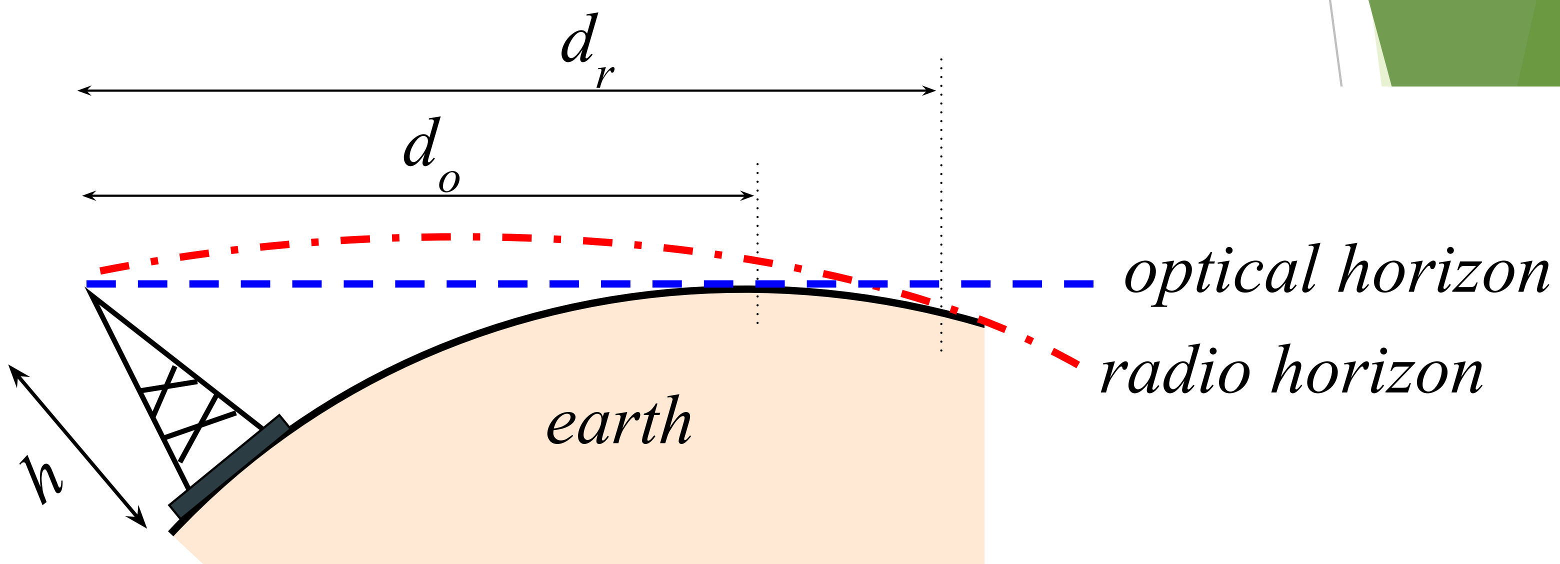
- Signal reflected from ionized layer of upper atmosphere back down to earth, which can travel a number of hops, back and forth between ionosphere and earth's surface.
- HF band with intermediate frequency range: 3MHz ~ 30MHz.
- Example International broadcast.

Line-of-Sight Propagation



- Above 30 MHz, neither ground wave nor sky wave propagation modes operate, and communication must be by line of sight (LOS)
- For satellite communication, signal above 30 MHz not reflected by ionosphere.
- For ground communication, antennas within *effective* LOS due to refraction.
- Frequency bands: VHF, UHF, SHF, EHF, Infrared, optical light
- Spectrum range : 30MHz ~ 900THz.

LOS calculations



- **What is the relationship between *h* and *d* ?**
  - For optical LOS:

$$d_o = 3.57\sqrt{h}$$

  - For effective or radio LOS:

$$d_r = 3.57\sqrt{\mathrm{K}h}$$

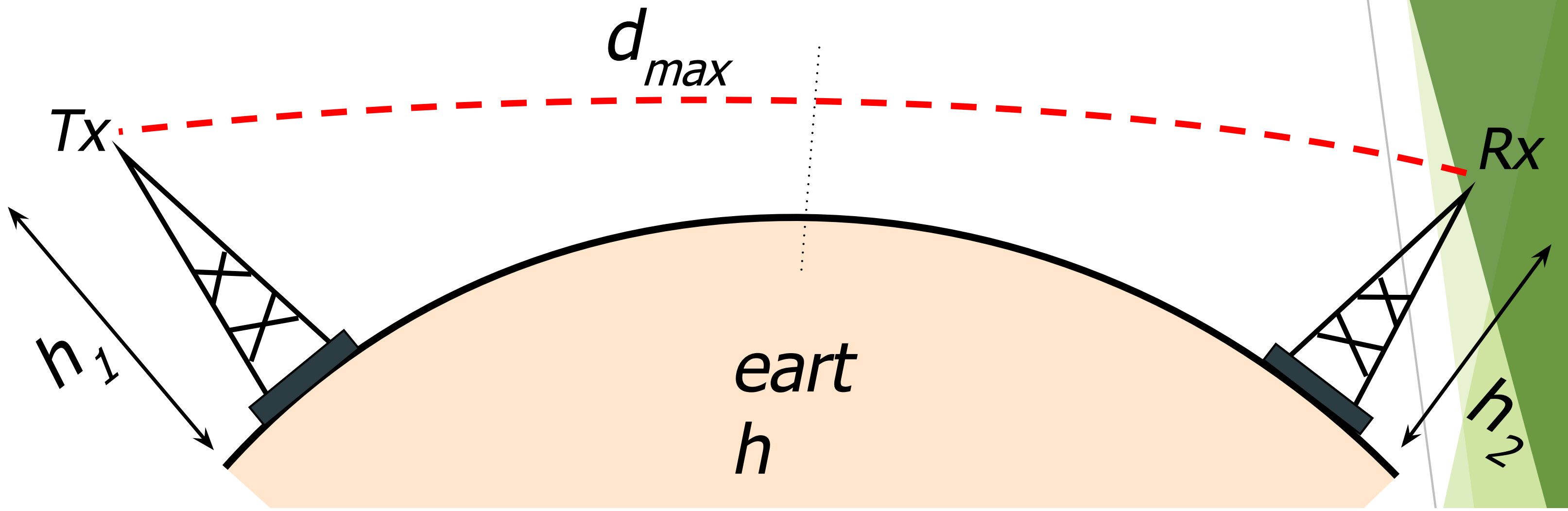
where

h = antenna height (m)

d = distance between antenna and horizon (km)

K = adjustment factor for refraction, K = 4/3

LOS calculations (2)

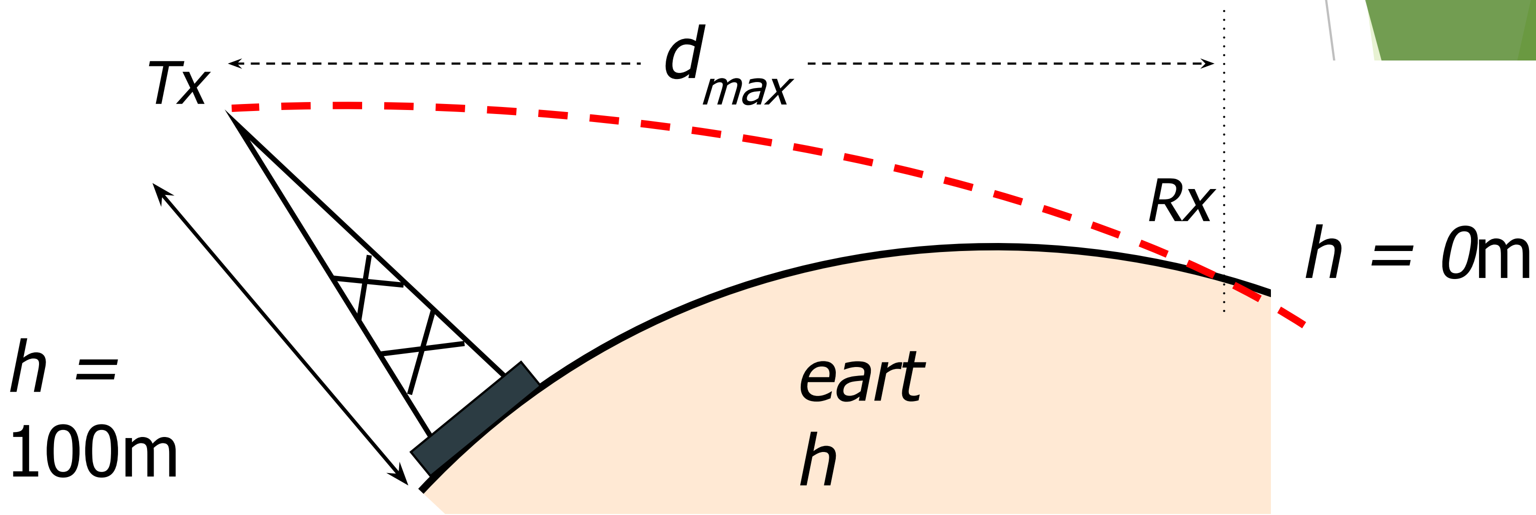


- **What is the Maximum distance between two antennas for LOS propagation ?**

$$d_{max} = 3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right)$$

where h_1 = height of antenna 1
h_2 = height of antenna 2

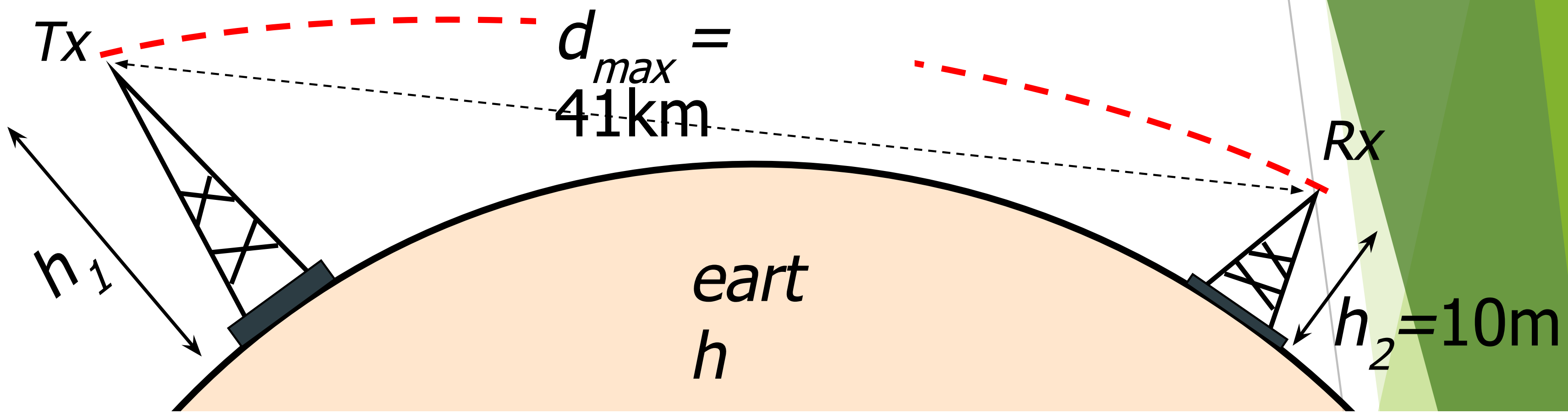
Example (1)



- What is the maximum distance between two antennas for LOS transmission if one antenna is 100m and the other is at ground level?

Solution: $d_{max} = 3.57\left(\sqrt{Kh_1} + 0\right) = 3.57\sqrt{\frac{4}{3}\times 100} = 41\text{km}$

Example (2)



- Now, suppose the receiving antenna is 10m high, what is the height of the transmitting antenna in order to achieve same distance above?

$$d_{max} = 3.57\left(\sqrt{Kh_1} + \sqrt{Kh_2}\right) \Rightarrow 41 = 3.57\left(\sqrt{Kh_1} + \sqrt{\frac{4}{3}\times 10}\right)$$

$$\sqrt{Kh_1} = \frac{41}{3.57} - \sqrt{13.33} = 7.84$$

$$\therefore \quad h_1 = 7.84^2/1.33 = 46.2\text{m}$$ (Saving over 50m)

Problems

1. Find the optimum distance from the ground level for a half-wave dipole antenna of frequency 15 MHz.

2. Determine the height of an antenna for a TV station that must be able to reach customers up to 80 km away.

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LOS Wireless Transmission Impairments

With any communications system, the signal that is received will differ from the signal that is transmitted, due to various transmission impairments:

- Attenuation and attenuation distortion
- Free space loss
- Noise
- Atmospheric absorption
- Multipath
- Refraction

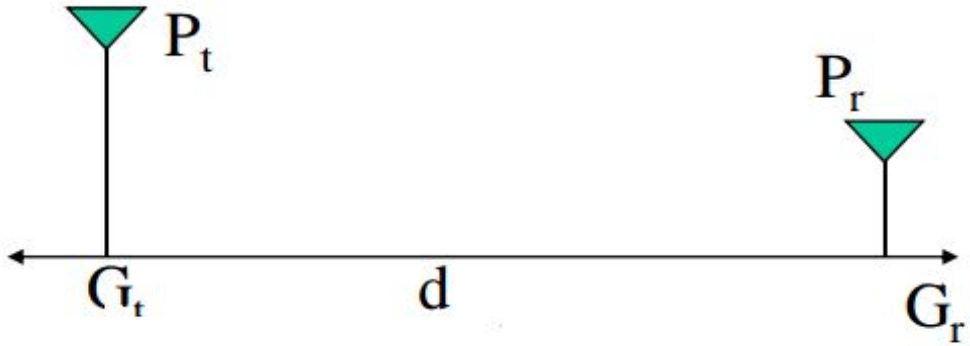
Free Space Loss

- For any type of wireless communication the signal disperses with distance.
- If no other sources of attenuation or impairment are assumed, a transmitted signal attenuates over distance because the signal is being spread over a larger and larger area.This form of attenuation is known as free space loss.
- The free space power received by an antenna which is separated from a radiating antenna by a distance is given by Friis free space equation.

Friis Free Space Equation

- The relation between the transmit and receive power is given by Friis free space equations:

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



- G_t and G_r are the transmit and receive antenna gains
- λ is the wavelength
- d is the T-R separation
- P_t is the transmitted power
- P_r is the received power
- P_t and P_r are in same units

Free Space Loss

- Free space loss, ideal isotropic antenna

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

  - P_t = signal power at transmitting antenna
  - P_r = signal power at receiving antenna
  - λ = carrier wavelength
  - d = propagation distance between antennas
  - c = speed of light (3×10^8 m/s)

  where d and λ are in the same units (e.g., meters)

  $G_t = G_r = 1$

Free Space Loss

- Free space loss equation can be recast:

$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

$$= -20\log(\lambda) + 20\log(d) + 21.98\ \text{dB}$$

$$= 20\log\left(\frac{4\pi f d}{c}\right) = 20\log(f) + 20\log(d) - 147.56\ \text{dB}$$

Free Space Loss

- Free space loss accounting for gain of other antennas

$$\frac{P_t}{P_r} = \frac{(4\pi)^2 (d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t} = \frac{(cd)^2}{f^2 A_r A_t}$$

  - G_t = gain of transmitting antenna
  - G_r = gain of receiving antenna
  - A_t = effective area of transmitting antenna
  - A_r = effective area of receiving antenna

Free Space Loss

- Free space loss accounting for gain of other antennas can be recast as

$$L_{dB} = 20\log(\lambda) + 20\log(d) - 10\log(A_t A_r)$$
$$= -20\log(f) + 20\log(d) - 10\log(A_t A_r) + 169.54\text{dB}$$

Examples

1. Assume that two antennas are half-wave dipoles and each has a directive gain of 3 dB. If the transmitted power is 1 W and the two antennas are separated by a distance of 10 km, what is the received power? Assume that the antennas are aligned so that the directive gain numbers are correct and that the frequency used is 100 MHz.

2. If a transmitter produces 50 watts of power, express the transmit power in units of (a) dBm, and (b) dBW. If 50 watts is applied to a unity gain antenna with a 900 MHz carrier frequency, find the received power in dBm at a free space distance of 100 m from the antenna, What is P (10 km) ? Assume unity gain for the receiver antenna.

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Example-3

- Determine the **isotropic free space loss** at 4 GHz for the shortest path to a synchronous satellite from earth (35,863 km). What is the power received at the satellite antenna? (Assume antenna gain of both the satellite- and ground-based antennas are 44 dB and 48 dB, respectively. a transmit power of 250 W at the earth station.)

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