V

Mobile Communication Networks

Wireless Channel

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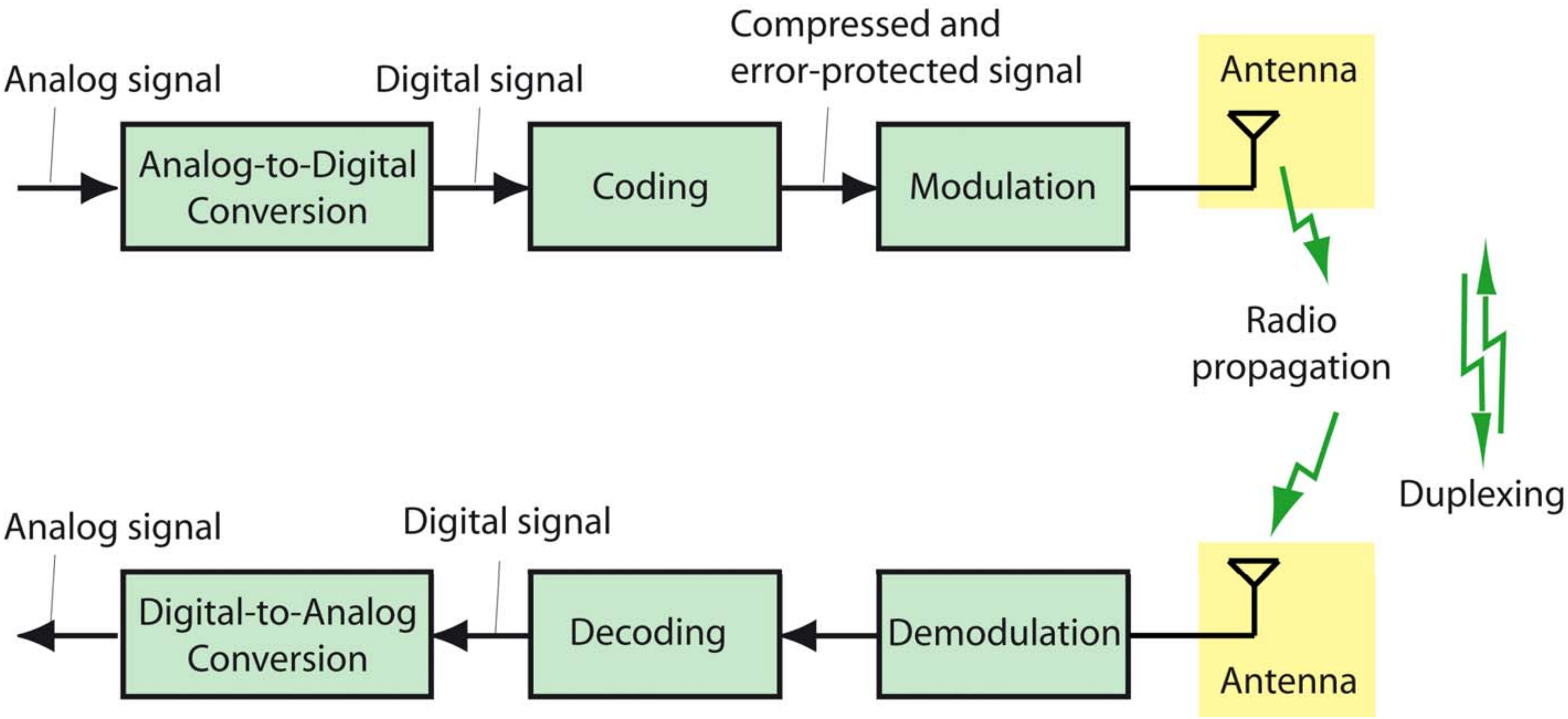
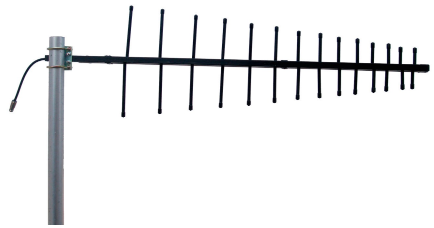

Compressed and
error-protected signal
Analog signal
Digital signal
Antenna
Analog-to-Digital
Conversion
Coding
Modulation
Radio
propagation
Duplexing
Analog signal
Digital signal
Digital-to-Analog
Conversion
Decoding
Demodulation
Antenna

V

Antennas

Antennas



Antennas

- An antenna is an electrical conductor or system of conductors
  - **Transmission** - radiates electromagnetic energy into space
  - **Reception** - collects electromagnetic energy from space

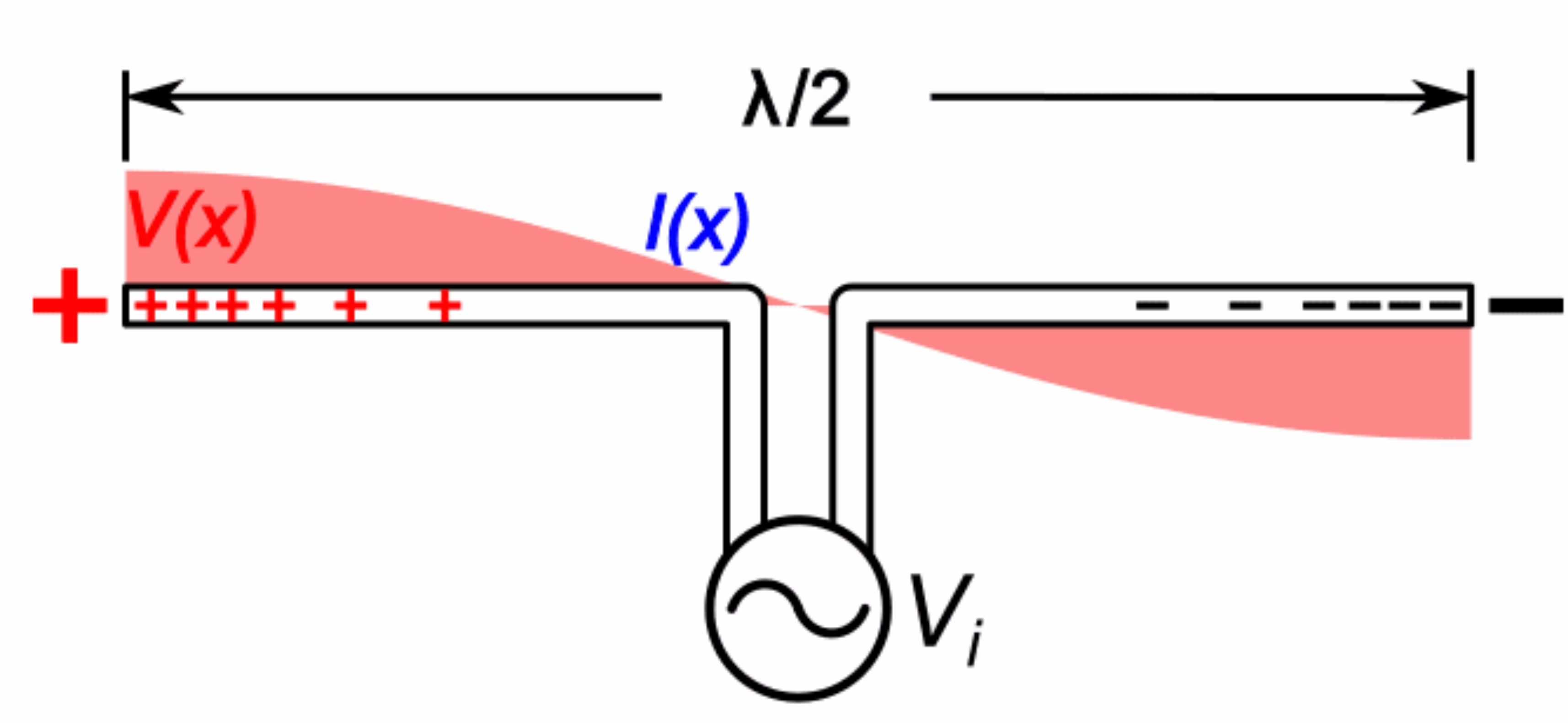
- In two-way communication, the same antenna can be used for transmission and reception

Antennas

- Antennas transmit/receive electromagnetic waves
  - accelerated electric charges radiate electromagnetic waves (EM)
  - EM propagate through space (vacuum) at the speed of light

    c ~= $3x10^8$m/seg
  - EM carry energy

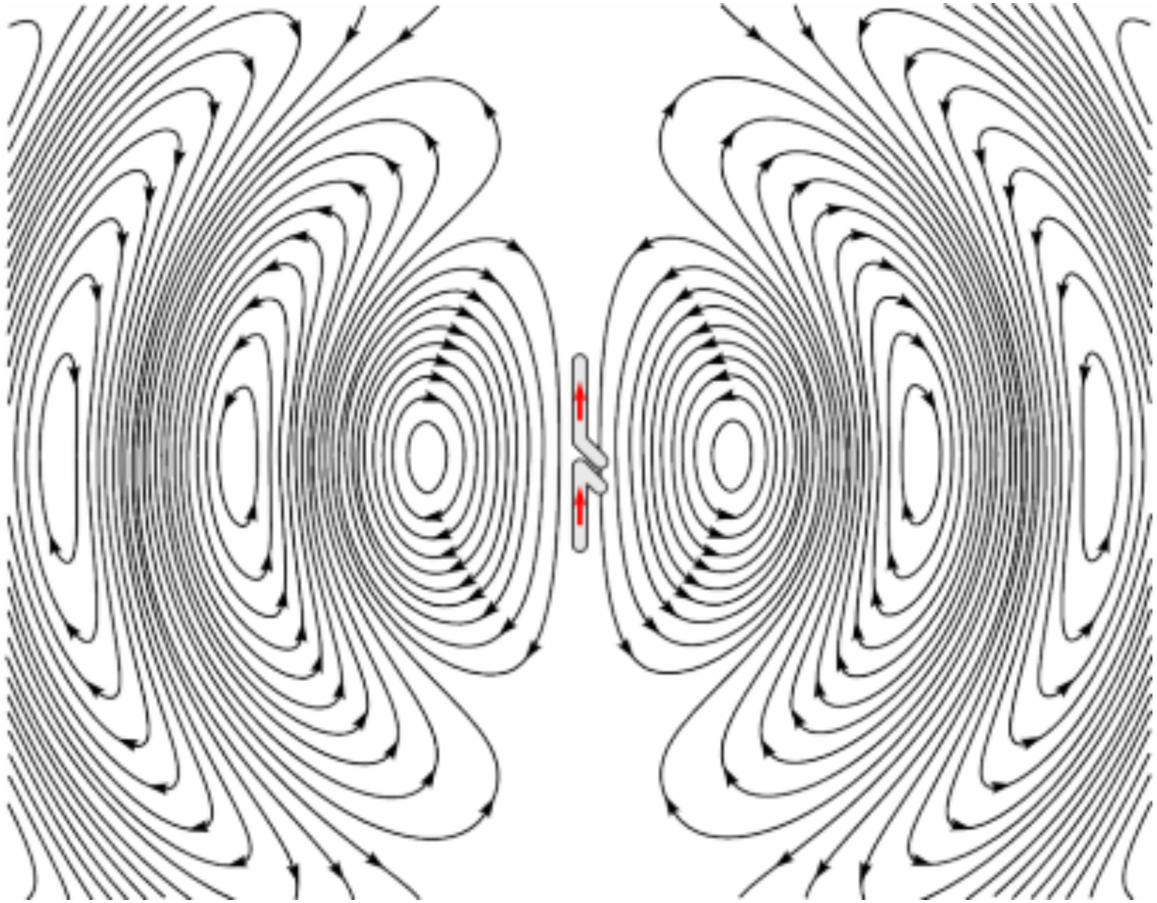
Antennas



https://en.wikipedia.org/wiki/File:Dipole_antenna_standing_waves_animation_1-10fps.gif

Animation: Animation showing standing waves on a half-wave dipole antenna driven by a sinusoidal voltage VO from a radio transmitter at its resonant frequency
Source: Wikimedia Commons

Antennas

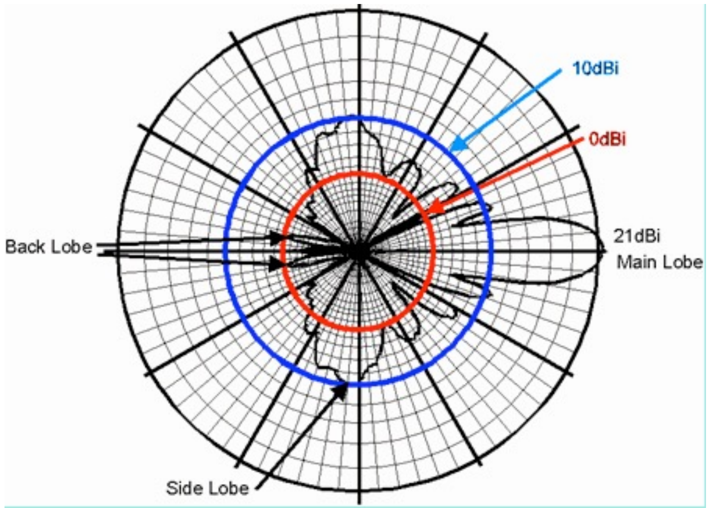


https://commons.wikimedia.org/wiki/File:Dipole_xmting_antenna_animation_4_408x318x150ms.gif

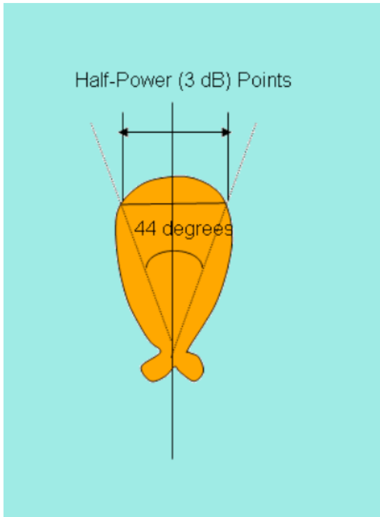
Animation: Animation of a half-wave dipole antenna transmitting radio waves, showing theelectric field lines
Source: Wikimedia Commons

Radiation Pattern

- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
  - Reception pattern - receiving antenna’s equivalent to radiation pattern

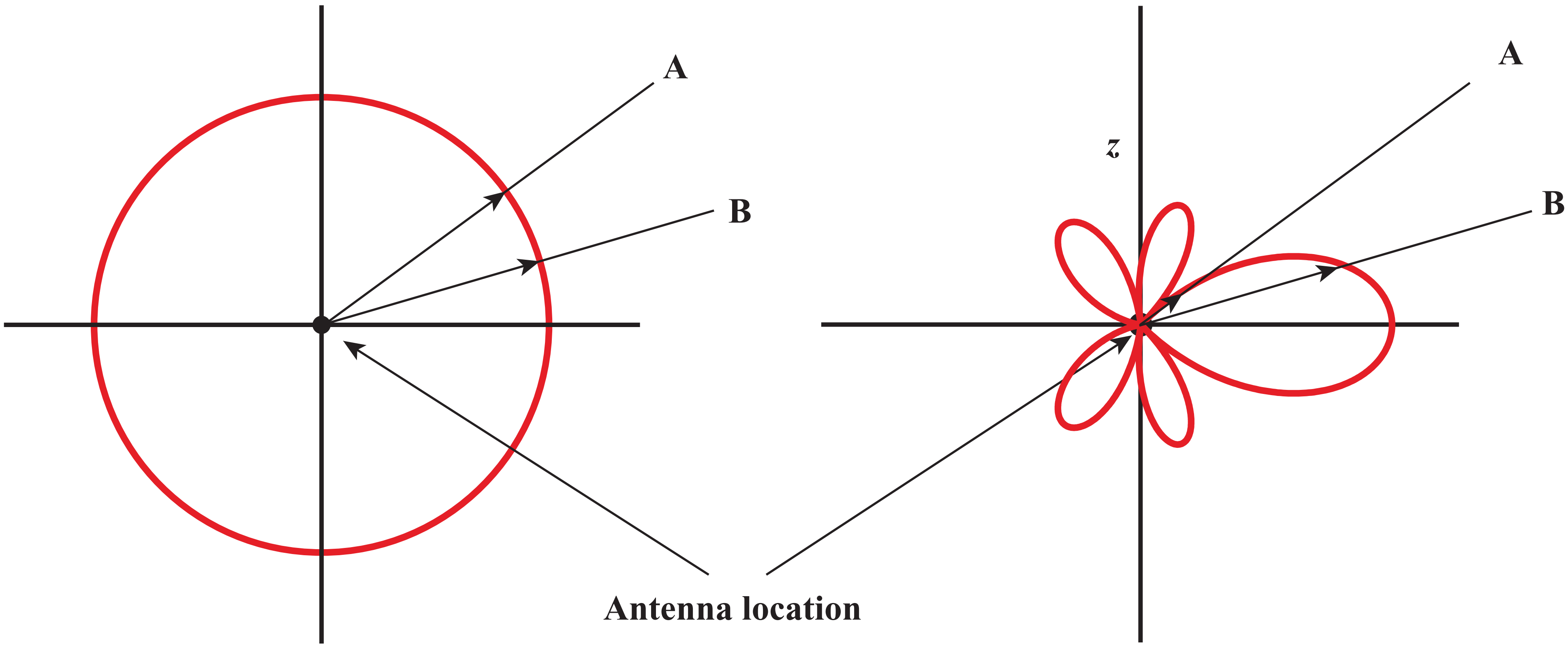


Beam width



Radiation Pattern

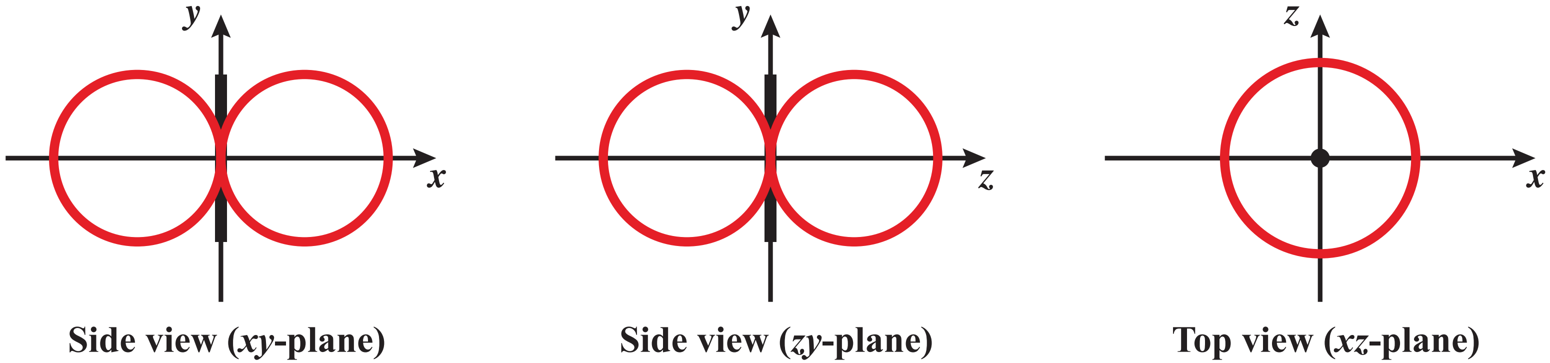
Anim 6.1



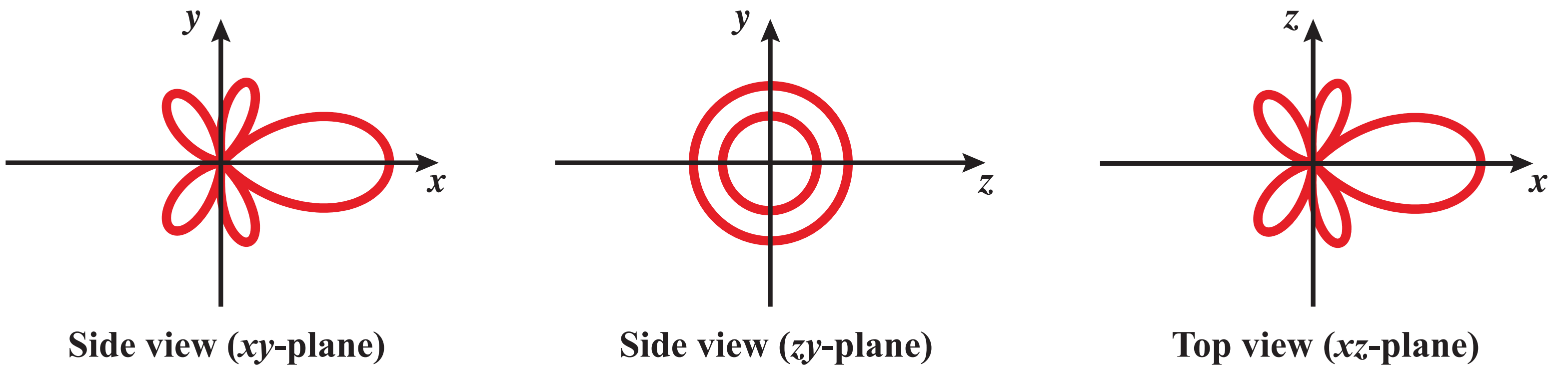
(a) Omnidirectional

(b) Directional

Radiation Pattern in Three Dimensions



(a) Simple dipole



(b) Directed antenna

Anim 6.3

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)

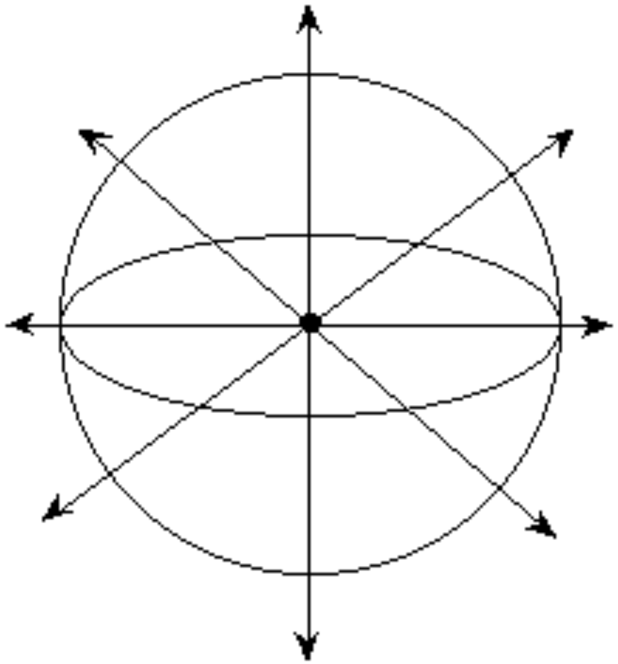
- **Parabolic** Reflective Antenna (Directional)

- Other **Directional** Antennas
  - Arrays of antennas
    - In a linear array or other configuration
  - 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
- Convenient reference for expressing the properties of real antennas

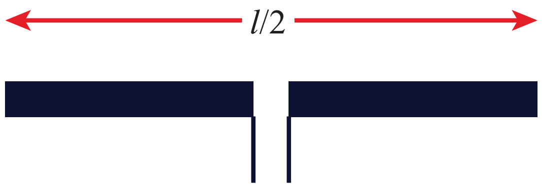


Types of Antennas

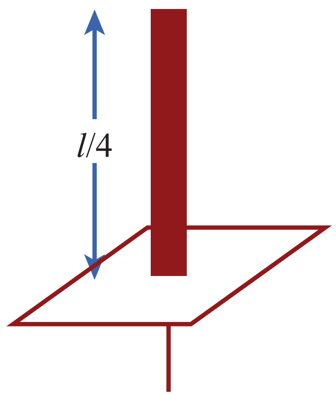
Dipole antennas

- Real antennas are not isotropic radiators but, e.g.:
  - dipoles with lengths $\lambda/4$ (or Marconi antenna) on car roofs
  - or $\lambda/2$ as Hertzian dipole
  -

    → shape of antenna proportional to wavelength



(a) Half-wave dipole

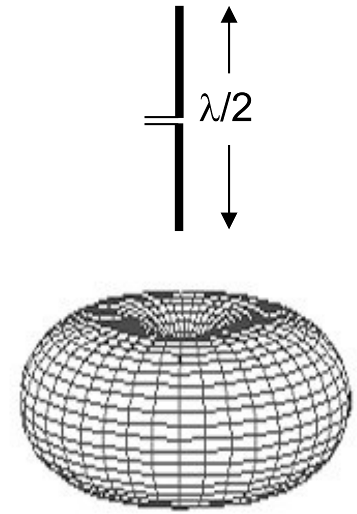


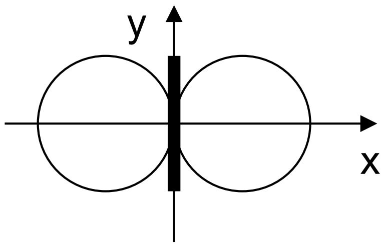
(b) Quarter-wave antenna

Types of Antennas

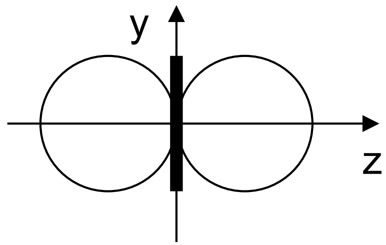
Dipole antennas

- Example: Radiation pattern of a simple Hertzian dipole
- Omnidirectional radiation pattern

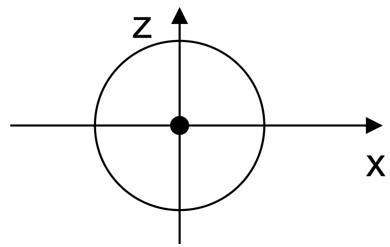




side view (xy-plane)



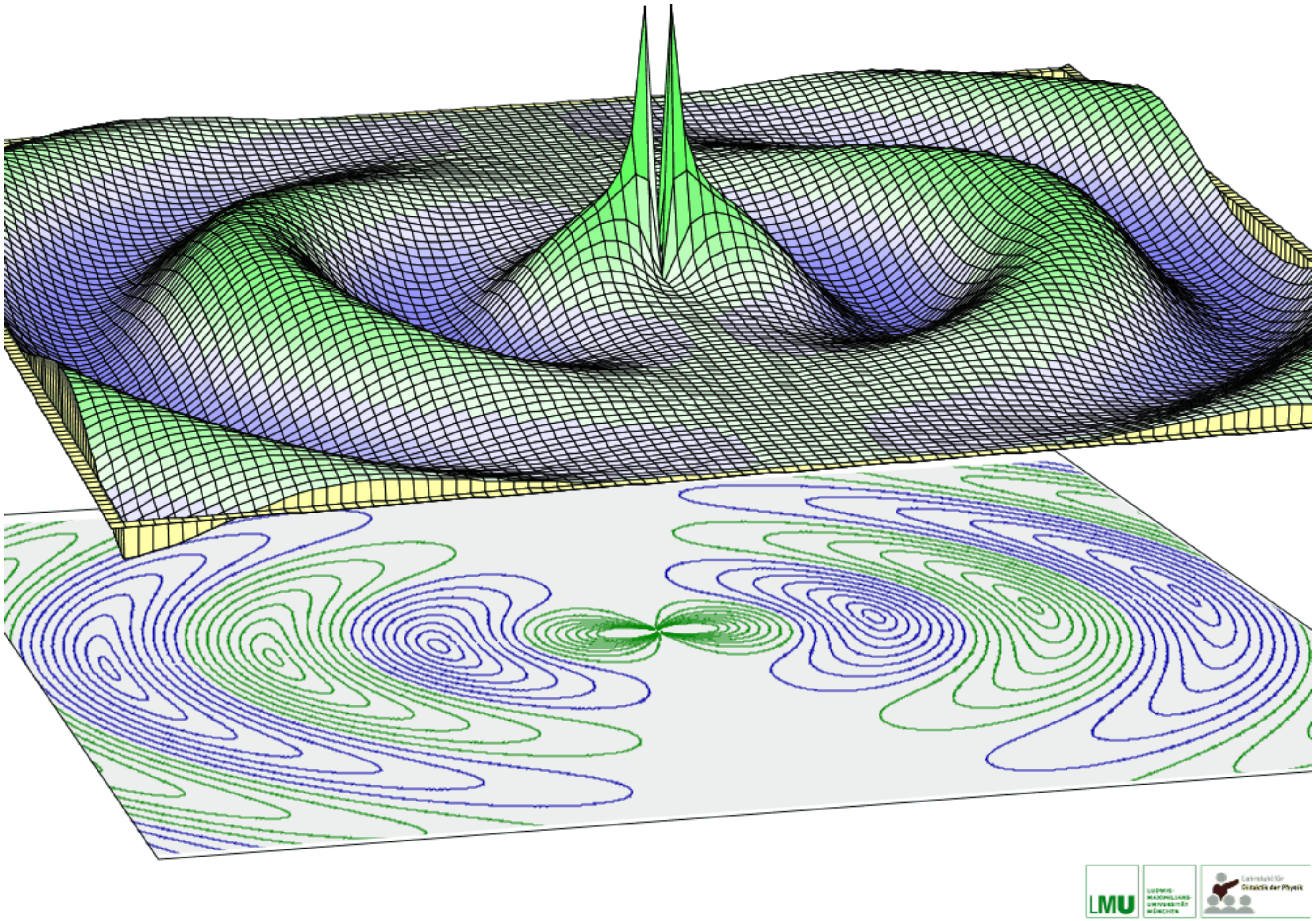
side view (yz-plane)

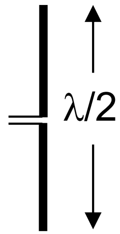


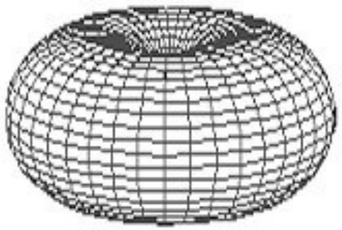
top view (xz-plane)

Types of Antennas

Dipole antennas

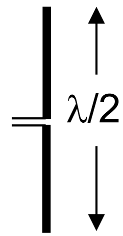


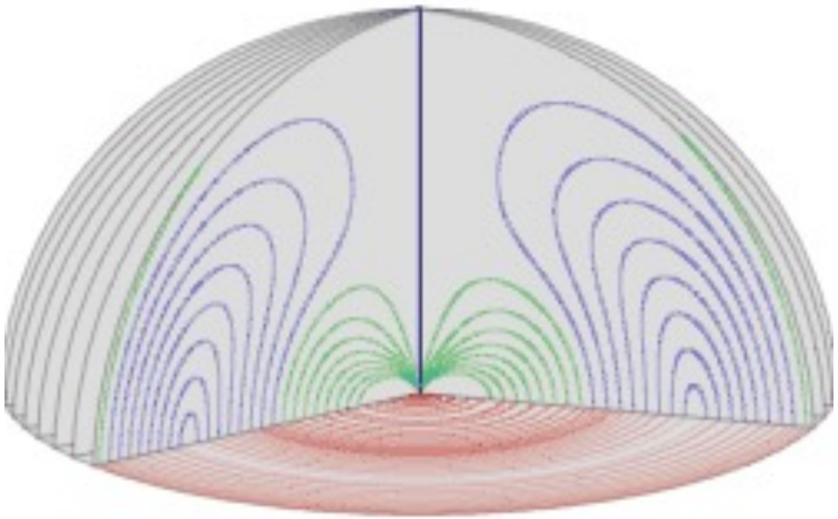


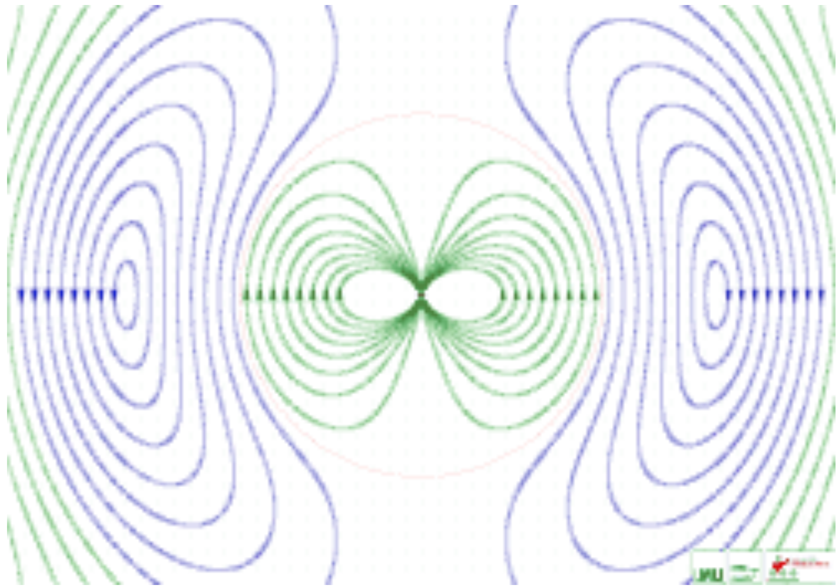


Types of Antennas

Dipole antennas



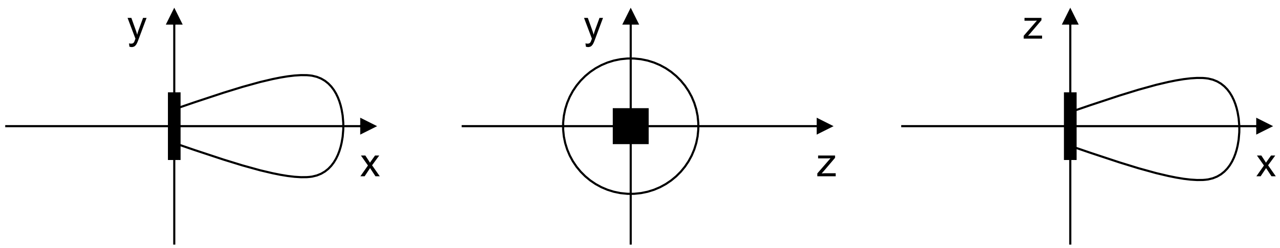




Types of Antennas

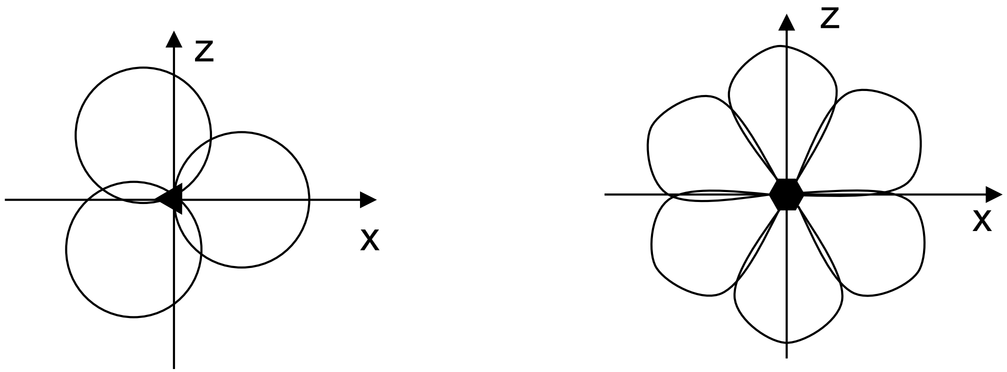
Directed and sectorized antennas

- Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)



side view (xy-plane) side view (yz-plane) top view (xz-plane)

directed antenna

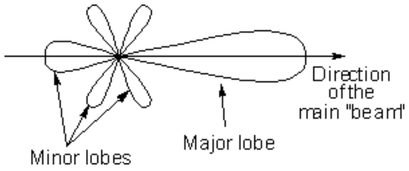


top view, 3 sector top view, 6 sector

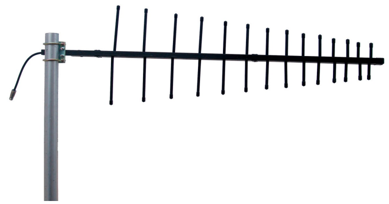
sectorized antennas

Types of Antennas (directed)

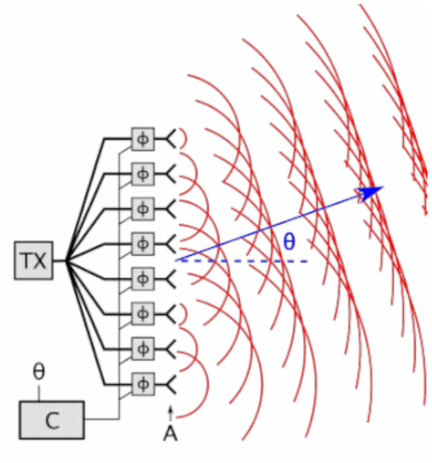
Antenna arrays



- Arrays of antennas
  - In a linear array or other configuration
  - Passive or Active



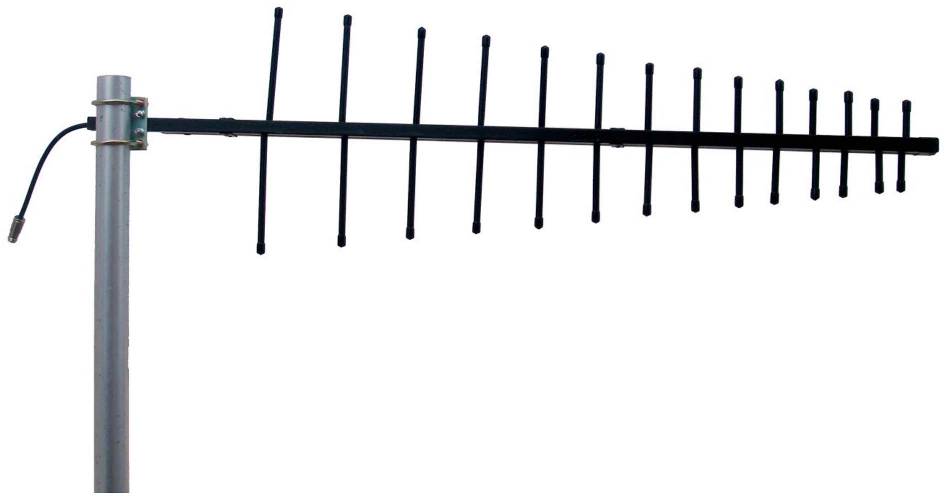
- In *Phased Array of Antennas*, signal amplitudes and phases to each antenna are adjusted to create a directional pattern

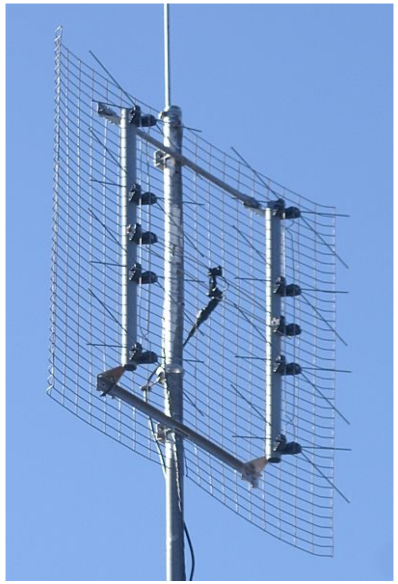


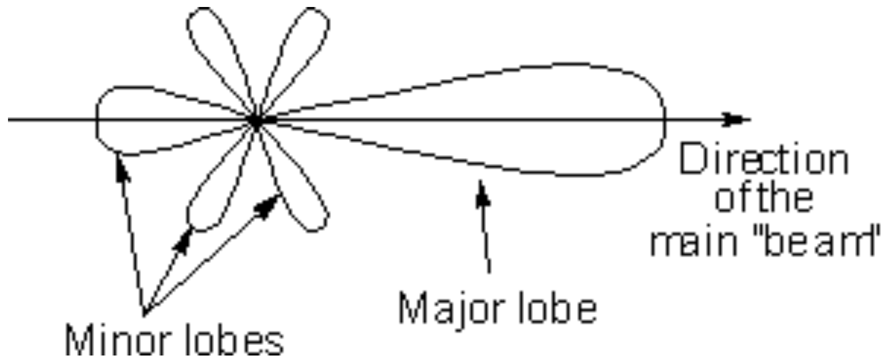
- Very useful in modern systems

Types of Antennas (directed)

Antenna arrays

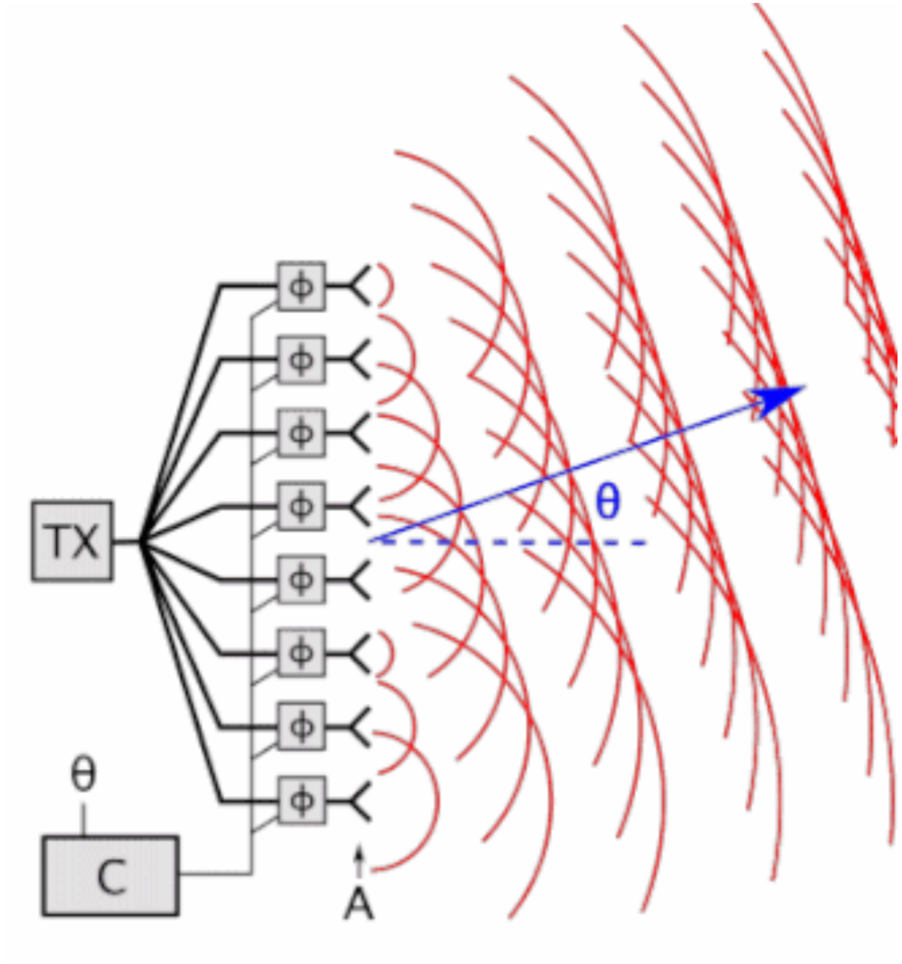






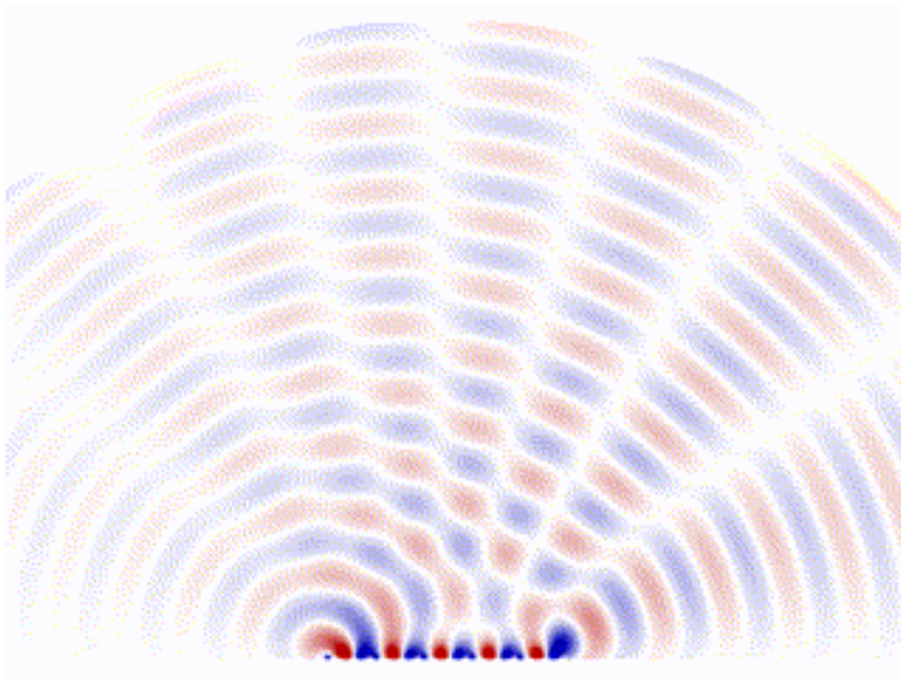
Phased Array of Antennas

Signal amplitudes and phases to each antenna are adjusted to create a directional pattern

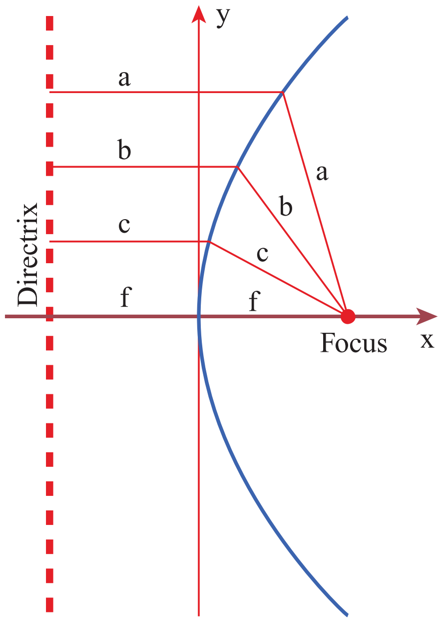


Types of Antennas

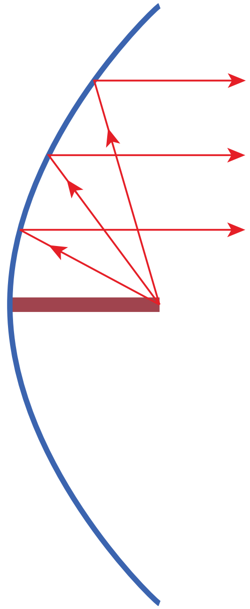
Phased Array of Antennas



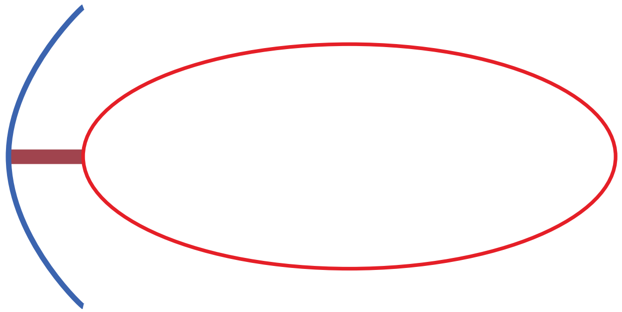
Parabolic Reflective Antenna



(a) Parabola



(b) Cross section of parabolic antenna
showing reflective property



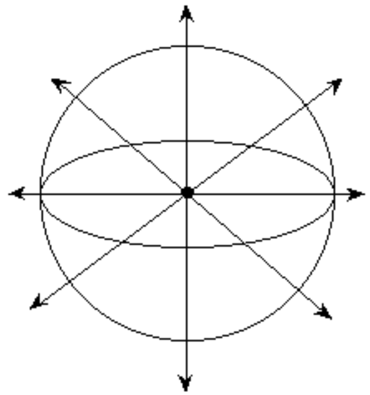
(c) Cross section of parabolic antenna
showing radiation pattern

Antenna Gain vs Antenna effective area

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

Antenna Gain vs Antenna effective area

Effective area of an isotropic antenna



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

Antenna Gain vs Antenna effective area

- 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

Antenna Gain vs Antenna effective area

Table 6.2 Antenna Gains and Effective Areas

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	$0.81\,A$	$10A/\lambda^2$
Parabolic, face area A	$0.56\,A$	$7A/\lambda^2$
Turnstile (two crossed, perpendicular dipoles)	$1.15\,\lambda^2/4\pi$	1.15

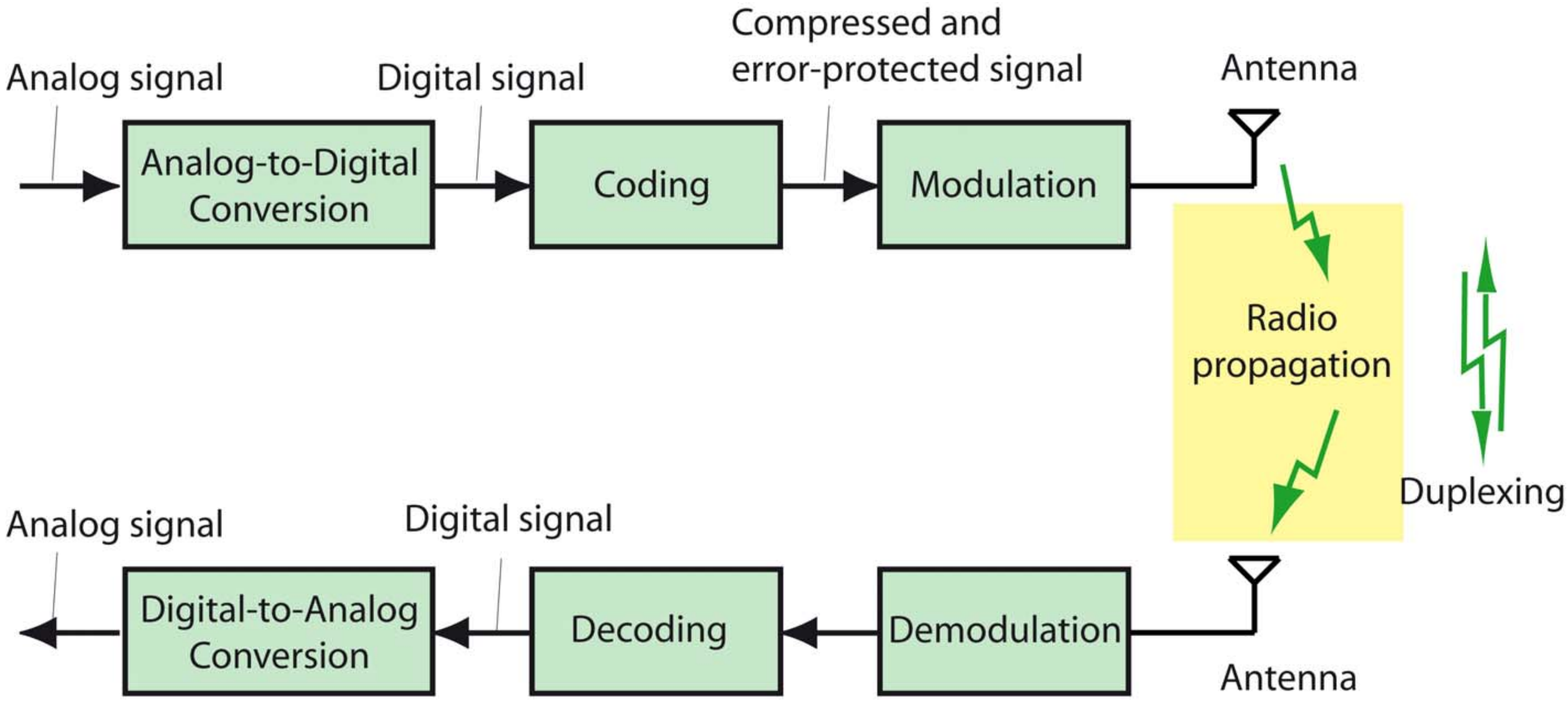
Parabolic Reflective Antenna

Diameter vs Beam Width

Table 6.1 Antenna Beamwidths for Various Diameter Parabolic Reflective Antennas at $f = 12\,\text{GHz}$

Antenna Diameter (m)	Beam Width (degrees)
0.5	3.5
0.75	2.33
1.0	1.75
1.5	1.166
2.0	0.875
2.5	0.7
5.0	0.35

Transmission Chain



Free-space propagation

V

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** *(Recall Shannon)*

  - **Attenuation** is greater at **higher frequencies**, causing distortion

Power Reception (free space)

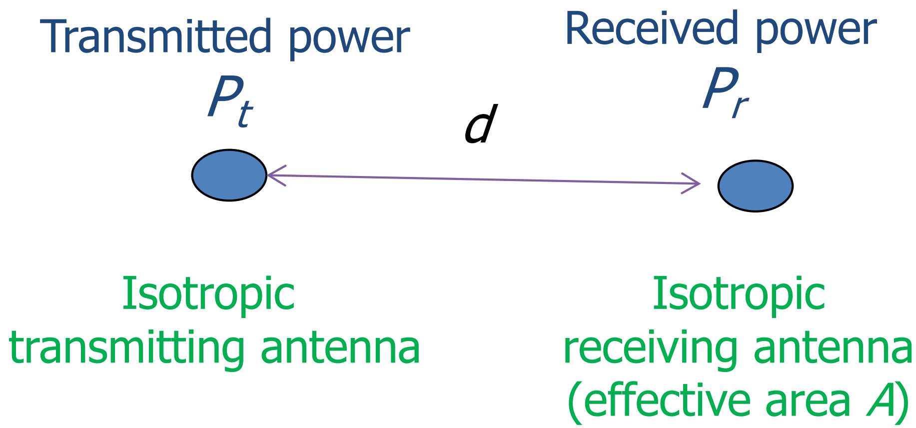
How much power is received at a certain distance?

- A sender transmits an average power P_t
- The power density at a distance *d* from the sender is:

$$W_{av} = \frac{P_t}{4\pi d^2}$$

- The received power can be written as:

$$P_r = W_{av}\, A$$



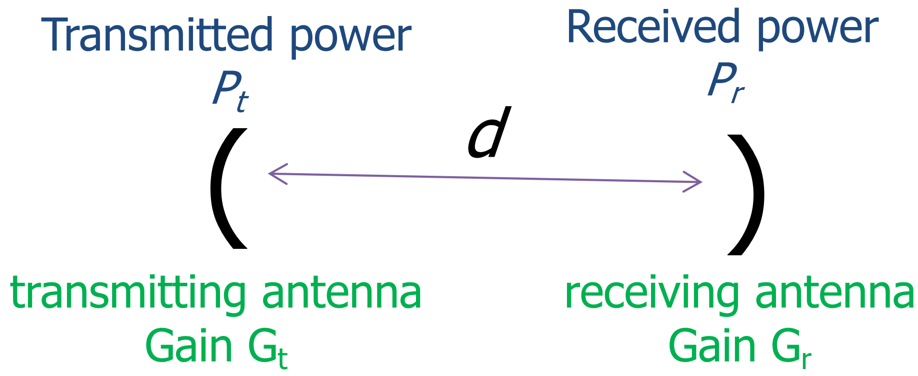
- The effective area of an isotropic antenna is:

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

Power Reception (free space)

Non-isotropic antennas:

- We must account, in the direction of propagation:
  - The gain of the transmitting antenna G_t
  - The gain of the receiving antenna G_r



Therefore:

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

(Frii's law)

Exercise

An “CS student” designed a wireless communication system for use in free space with transmission frequency f = 300 MHz, isotropic antennas, and transmission power Pt = 1 W.

However, he realized that the received power is still two times lower than the required threshold.

Assuming that the distance remains the same, and the “CS student” can change only one system parameter, provide him all possible options and corresponding numerical values to guarantee successful data transmission.

Free Space Loss

- Free space **loss** (<u>ideal isotropic </u>antenna)

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

- 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 (in dB)

- Free space loss equation can be recast:

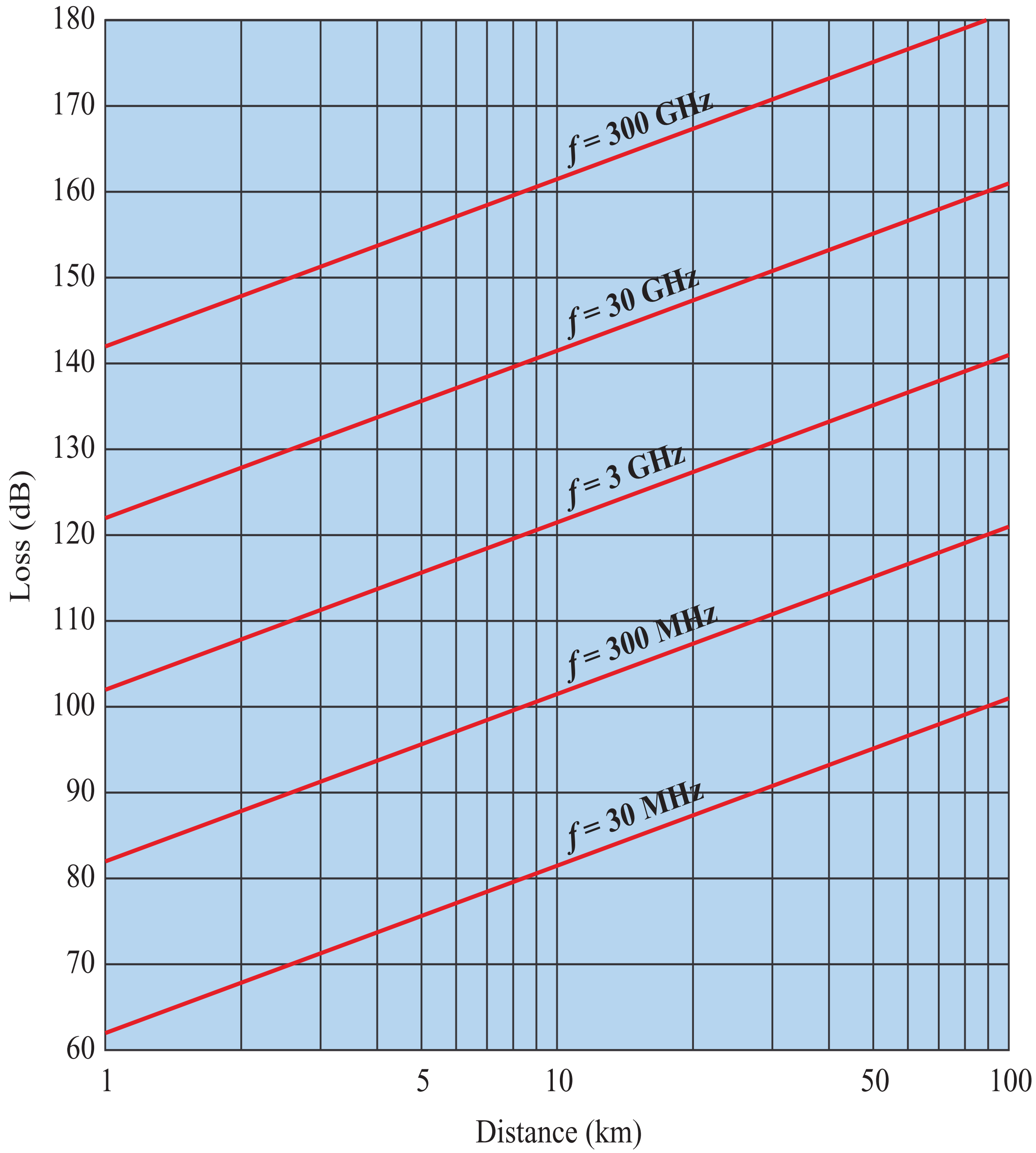
$$L_{dB} = 10\log\frac{P_t}{P_r} = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

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

or

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

Free Space Loss



Exercise

Example 6.3 Determine the isotropic free-space loss at 4 GHz for the shortest path to a synchronous satellite from earth (35,863 km). At 4 GHz, the wavelength is $(3 \times 10^8)/(4 \times 10^9) = 0.075$ m. Then,

$$L_{dB} = -20 \log (0.075) + 20 \log(35.853 \times 10^6) + 21.98 = 195.6 \text{ dB}$$

Now consider the antenna gain of both the satellite- and ground-based antennas. Typical values are 44 dB and 48 dB, respectively. The free space loss is:

$$L_{dB} = 195.6 - 44 - 48 = 103.6 \text{ dB}$$

Now assume a transmit power of 250 W at the earth station. What is the power received at the satellite antenna? A power of 250 W translates into 24 dBW, so the power at the receiving antenna is $24 - 103.6 = -79.6$ dBW, where dBW is decibel-watt, defined in Appendix 2A. This signal is approximately 10^{-8} W, but still usable by receiver circuitry.

Path Loss Exponent in practical systems

- Practical systems – reflections, scattering, etc.
- Beyond a certain distance, received power decreases logarithmically with distance
  - Based on many measurement studies

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

$$L_{dB} = 20\log(f) + 10n\log(d) - 147.56 \text{ dB}$$

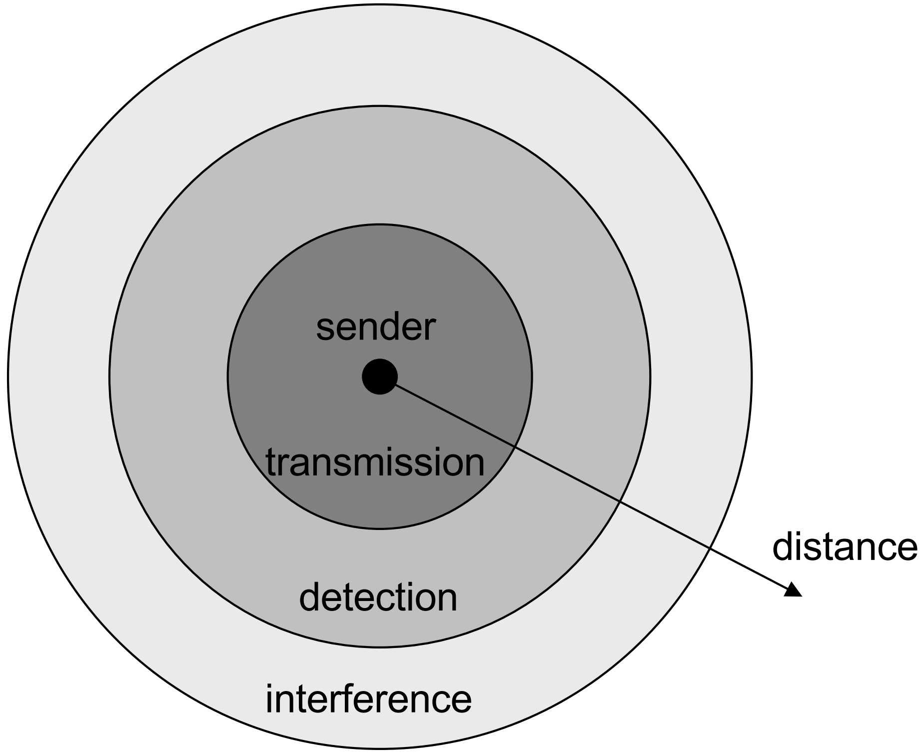
Path Loss Exponent in practical systems

Table 6.5 Path Loss Exponents for Different Environments [RAPP02]

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Signal propagation ranges

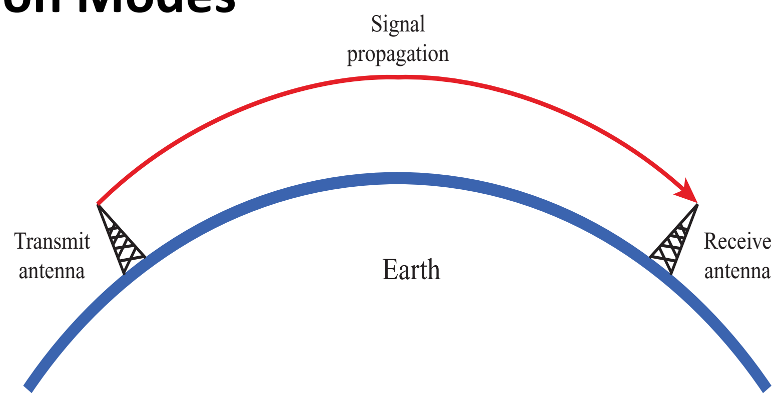
- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise
- Warning: figure misleading – bizarre shaped, time-varying ranges in reality!



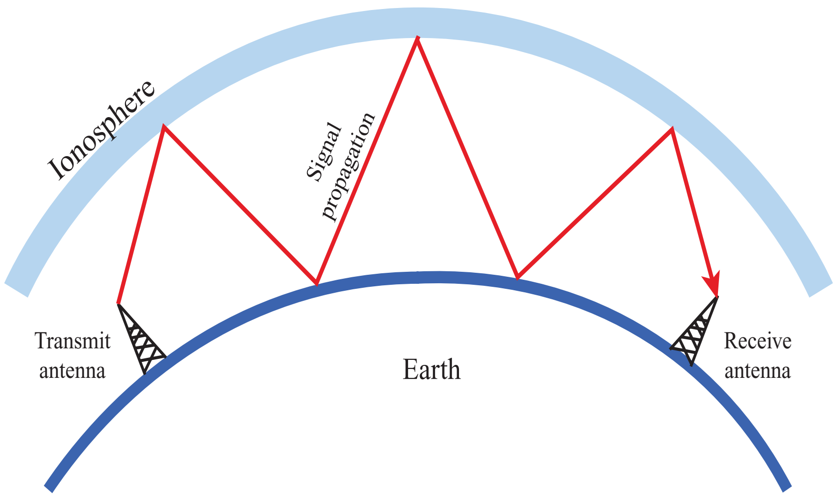
Propagation Modes

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

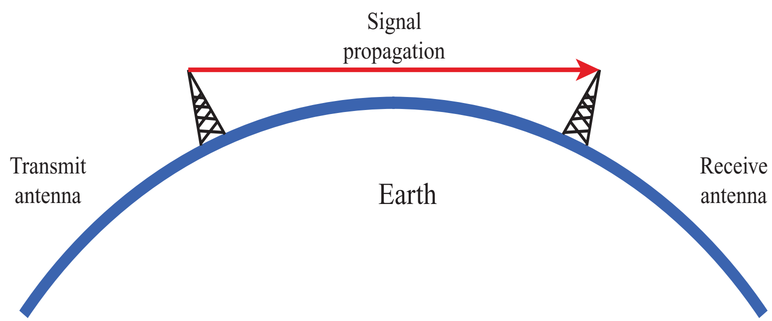
Wireless Propagation Modes



(a) Ground wave propagation (below 2 MHz)



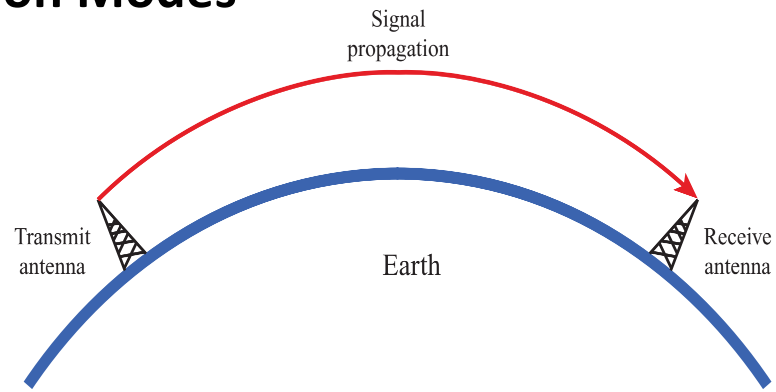
(b) Sky wave propagation (2 to 30 MHz)



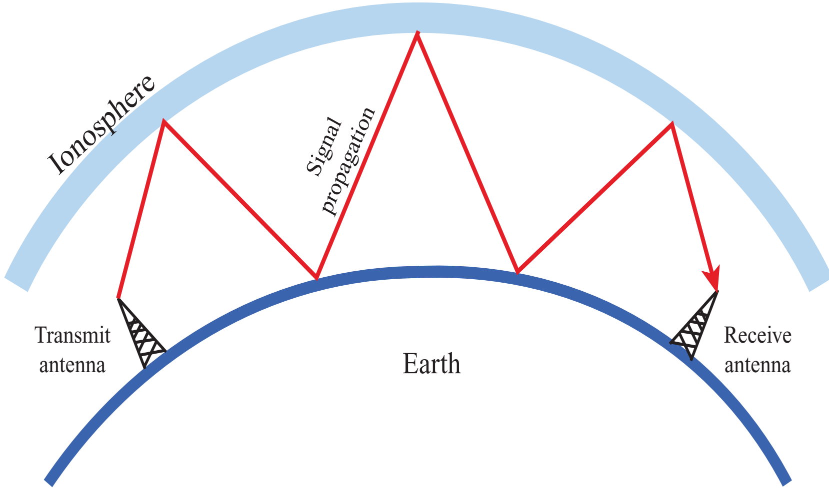
(c) Line-of-sight (LOS) propagation (above 30 MHz)

Anim 6.5

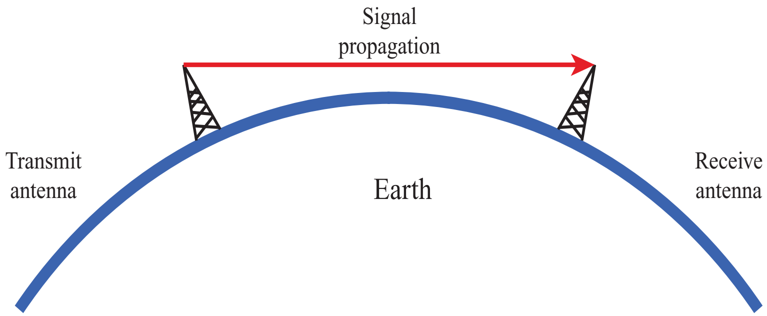
Wireless Propagation Modes



(a) Ground wave propagation (below 2 MHz)



(b) Sky wave propagation (2 to 30 MHz)



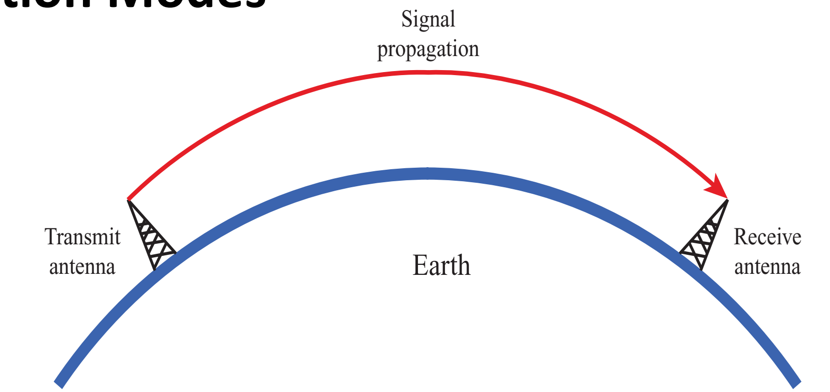
(c) Line-of-sight (LOS) propagation (above 30 MHz)

Anim 6.5

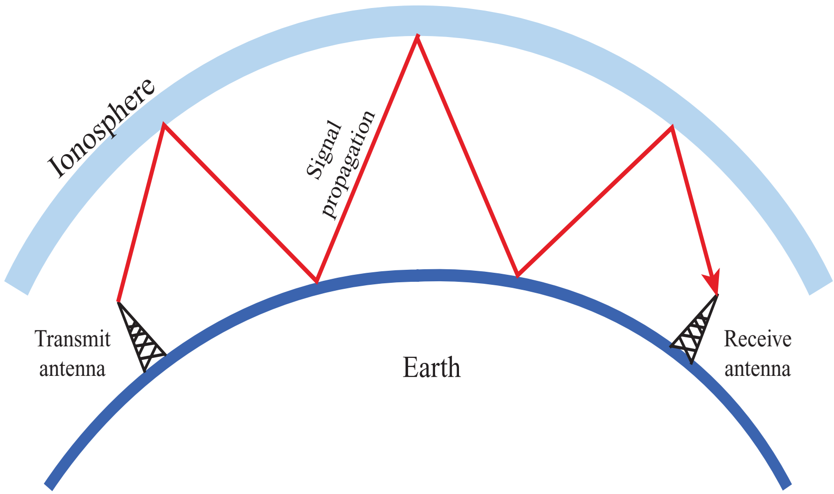
Ground Wave Propagation

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

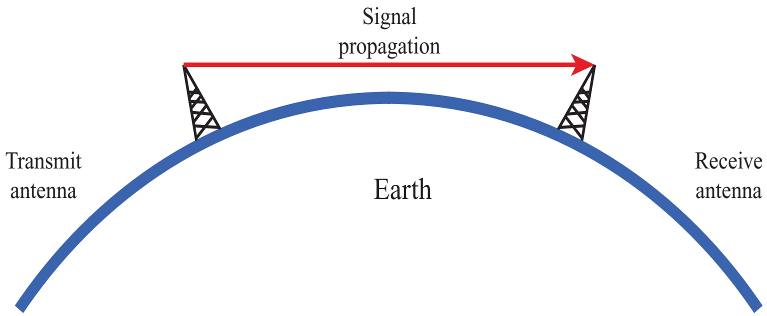
Wireless Propagation Modes



(a) Ground wave propagation (below 2 MHz)



(b) Sky wave propagation (2 to 30 MHz)



(c) Line-of-sight (LOS) propagation (above 30 MHz)

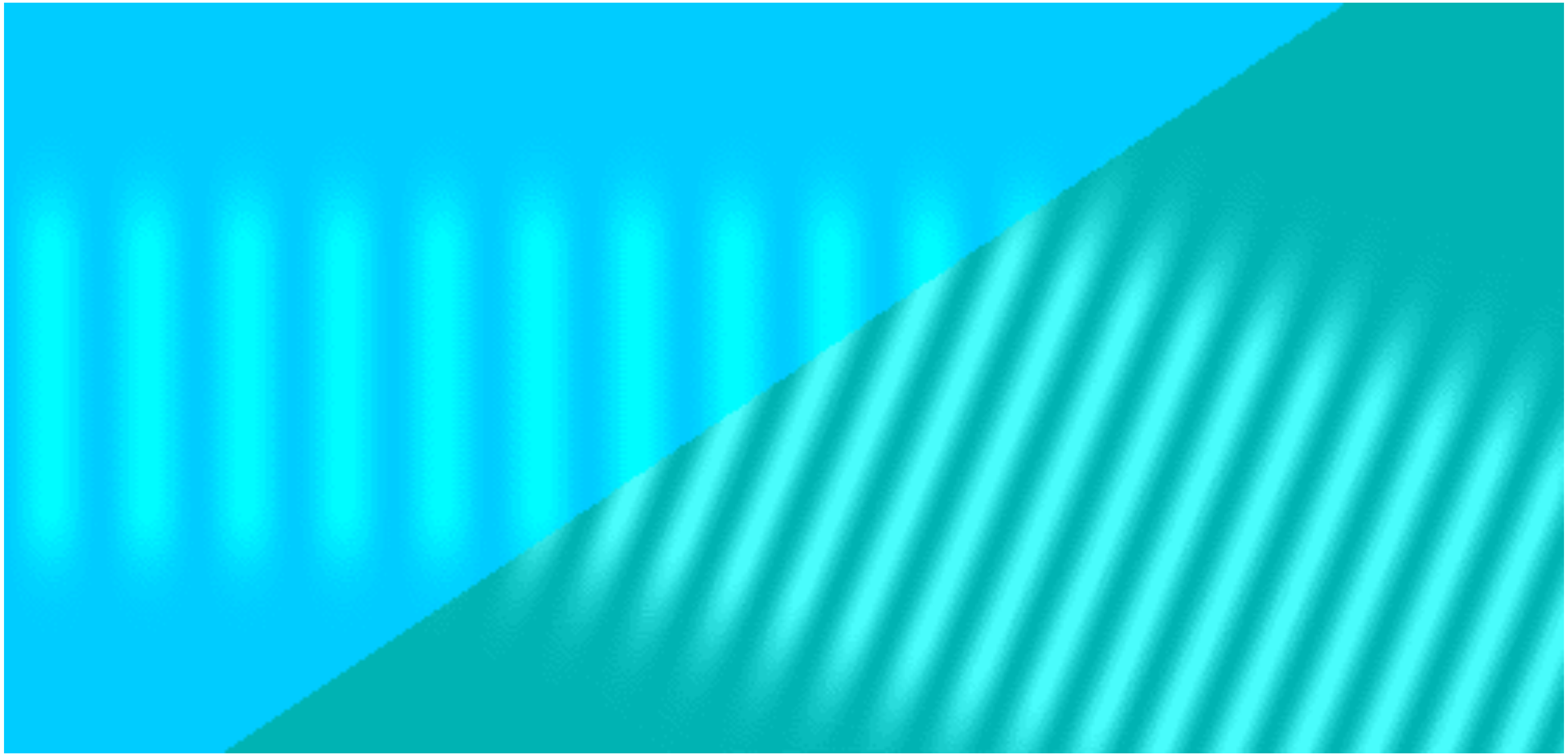
Sky Wave Propagation

- Frequencies between 2 and 30 MHz
- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel several hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by **refraction**
- Examples
  - Amateur radio

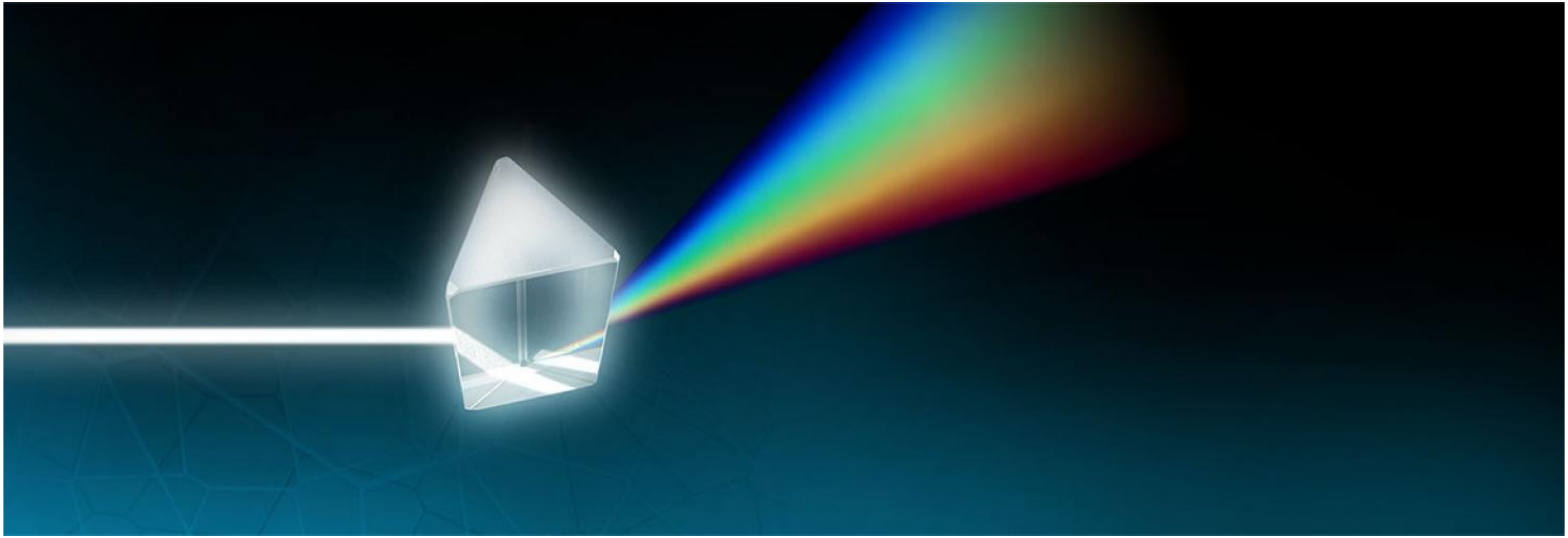
Refraction – bending of microwaves by the atmosphere

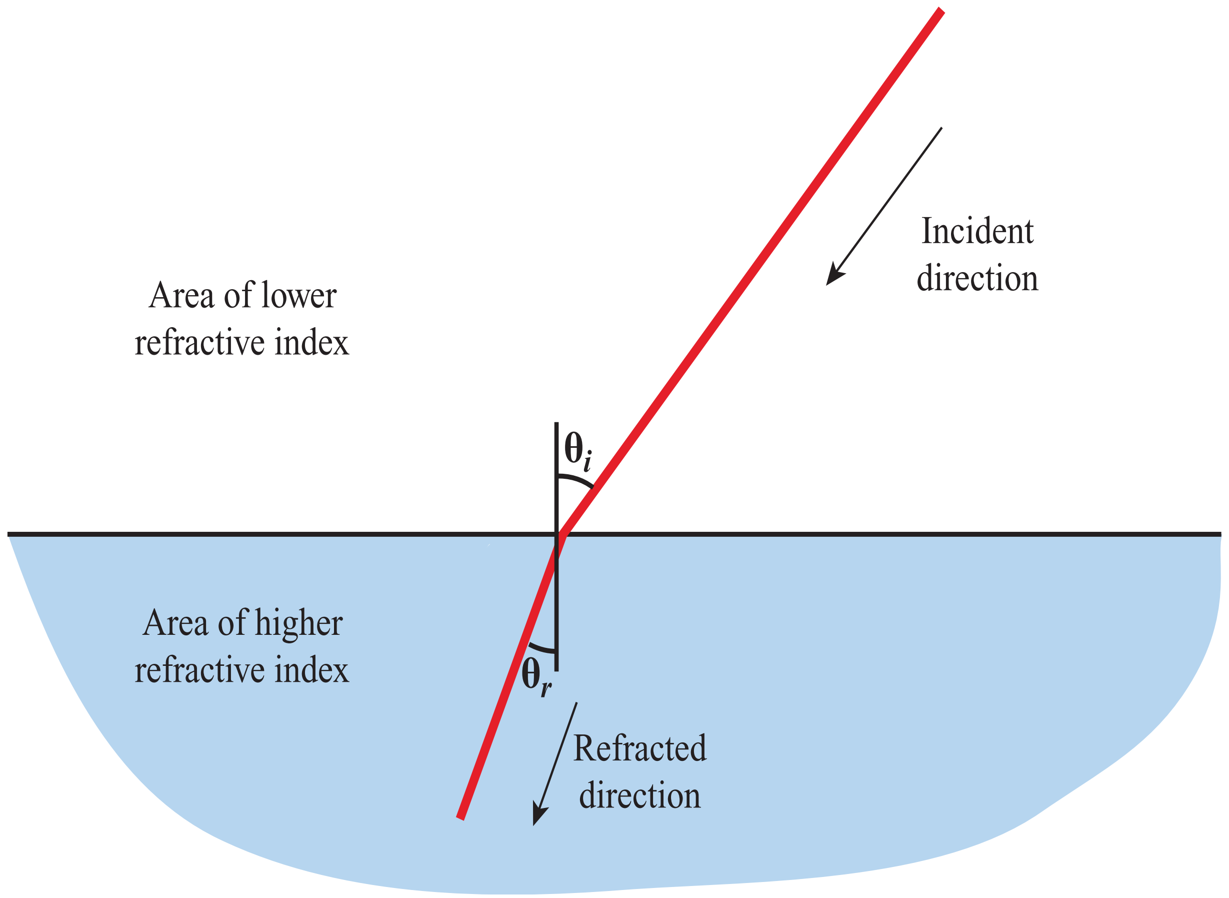
- Velocity of electromagnetic wave is a function of the density of the medium
- When wave changes medium, speed changes
- Wave bends at the boundary between mediums

Refraction



Refraction

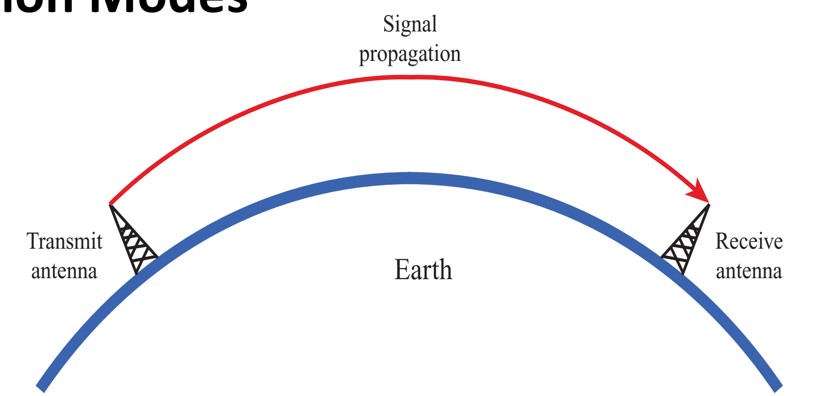




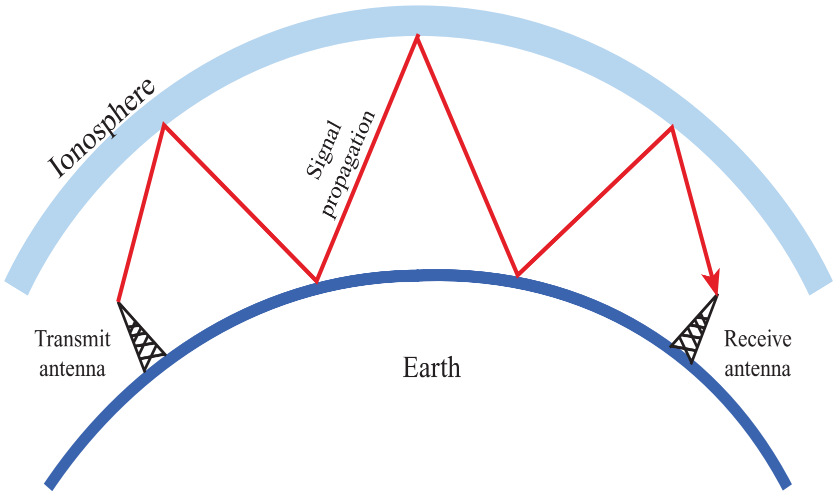
Refraction of an Electromagnetic Wave

Refraction of an Electromagnetic Wave (visible light)

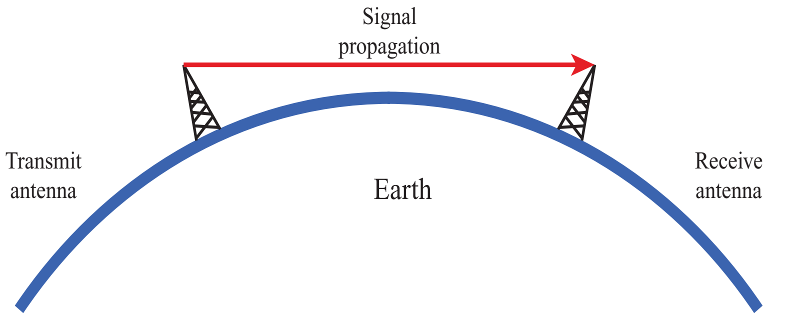
Wireless Propagation Modes



(a) Ground wave propagation (below 2 MHz)



(b) Sky wave propagation (2 to 30 MHz)

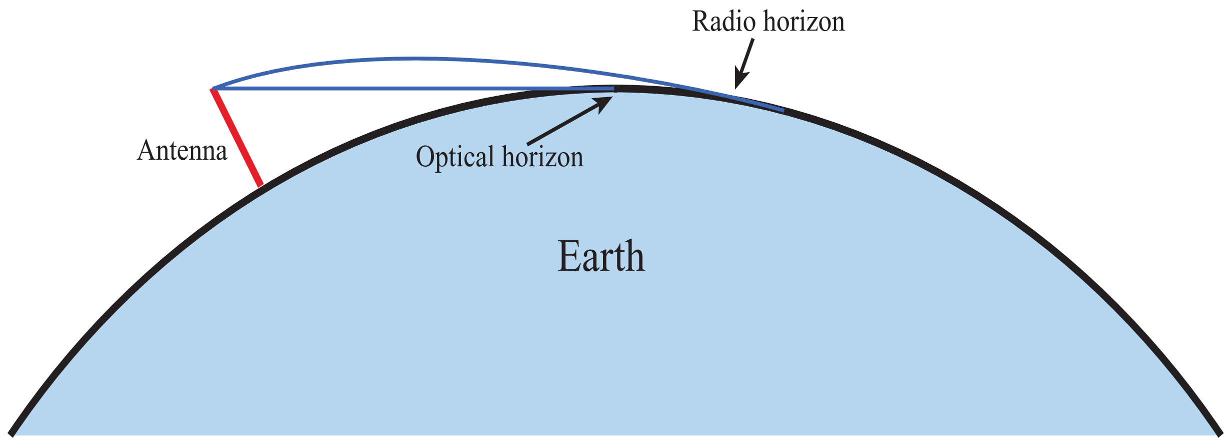


(c) Line-of-sight (LOS) propagation (above 30 MHz)

Line-of-Sight Propagation

- Frequencies above 30 MHz

- 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



Optical and Radio Horizons

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:

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

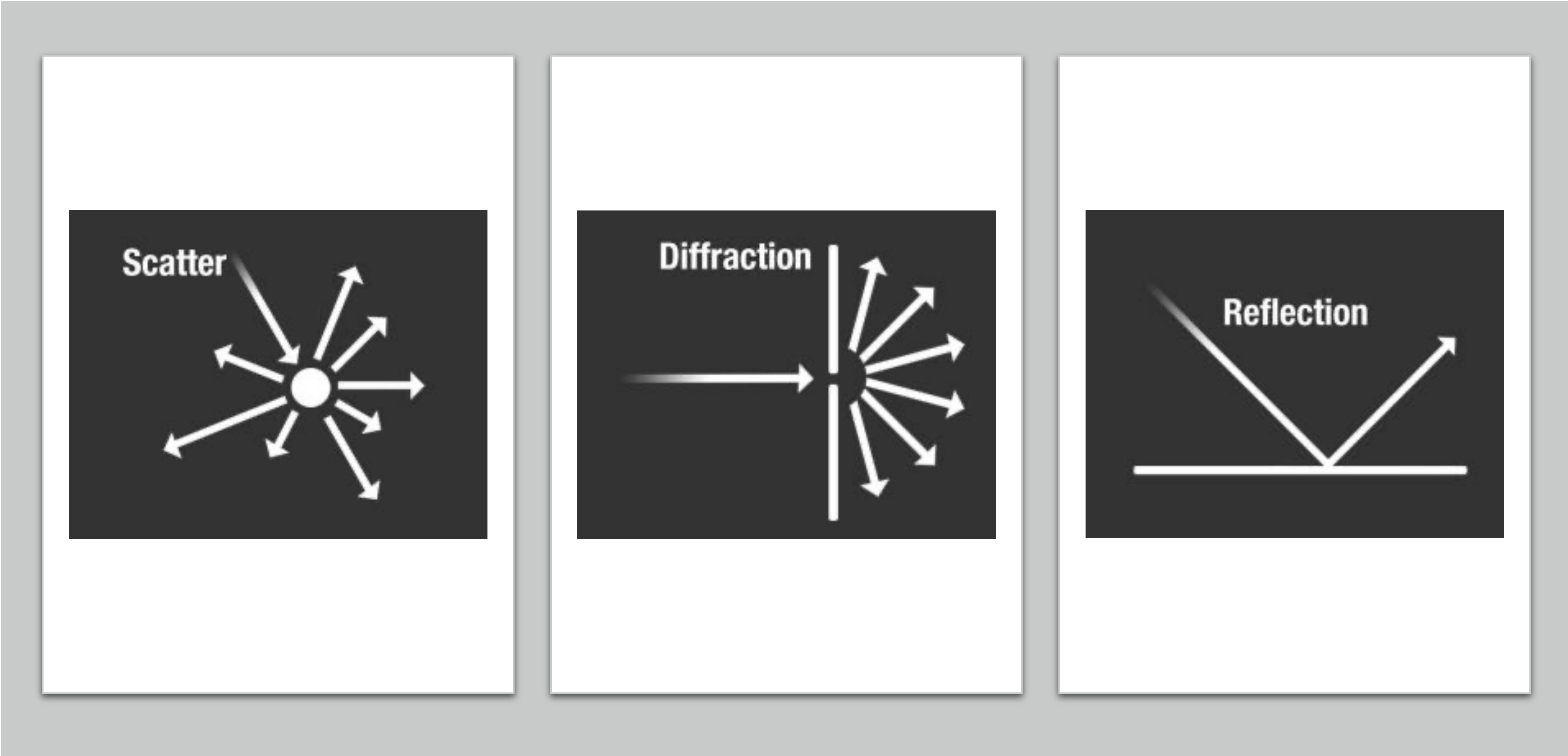
  - d = distance between antennas (km)
  - h_1 = height of first antenna (m)
  - h_2 = height of second antenna (m)

Multipath Propagation and Fading

V

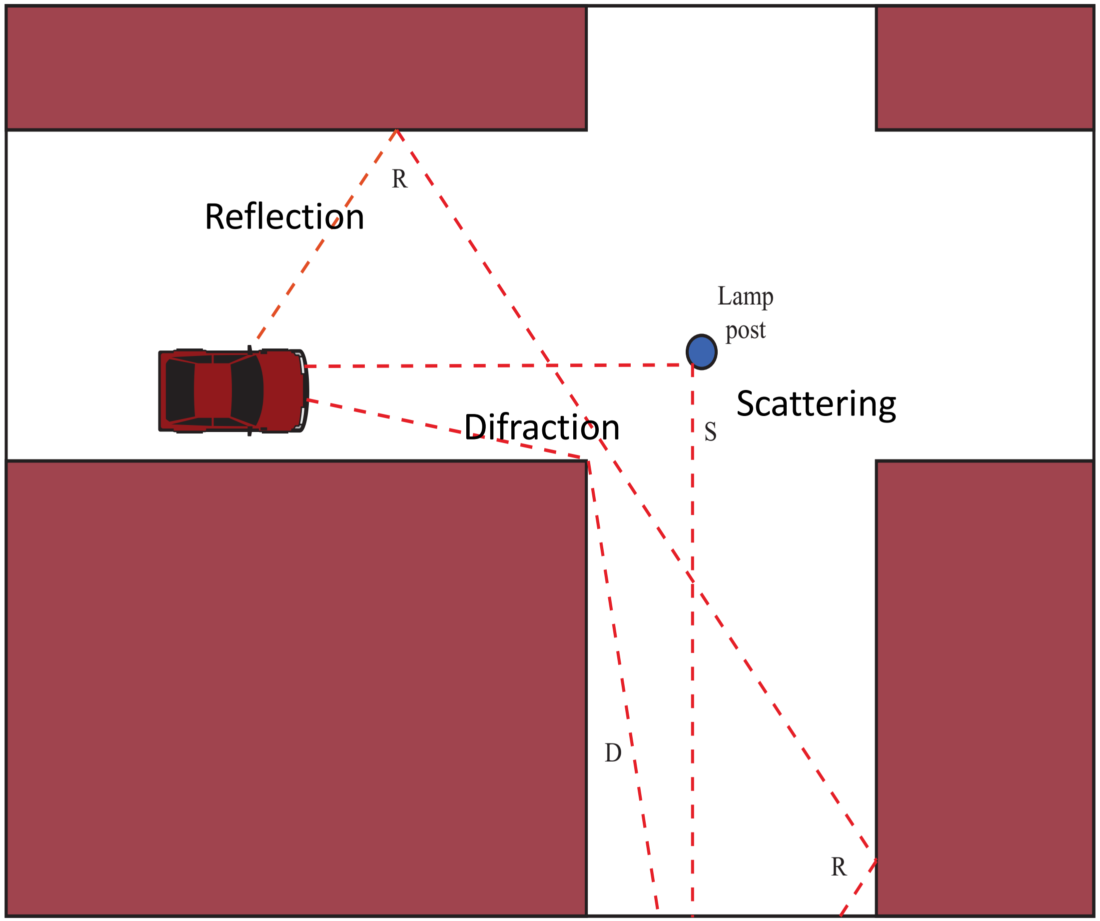
Five basic propagation mechanisms

1. Free-space propagation
2. Transmission
   - Through a medium
   - Refraction occurs at boundaries
3. Reflections
   - Waves impinge upon surfaces that are large compared to the signal wavelength
4. Diffraction
   - Secondary waves behind objects with sharp edges
5. Scattering
   - Interactions between small objects or rough surfaces



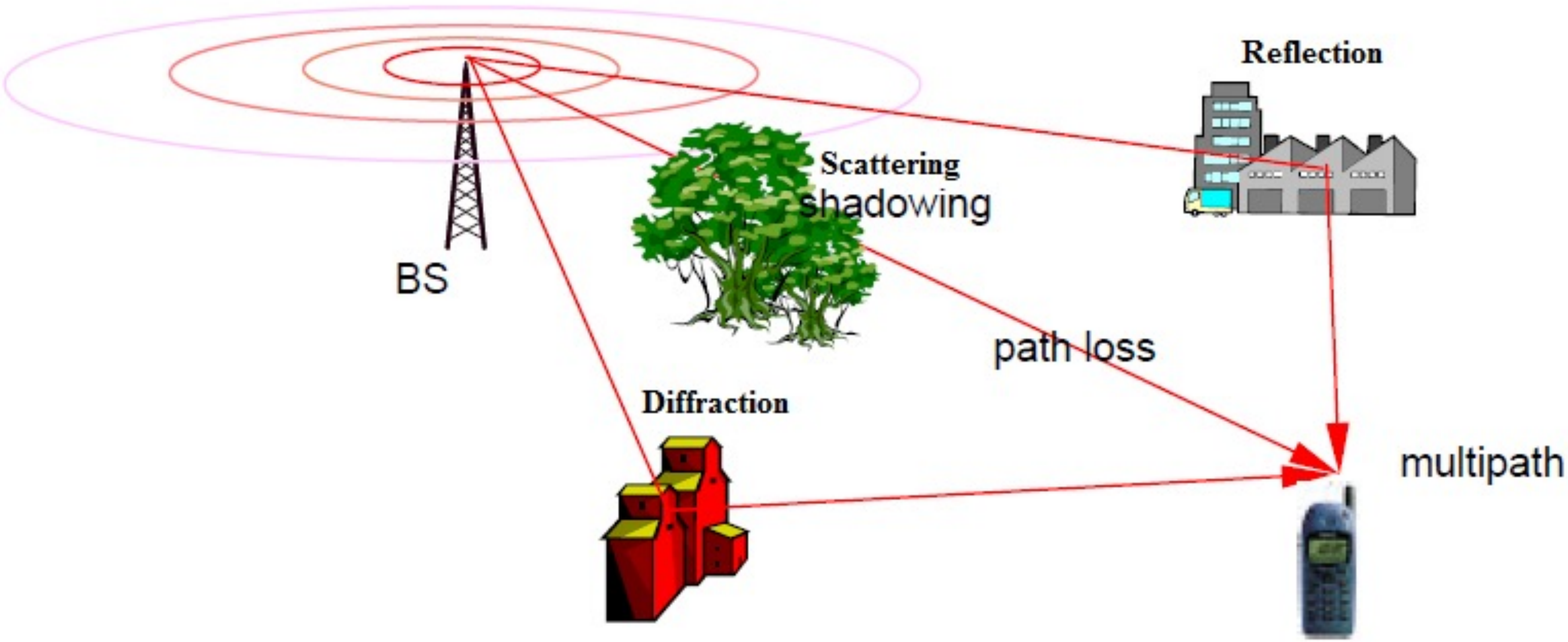
Reflection, diffraction, and scattering

Reflection, diffraction, and scattering



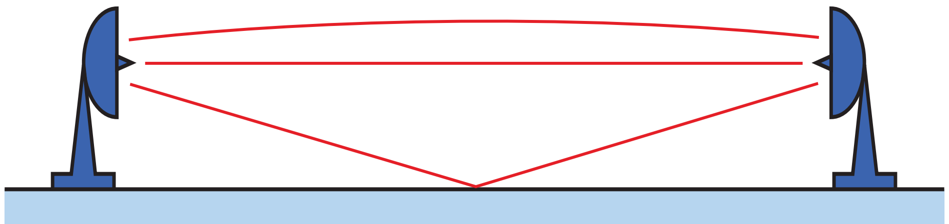
Multipath Propagation

Reflection, diffraction, and scattering

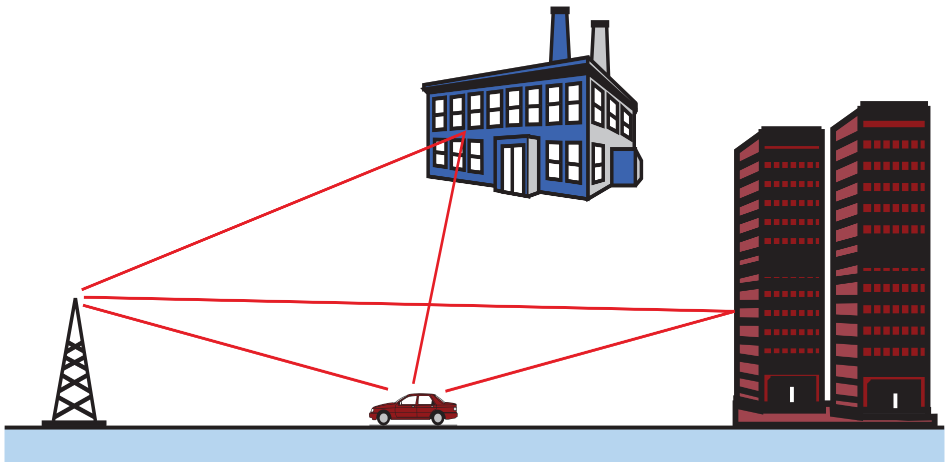


Multipath Propagation

Reflection, diffraction, and scattering



(a) Microwave line of sight



(b) Mobile radio

Multipath Propagation

- Reflection, diffraction, and scattering cause **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 (or symbol)
- Rapid signal fluctuations
  - Over a few centimeters

To be continued…

Literature

Wireless Communication Networks and Systems,

C. Beard and W. Stallings, Prentice Hall

- Chap 6