Antennas and Propagation

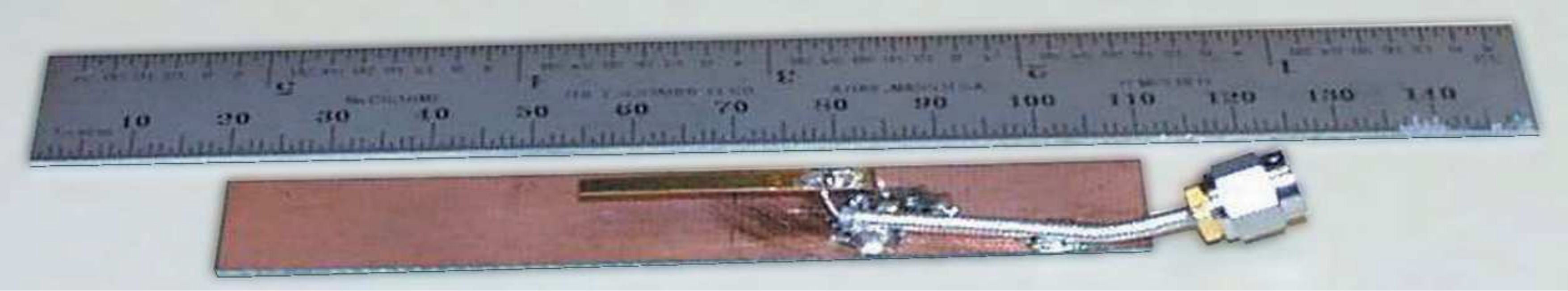
Chapter 5

The Arecibo Observatory Antenna System

The world's largest single radio telescope

304.8-m spherical reflector

National Astronomy and Ionosphere Center (USA), Arecibo, Puerto Rico



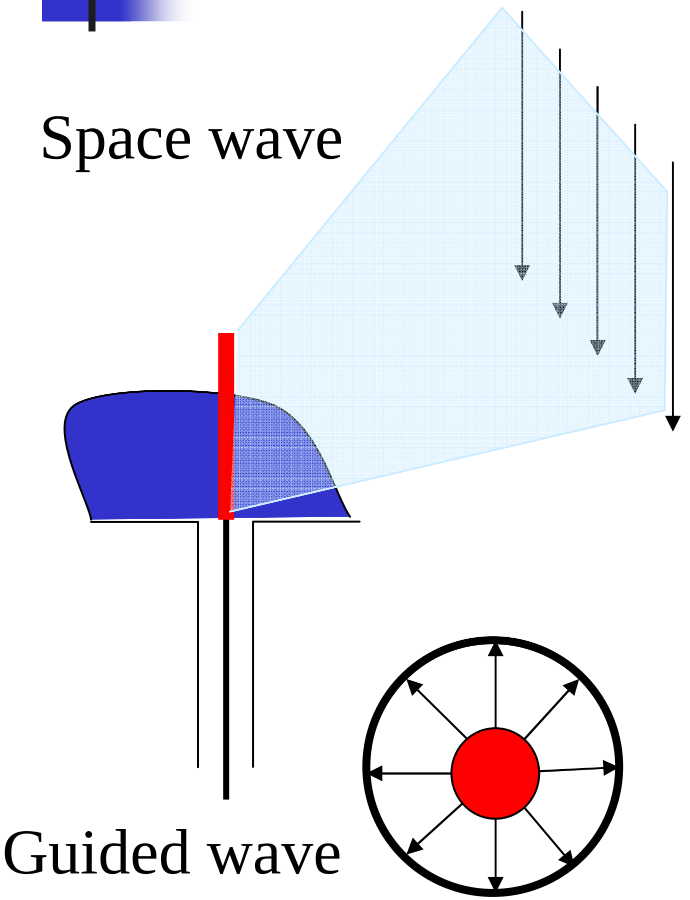
- Patch and slot antennas derived from printed-circuit and micro-strip technologies

- Ceramic chip antennas are typically helical with high dielectric loading to reduce the antenna size

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

Antenna purpose

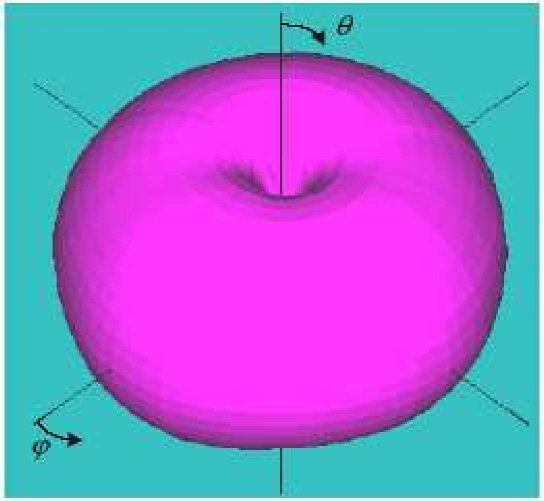


- Transformation of a guided EM wave in transmission line (waveguide) into a freely propagating EM wave in space (or vice versa) with specified directional characteristics
  - Transformation from time-function in one-dimensional space into time-function in three dimensional space
  - The specific form of the radiated wave is defined by the antenna structure and the environment

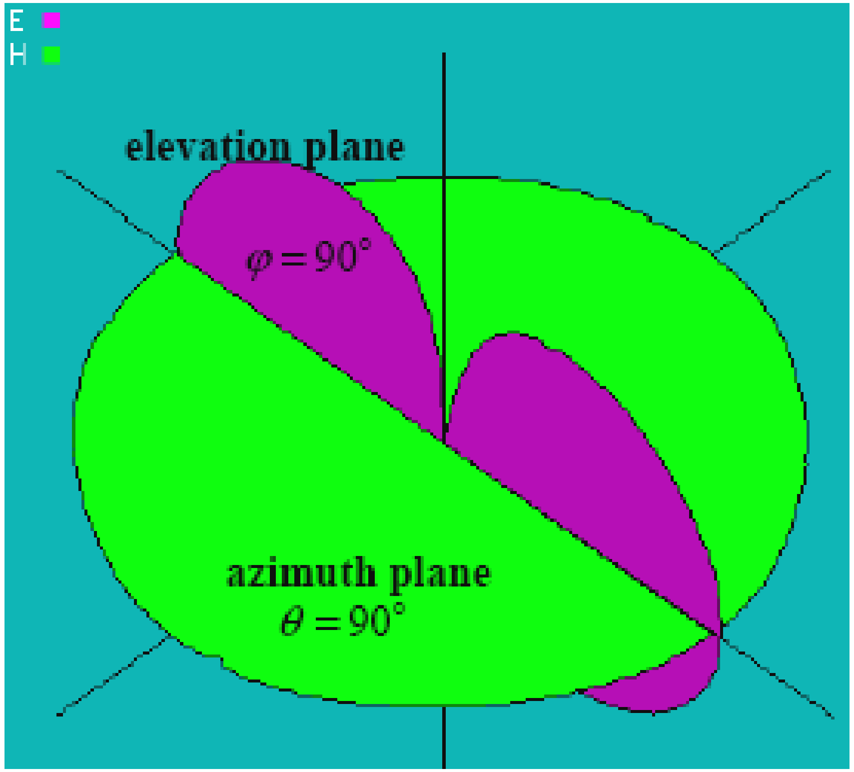
Radiation Patterns

- Radiation pattern
  - Graphical representation of radiation properties of an antenna
- The *radiation pattern of antenna* is a representation of the distribution of the power out-flowing (radiated) from the antenna (in the case of transmitting antenna), or inflowing (received) to the antenna (in the case of receiving antenna) as a function of direction angles from the antenna

Antenna radiation pattern
is 3-dimensional



2-D pattern

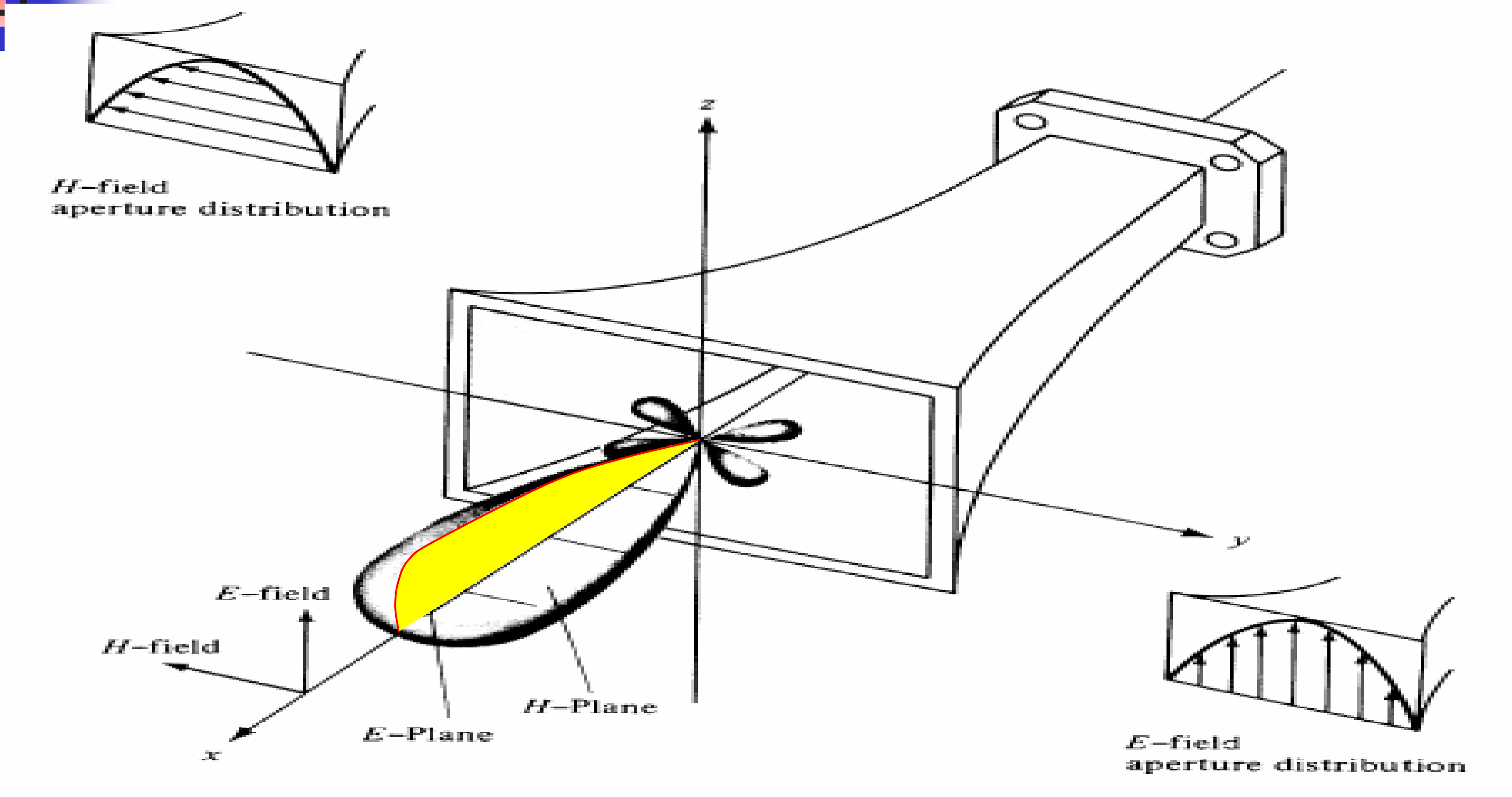


Two 2-D patterns

- Usually the antenna pattern is presented as a 2-D plot, with only one of the direction angles, θ or ϕ varies
- It is an intersection of the 3-D one with a given plane
  - usually it is a θ = *const* plane or a ϕ= *const* plane that contains the pattern’s maximum

Source: NK Nikolova

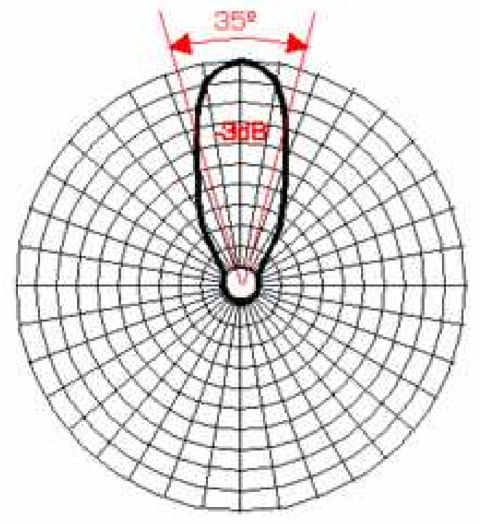
Example



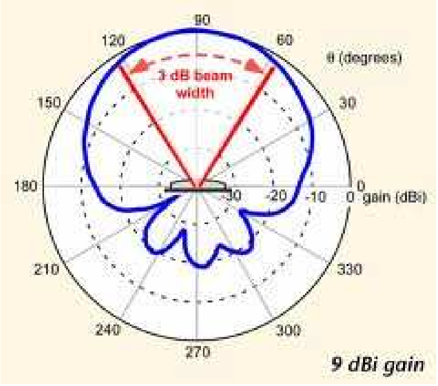
Source: NK Nikolova

Radiation Patterns

- Beam width (or half-power beam width)
  - Measure of directivity of antenna
  - The angle between the half-power (-3 dB) of the main lobe
  - Beamwidth is usually expressed in degrees. expressed for the horizontal plane
  - For the optical regime, *see* **beam divergence**

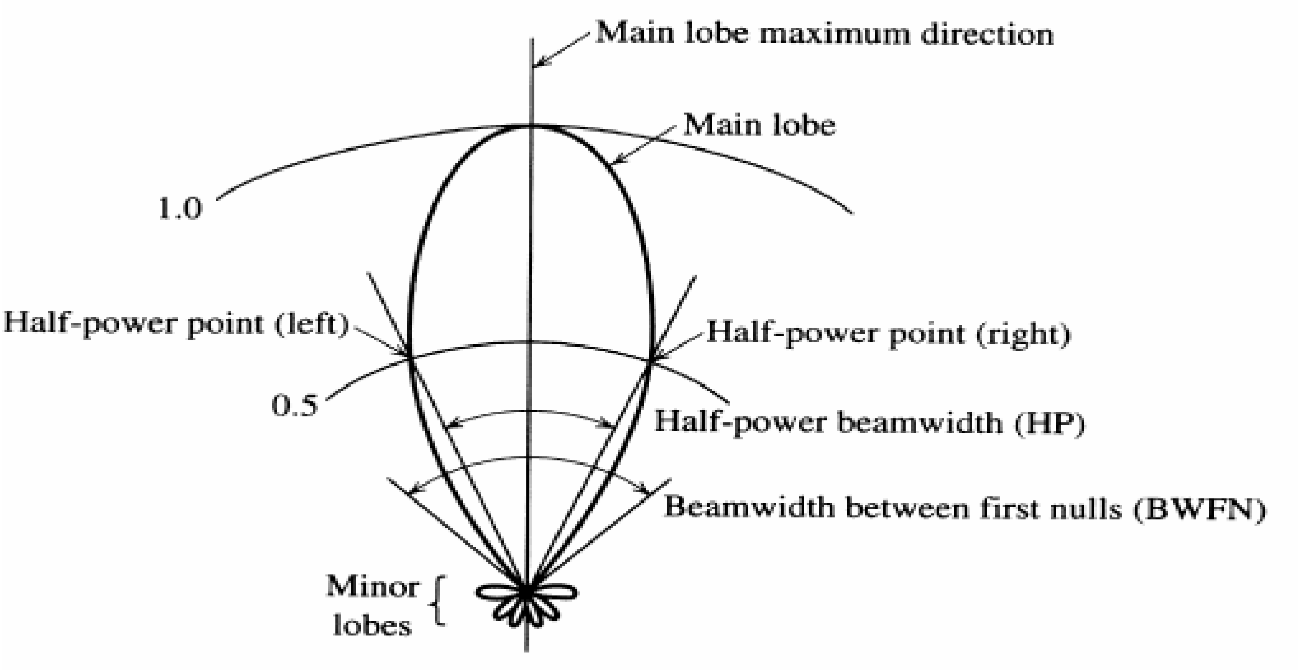


- Reception pattern
  - Receiving antenna's equivalent to
  - radiation pattern

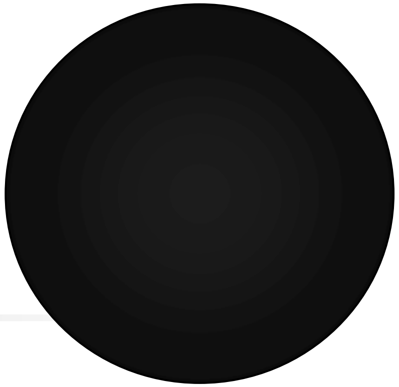


Beam Width (continue)

- ***Half-power beamwidth*** (HPBW): is the angle between two vectors from the pattern's origin to the points of the major lobe where the radiation intensity is half its maximum (antenna resolution properties)
  - Important in radar technology, radioastronomy, etc.



Types of Antennas



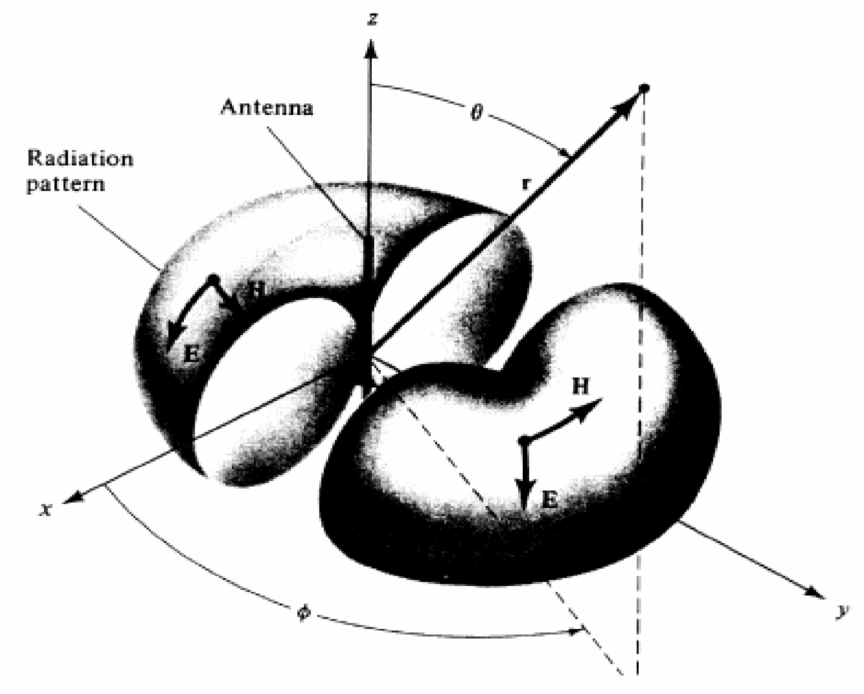
- ***Isotropic antenna or isotropic radiator*** (idealized)
  - Radiates power equally in all directions
  - Is a hypothetical (not physically realizable) concept, used as a useful reference to describe real antennas.
  - Isotropic antenna radiates equally in all directions.
  - Its radiation pattern is represented by a sphere whose center coincides with the location of the isotropic radiator.

Directional antenna

- ***Directional antenna*** is an antenna, which radiates (or receives) much more power in (or from) some directions than in (or from) others.
  - Note: Usually, this term is applied to antennas whose directivity is much higher than that of a half-wavelength dipole.

Source: NK Nikolova

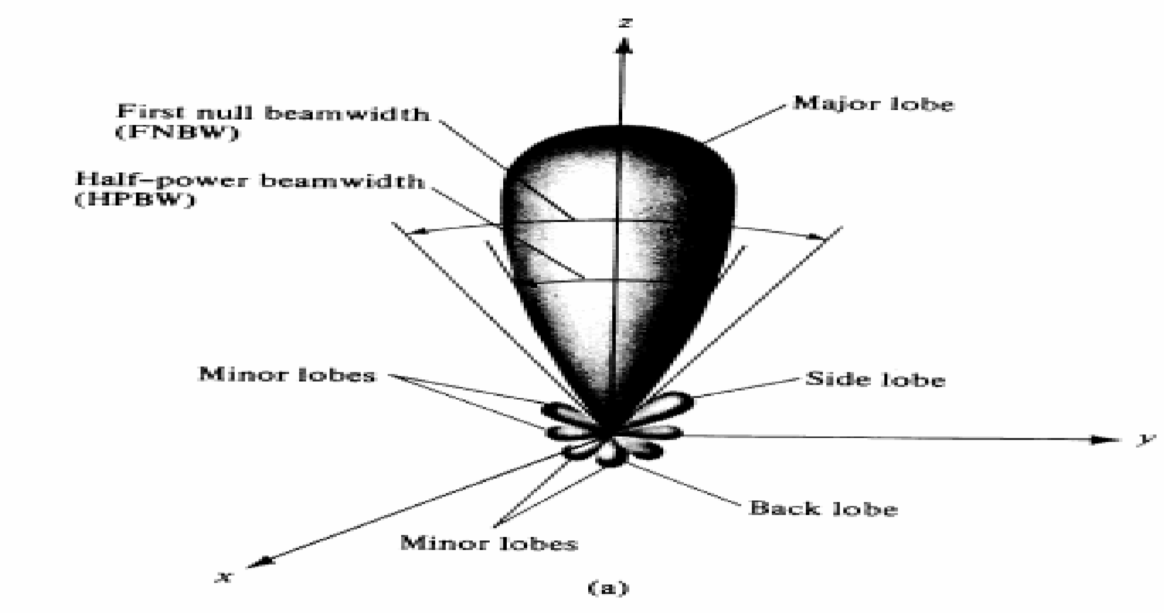
Omnidirectional antenna

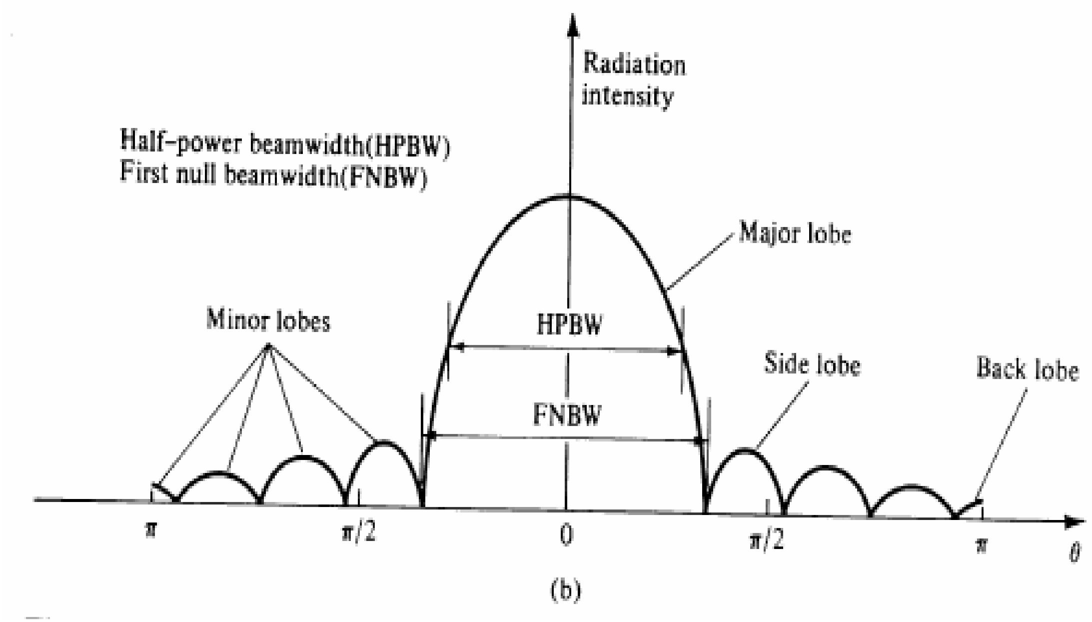


- An antenna, which has a non-directional pattern in a plane
  - It is usually directional in other planes

Source: NK Nikolova

Pattern lobes





Pattern lobe is a portion of the radiation pattern with a local maximum

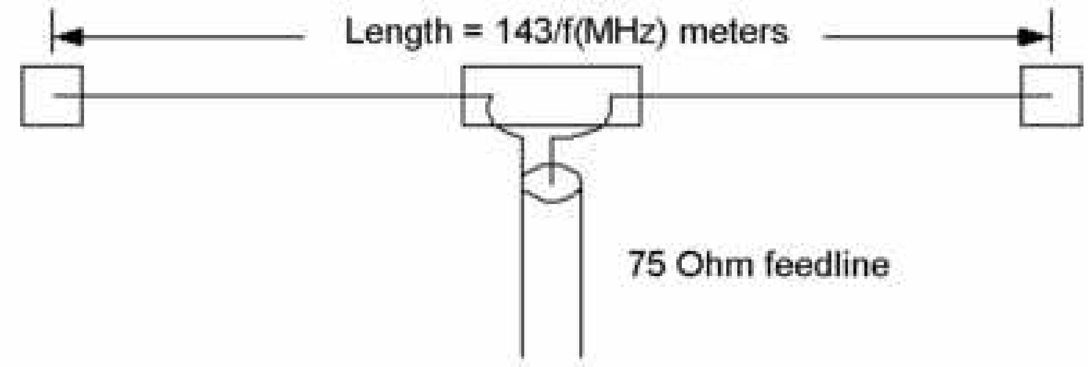
Lobes are classified as: major, minor, side lobes, back lobes.

Source: NK Nikolova

Antenna Types

Dipole antennas

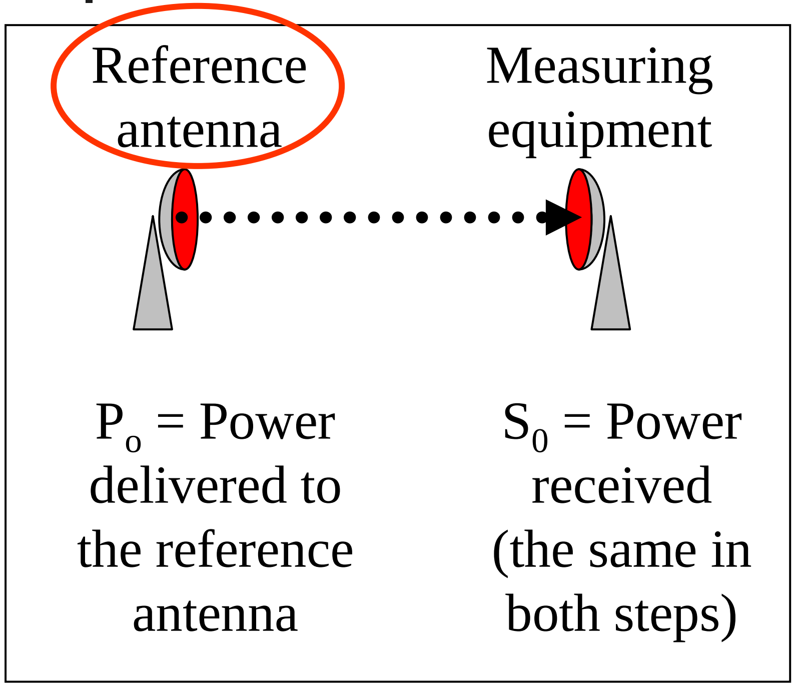
- Half-wave dipole antenna (or Hertz antenna)
- Quarter-wave vertical antenna (or Marconi antenna)
- It consists of two metal conductors of rod or wire, oriented parallel and collinear with each other (in line with each other), with a small space between them.



Antenna Types (continue)

- **Parabolic Reflective Antenna**
- uses a parabolic reflector, a curved surface with the cross-sectional shape of a parabola, to direct the radio waves.
- The most common form is shaped like a dish and is popularly called a **dish antenna** or **parabolic dish**.
- The main advantage of a parabolic antenna is that it is highly directive; it directs the radio waves in a narrow beam, or receive radio waves from one particular direction only.
- Parabolic antennas have some of the highest gains,

Antenna gain measurement



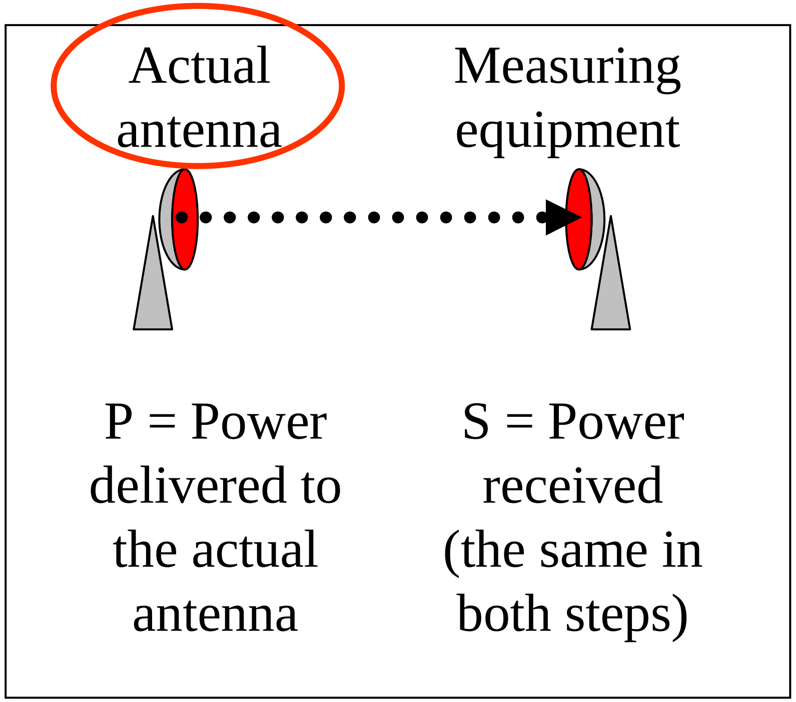
Reference antenna

Measuring equipment

P_o = Power delivered to the reference antenna

S_0 = Power received (the same in both steps)

Step 1: reference



Actual antenna

Measuring equipment

P = Power delivered to the actual antenna

S = Power received (the same in both steps)

Step 2: substitution

$$\text{Antenna Gain} = (P/P_o)_{S=S0}$$

Antenna Gain

- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna)
- Effective area
  - Related to physical size and shape of antenna

Antenna Gain

- 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 ($\approx 3 \times 10^8$ m/s)
  - λ = carrier wavelength

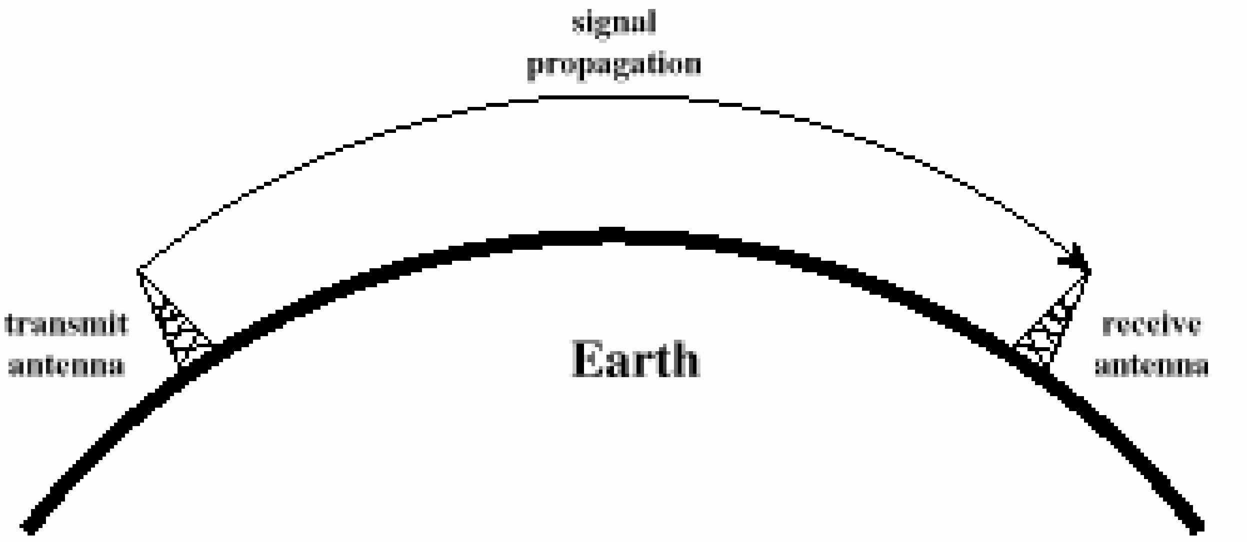
Typical Gain and Beamwidth

Type of antenna	G_i [dB]	BeamW.
Isotropic	0	360^0x360^0
Half-wave Dipole	2	360^0x120^0
Helix (10 turn)	14	35^0x35^0
Small dish	16	30^0x30^0
Large dish	45	1^0x1^0

Propagation Modes

- Ground-wave propagation
- Sky-wave propagation
- Line-of-sight propagation

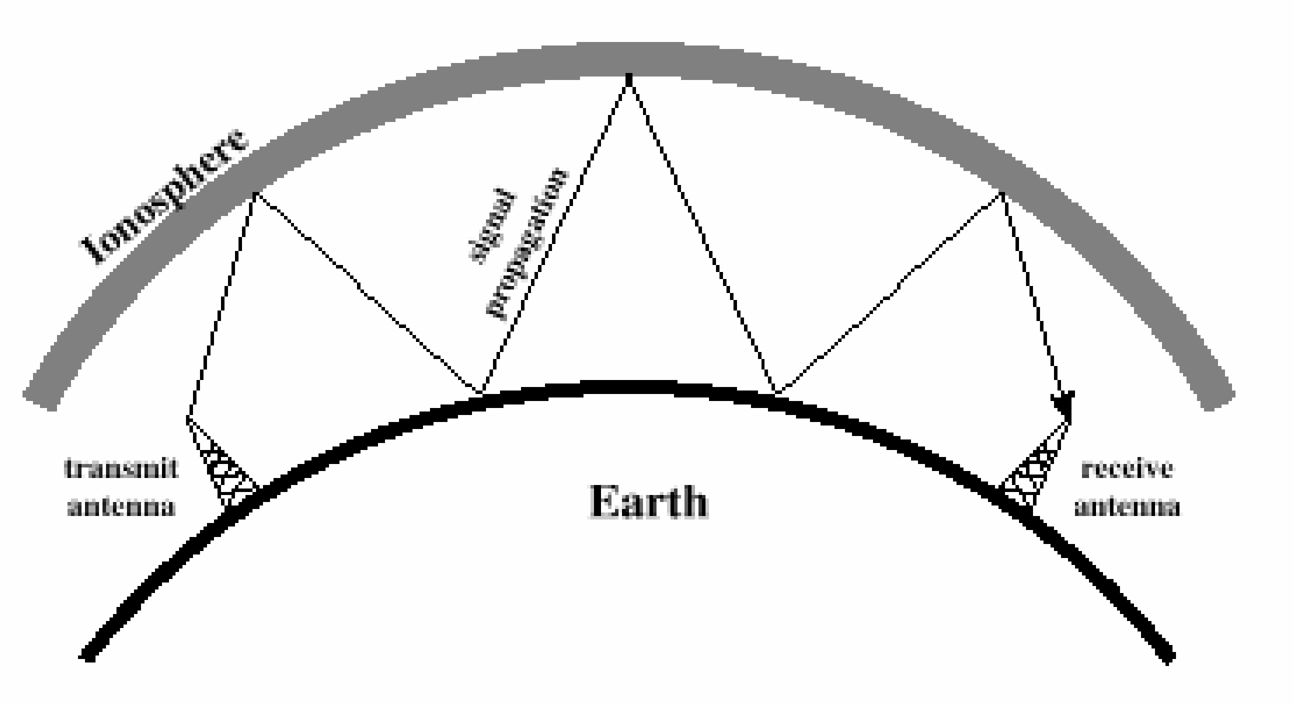
Ground Wave Propagation



Ground Wave Propagation

- Follows contour of the earth
- Can Propagate considerable distances
- Frequencies up to 2 MHz
- Example
  - AM radio

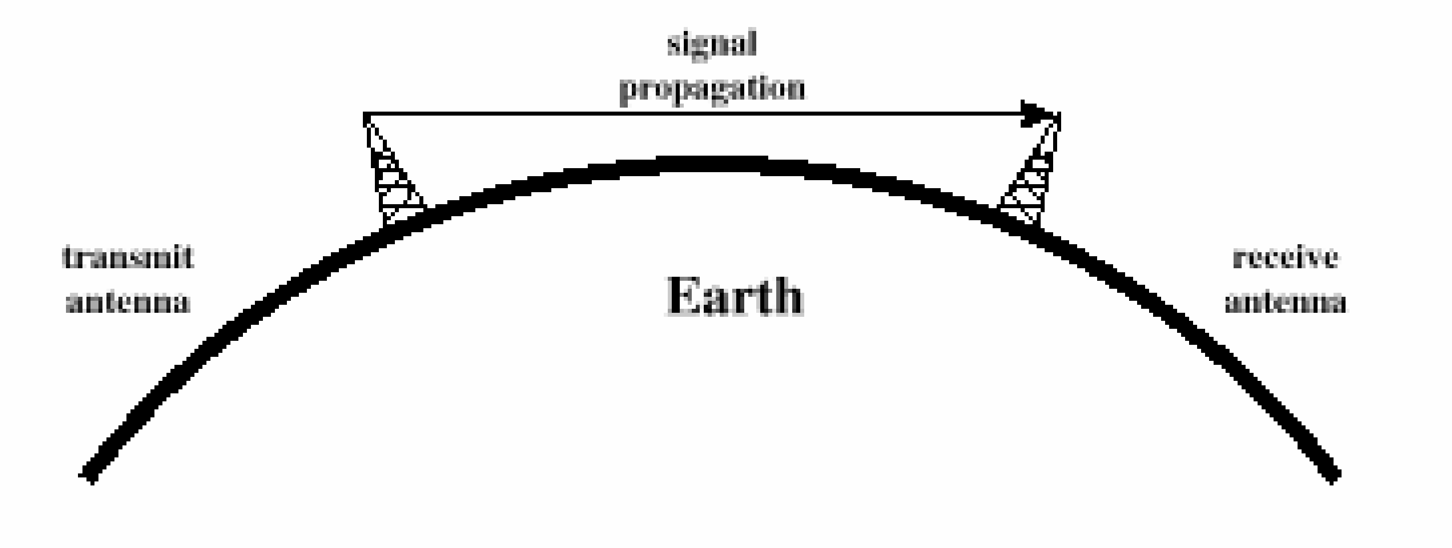
Sky Wave Propagation



Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by refraction
- Examples
  - Amateur radio
  - CB radio

Line-of-Sight Propagation



Line-of-Sight Propagation

- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within *effective* line of site due to refraction
- Refraction – bending of microwaves by the atmosphere
  - Velocity of electromagnetic wave is a function of the density of the medium
  - When wave changes medium, speed changes
  - Wave bends at the boundary between mediums

Line-of-Sight Equations

- Optical line of sight

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

- Effective, or radio, line of sight

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

  - d = distance between antenna and horizon (km)
  - h = antenna height (m)
  - K = adjustment factor to account for refraction, rule of thumb K = 4/3

Line-of-Sight Equations

- Maximum distance between two antennas for LOS propagation:

$$3.57\left(\sqrt{\mathrm{K}h_1}+\sqrt{\mathrm{K}h_2}\right)$$

  - h_1 = height of antenna one
  - h_2 = height of antenna two

LOS Wireless Transmission Impairments

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

Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion

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)

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

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

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

Categories of Noise

- Thermal Noise
- Intermodulation noise
- Crosstalk
- Impulse Noise

Thermal Noise

- Thermal noise due to agitation of electrons
- Present in all electronic devices and transmission media
- Cannot be eliminated
- Function of temperature
- Particularly significant for satellite communication

Thermal Noise

- Amount of thermal noise to be found in a bandwidth of 1Hz in any device or conductor is:

$$N_0 = \mathrm{k}T \left(\mathrm{W/Hz}\right)$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in kelvins (absolute temperature)

Thermal Noise

- Noise is assumed to be independent of frequency
- Thermal noise present in a bandwidth of *B* Hertz (in watts):

$$N = \mathrm{k}TB$$

or, in decibel-watts

$$N = 10 \log \mathrm{k} + 10 \log T + 10 \log B$$
$$= -228.6\,\mathrm{dBW} + 10 \log T + 10 \log B$$

Noise Terminology

- Intermodulation noise – occurs if signals with different frequencies share the same medium
  - Interference caused by a signal produced at a frequency that is the sum or difference of original frequencies
- Crosstalk – unwanted coupling between signal paths
- Impulse noise – irregular pulses or noise spikes
  - Short duration and of relatively high amplitude
  - Caused by external electromagnetic disturbances, or faults and flaws in the communications system

Expression E_b/N_0

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{kTR}$$

- The bit error rate for digital data is a function of E_b/N_0
  - Given a value for E_b/N_0 to achieve a desired error rate, parameters of this formula can be selected
  - As bit rate R increases, transmitted signal power must increase to maintain required E_b/N_0

Other Impairments

- Atmospheric absorption – water vapor and oxygen contribute to attenuation
- Multipath – obstacles reflect signals so that multiple copies with varying delays are received
- Refraction – bending of radio waves as they propagate through the atmosphere

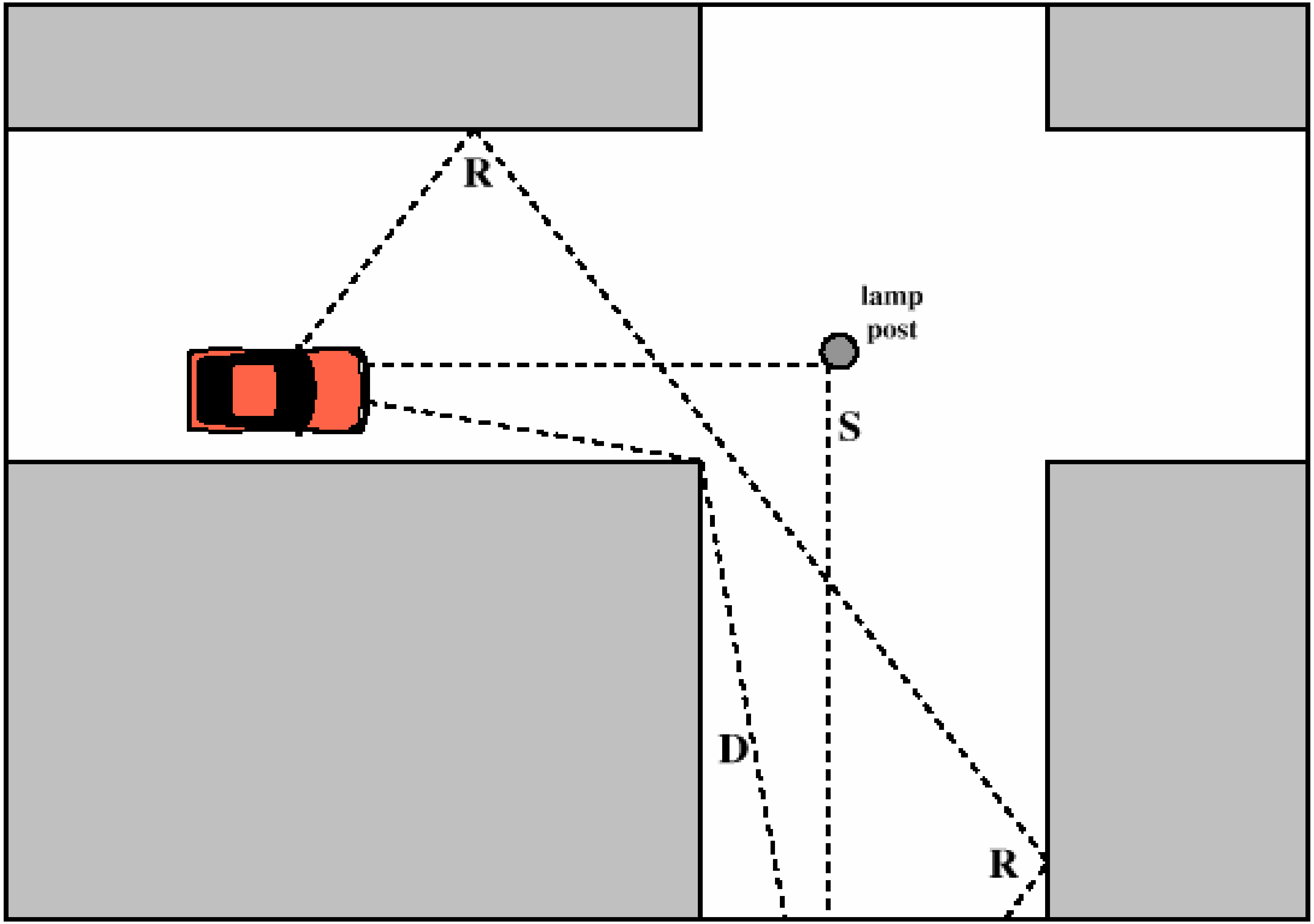


Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

Multipath Propagation

- Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave
- Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less

The Effects of Multipath Propagation

- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Types of Fading

- Fast fading
- Slow fading
- Flat fading
- Selective fading
- Rayleigh fading
- Rician fading

Error Compensation Mechanisms

- Forward error correction
- Adaptive equalization
- Diversity techniques

Forward Error Correction

- Transmitter adds error-correcting code to data block
    - Code is a function of the data bits
- Receiver calculates error-correcting code from incoming data bits
    - If calculated code matches incoming code, no error occurred
    - If error-correcting codes don't match, receiver attempts to determine bits in error and correct

Adaptive Equalization

- Can be applied to transmissions that carry analog or digital information
  - Analog voice or video
  - Digital data, digitized voice or video
- Used to combat intersymbol interference
- Involves gathering dispersed symbol energy back into its original time interval
- Techniques
  - Lumped analog circuits
  - Sophisticated digital signal processing algorithms

Diversity Techniques

- Diversity is based on the fact that individual channels experience independent fading events
- Space diversity – techniques involving physical transmission path
- Frequency diversity – techniques where the signal is spread out over a larger frequency bandwidth or carried on multiple frequency carriers
- Time diversity – techniques aimed at spreading the data out over time