Antennas and Propagation

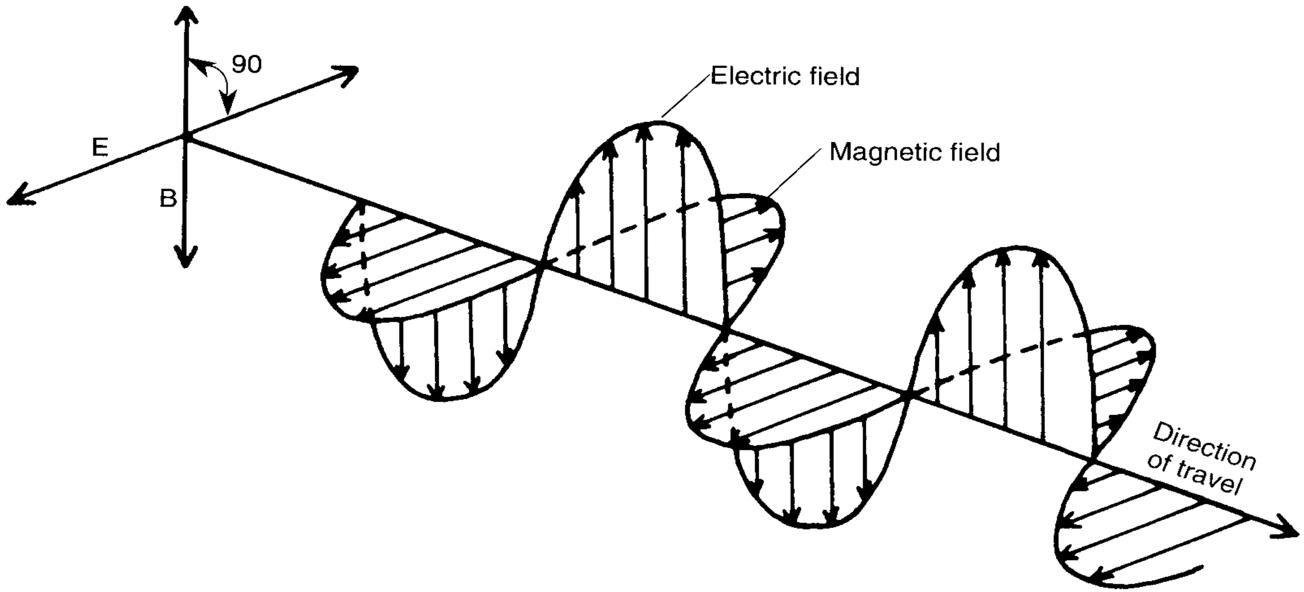
Prelude to Chapter 4

Propagation

Introduction

- An antenna is an electrical conductor or system of conductors for:
  - Transmission - radiates electromagnetic **energy** into space (involves both E and H fields as a TEM wave)
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception (simplex or with duplexers to isolate the different transmit and receive frequencies)
- *Reference Data for Radio Engineers* and similar handbooks provide good reference sources for antennas and propagation topics

Radio Wave (TEM Waves)



A radio wave moves outward from the radiator with its electric and magnetic fields at right angles to the direction of the wavefront motion and to each other. These waves moving through free space are ***transverse electromagnetic*** (TEM) ***waves*** consisting of mutually perpendicular electric and magnetic fields varying and travelling together in synchronism. A vertical polarized wavefront is shown above since the magnetic field component is parallel to the 'surface'.

Radiation Patterns

- Radiation pattern
  - A graphical representation of the radiation properties of an antenna (far-field)
  - Idealized (perfect ground); impacts by the surrounding environment normally neglected
  - Depicted as a two-dimensional cross section (elevation & azimuth)
- Beam width (or half-power beam width)
  - Measure of directivity of antenna
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern
- Antenna modeling software very common tool
  (computer based and very accurate, e.g., NEC, MININEC)

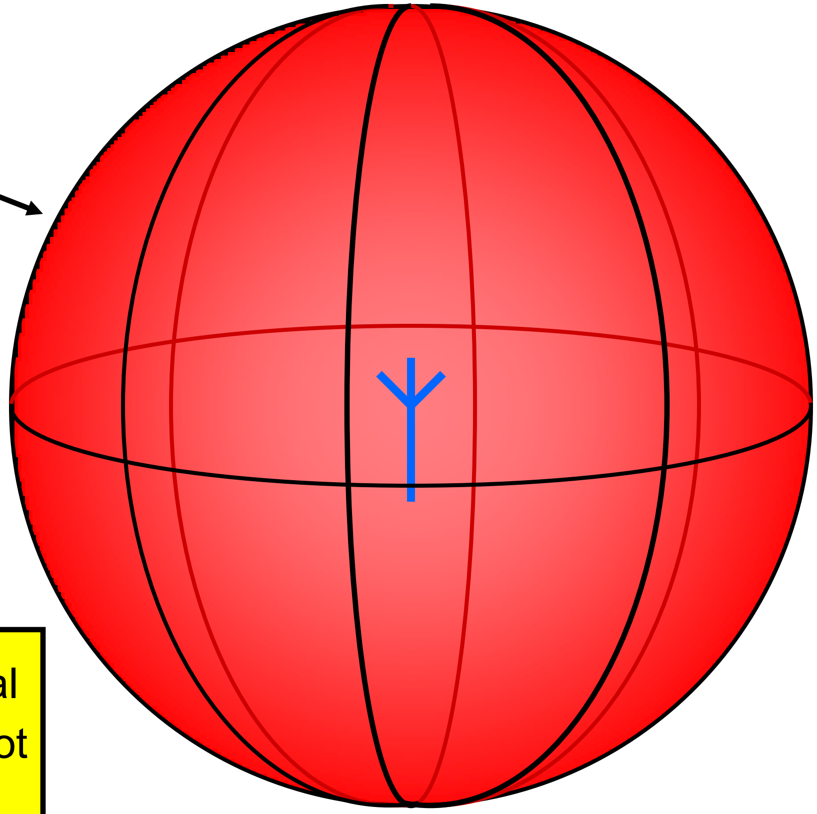
Types of Antennas

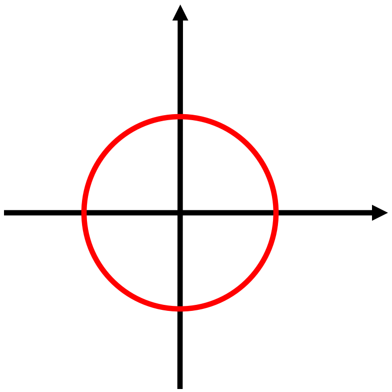
- Isotropic antenna (idealized, free space environment)
  - Radiates power equally in all directions
- Dipole antennas
  - Half-wave dipole antenna (or Hertz antenna)
  - Quarter-wave vertical antenna (or Marconi antenna, normally vertically polarized)
- Parabolic Reflective Antenna
  - Focus

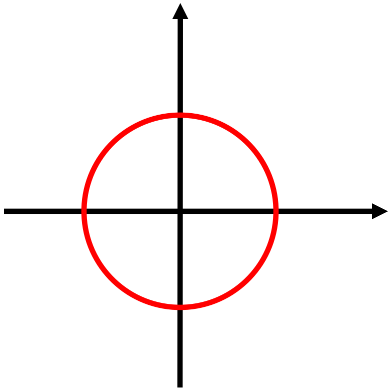
The isotropic antenna

The **isotropic antenna** radiates equally in all directions

Radiation pattern is spherical





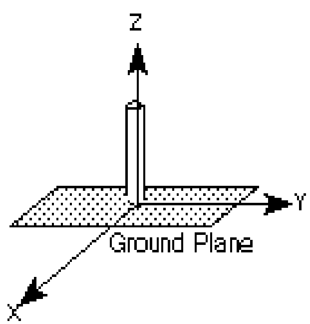
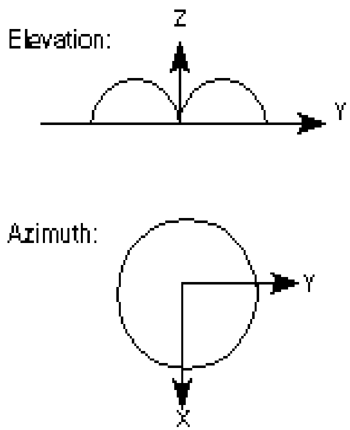
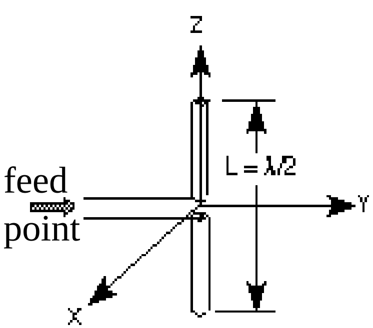
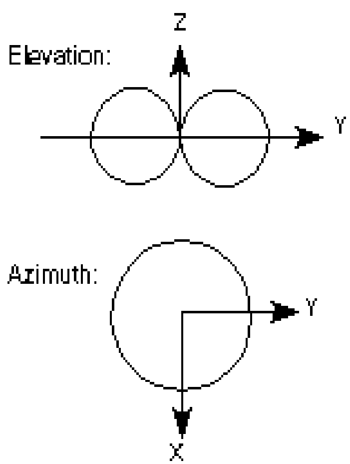


This is a theoretical antenna that cannot be easily realized.

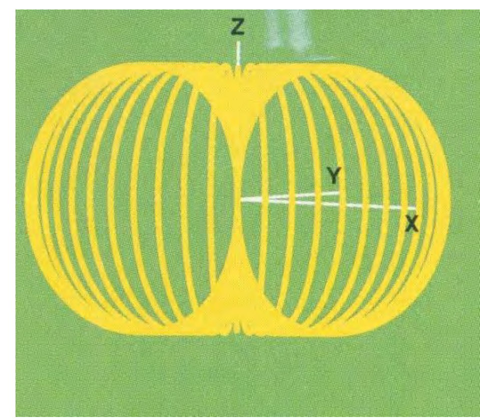
Antenna Gain

- Antenna Gain G (Directivity)
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna [usual reference is an isotropic antenna (dBi) but a real-world ½ λ antenna is a far more practical reference. A typical sales trick to use an isotropic reference when a dipole is inferred resulting in a 1.64 power gain]
  - Antenna gain doesn't increase power; only concentrates effective radiation pattern
- Effective area A_e (related to antenna aperture)
  - Physical size and shape of antenna as related to the operational wavelength of the antenna
  - For a parabolic reflector antenna (a dish antenna), the effective area is close to the physical aperture (minus the area blocked by the feed system and its supports)

Some Simple Antenna Patterns

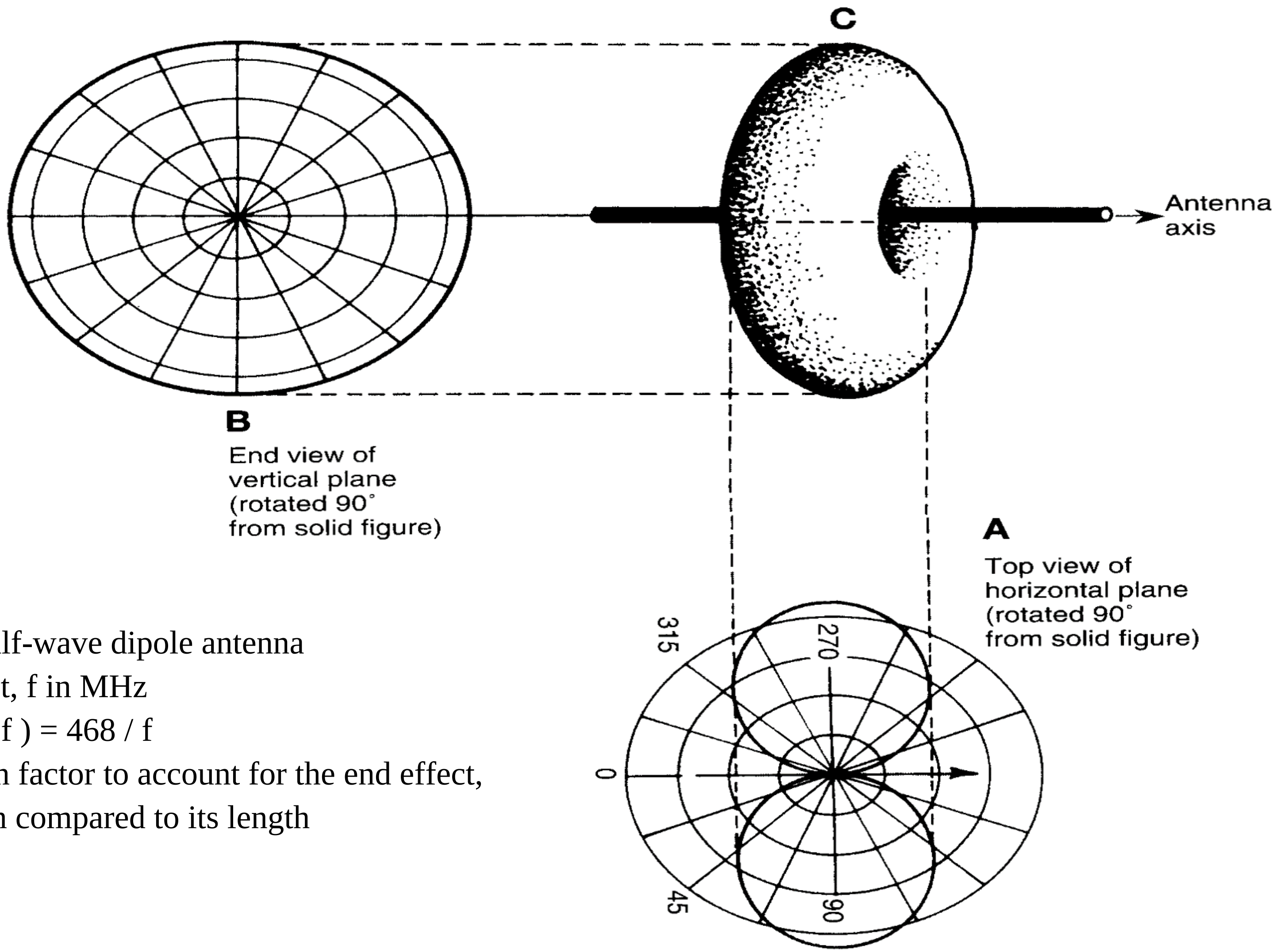
Antenna Type	Radiation Pattern	Characteristics
MONOPOLE  	 	**Polarization: Linear** Vertical as shown **Typical Half-Power Beamwidth** 45 deg x 360 deg **Typical Gain:** 2-6 dB at best **Bandwidth:** 10% or 1.1:1 **Frequency Limit** **Lower:** None **Upper:** None **Remarks:** Polarization changes to horizontal if rotated to horizontal
λ/2 DIPOLE  	 	**Polarization:** Linear Vertical as shown **Typical Half-Power Beamwidth** 80 deg x 360 deg **Typical Gain:** 2 dB **Bandwidth:** 10% or 1.1:1 **Frequency Limit** **Lower:** None **Upper:** 8 GHz (practical limit) **Remarks:** Pattern and lobing changes significantly with L/f. Used as a gain reference < 2 GHz.

Feed Point – one connection to vertical (monopole) and one connection to the ground plane



1/2 wave dipole balance feed point

Free-space radiation pattern of a λ/2 (half-wave) dipole



Length of a half-wave dipole antenna

for L in feet, f in MHz

L= 0.95(492 / f) = 468 / f

0.95 correction factor to account for the end effect, the wire is thin compared to its length

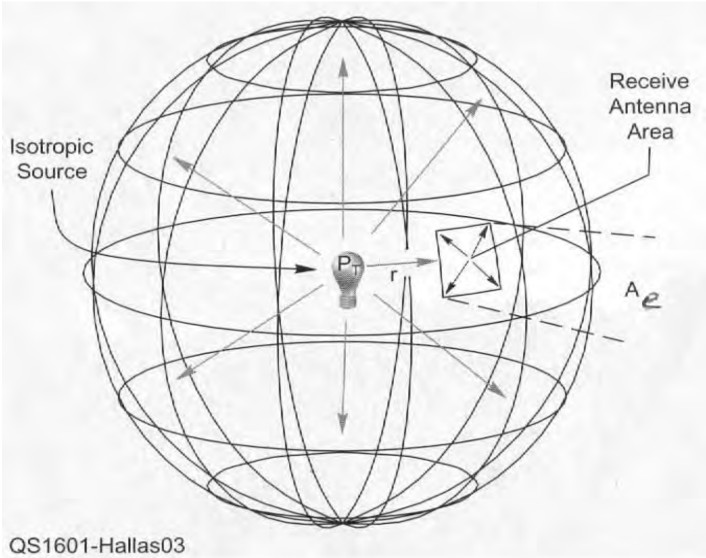
Antenna Gain

- 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 (Area to $\boldsymbol{A_e}$ relationships found in tables)
  - f = carrier frequency
  - c = speed of light (~ 3 x 10^8 m/s in a vacuum)
  - λ = carrier wavelength

Radiated Energy in Free Space

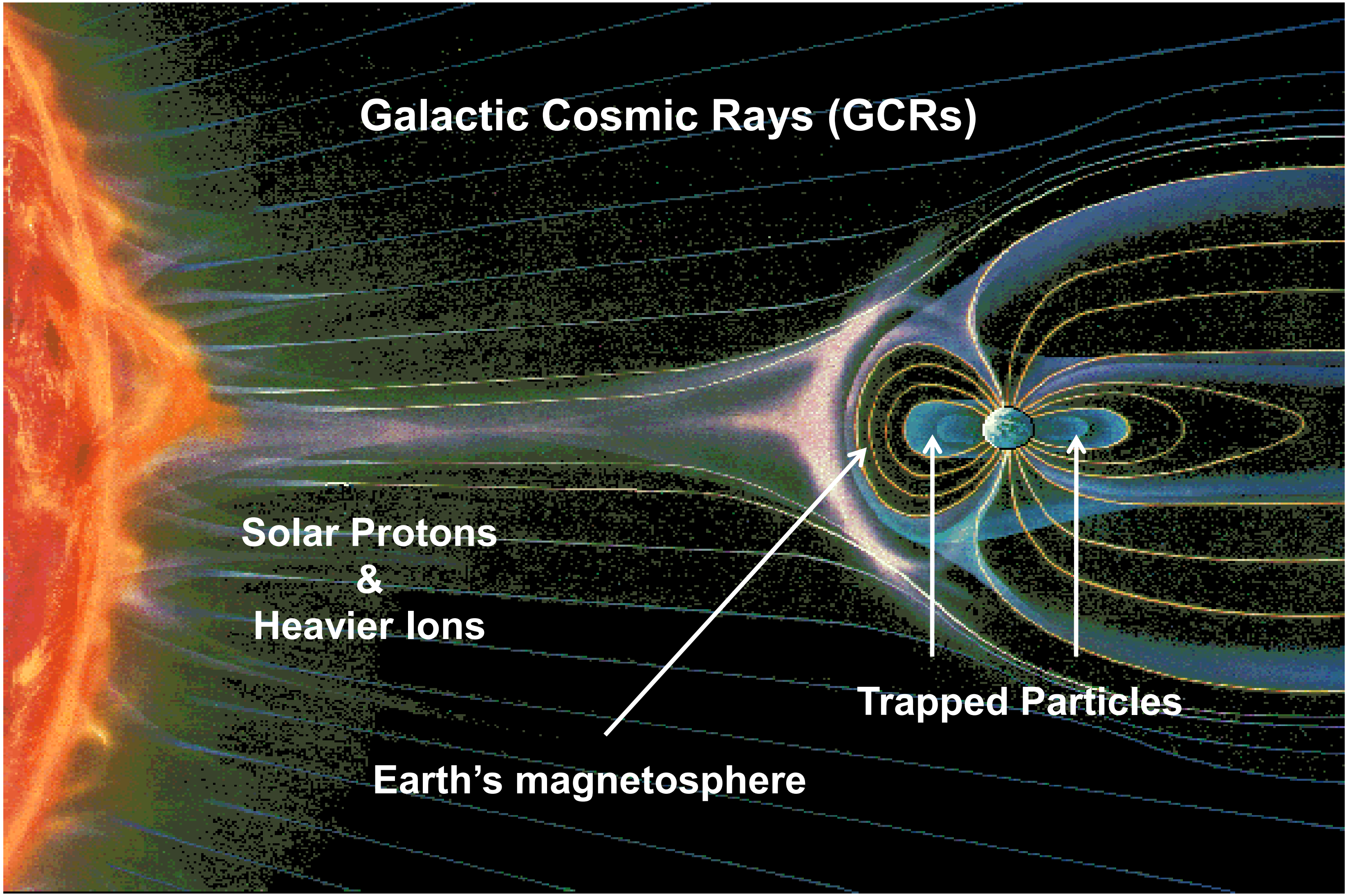


- P_r is the power intercepted by the receive antenna aperture A_e which is equal to the power transmitted by the isotropic source P_t times the ratio of A_e / A_s where A_s is the area of the entire sphere $A_s = 4\pi r^2$
  - $P_r = P_t (A_e / 4\pi r^2)$ where r is the radius of the sphere or the distance between the transmit and receive antennas
  - Note that the receive power is reduced by the square of the distance – the ***inverse square law***. Also the frequency of the transmitted signal is not specified since at this point it's just a matter of relative areas.

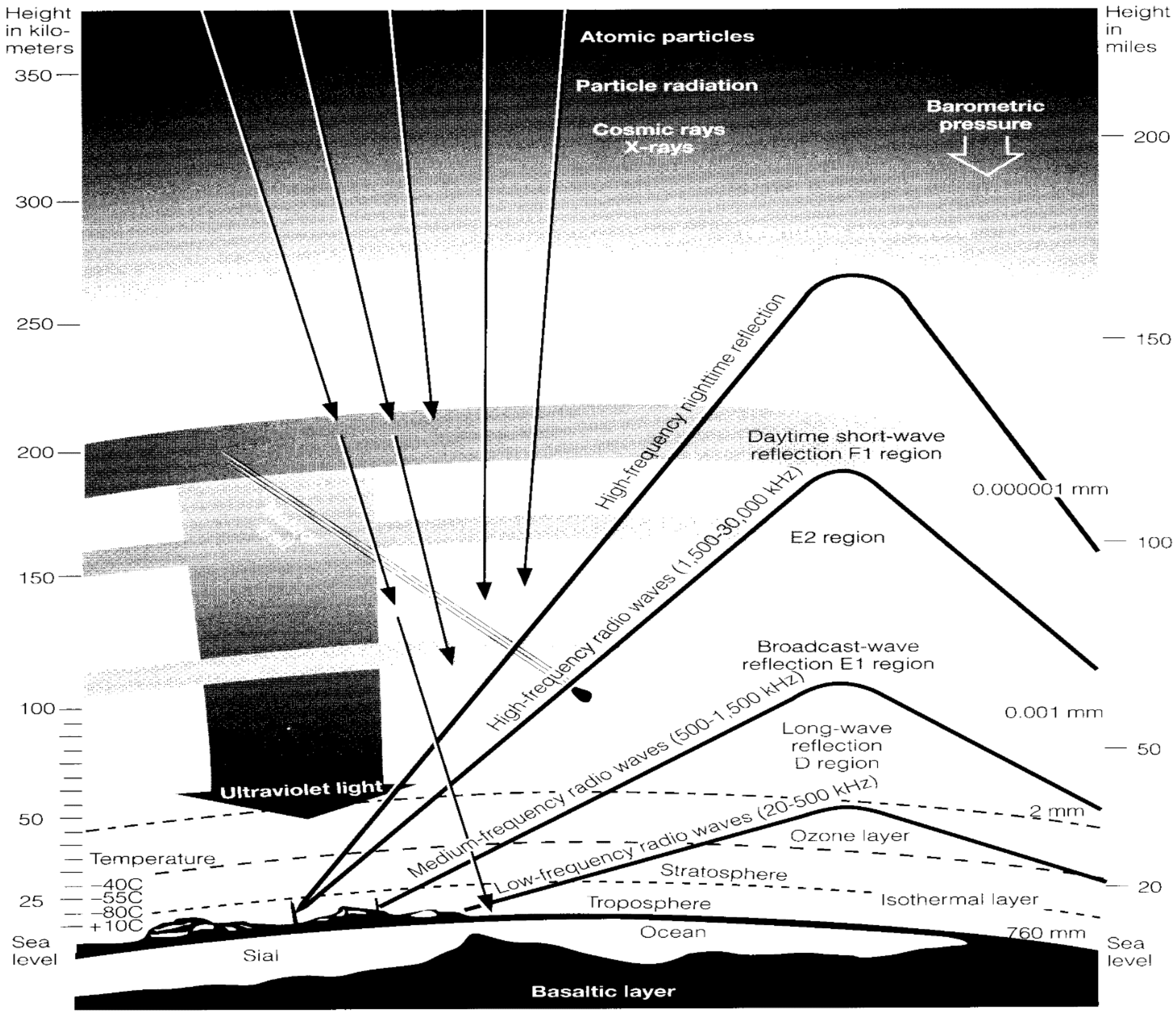
Propagation Modes

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

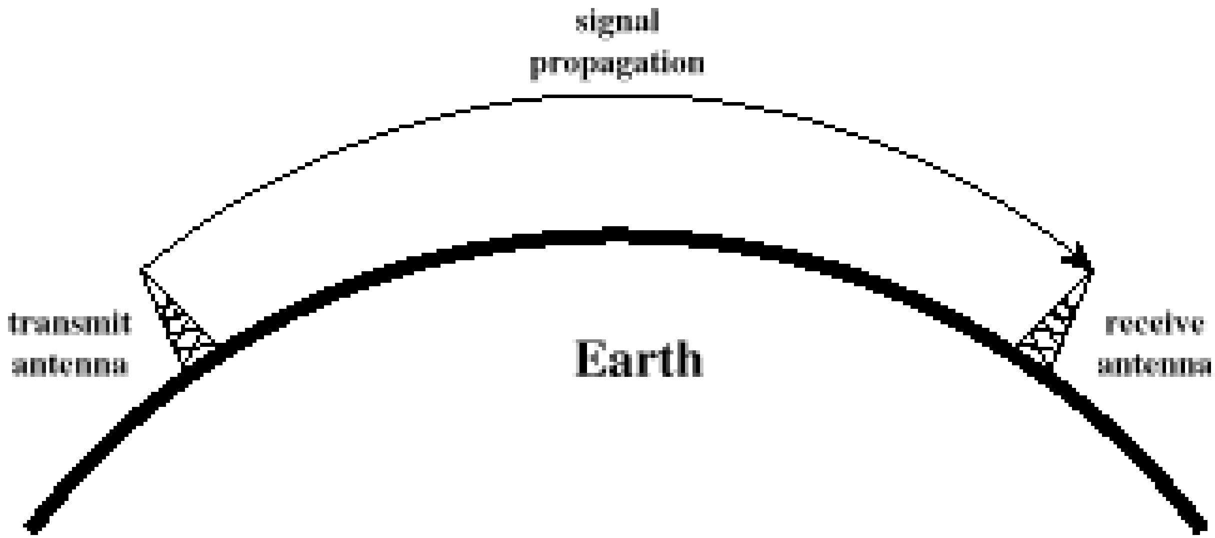
The Space Radiation Environment



Radio Waves in the Atmosphere



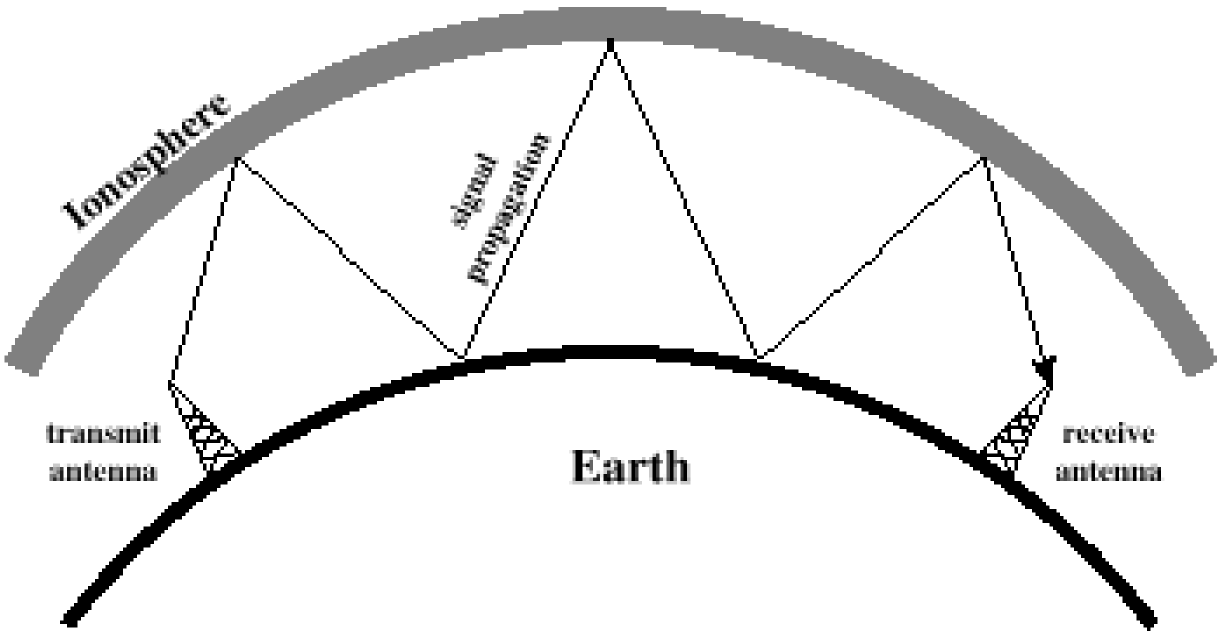
Ground Wave Propagation (LF/MF)



Ground Wave Propagation

- Follows contour of the earth
- Can propagate considerable distances
- Frequencies up to 2 MHz (all frequencies will have some ground wave/near field)
- Examples
  - AM radio (generally)
  - LF and MF
  - Low frequencies which can be effected by daytime/nighttime

Sky Wave Propagation (HF)



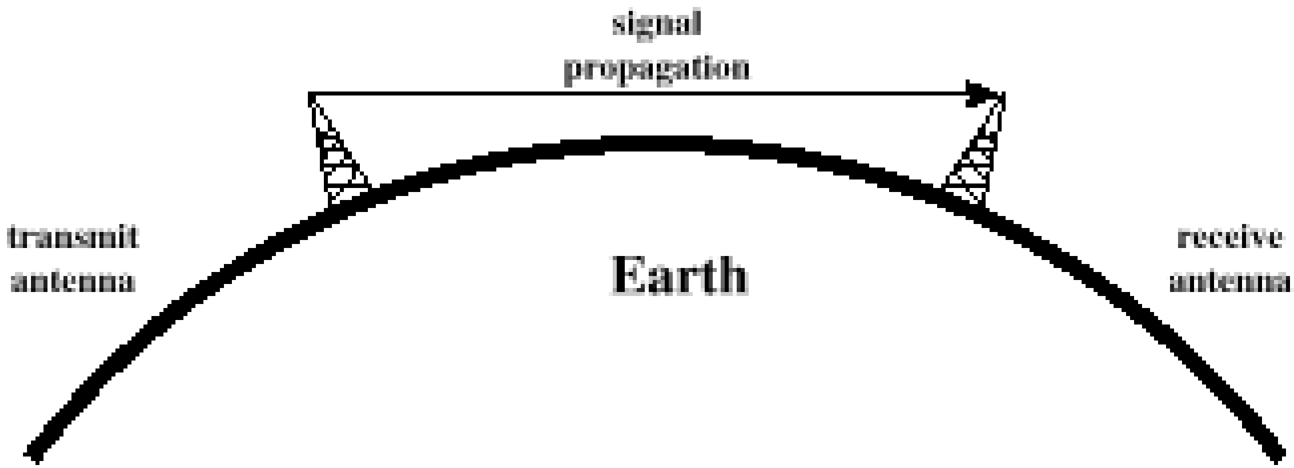
Normally only one hop

Sky Wave Propagation

- Signal reflected from ionized layer of atmosphere back down to earth (dependent on sun's radiation)
- Signal can travel for a number of hops, back and forth between ionosphere and earth's surface; both a short path and a long path (opposite direction around earth) can also occur
- Reflection effect caused by refraction
- Examples (3 – 30 MHz)
  - Amateur radio
  - Short-wave radio
- Good propagation models based on sun observations are readily available (MUF)

Line-of-Sight Propagation (VHF and above)

f > 30 MHz operationally f > 100 MHz



Line-of-Sight Propagation

- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 – 50 MHz not normally 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:

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

  - h_1 = height of antenna one in meters
  - h_2 = height of antenna two in meters
  - Note that **d is in kilometers (km)**

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 (exponential)
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal (without overloading the front-end of the receiver) – receiver sensitivity related to internally generated noise
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies
  - Any attenuation results in signal distortion

Free Space Loss

- Free space loss for an 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 [$c = \lambda f$]
  - d = propagation distance between antennas
  - c = speed of light (~ 3 x 10^8 m/s in a vacuum)

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

  - f = frequency in Hz

Free Space Loss

- Free space loss equation can be recast:

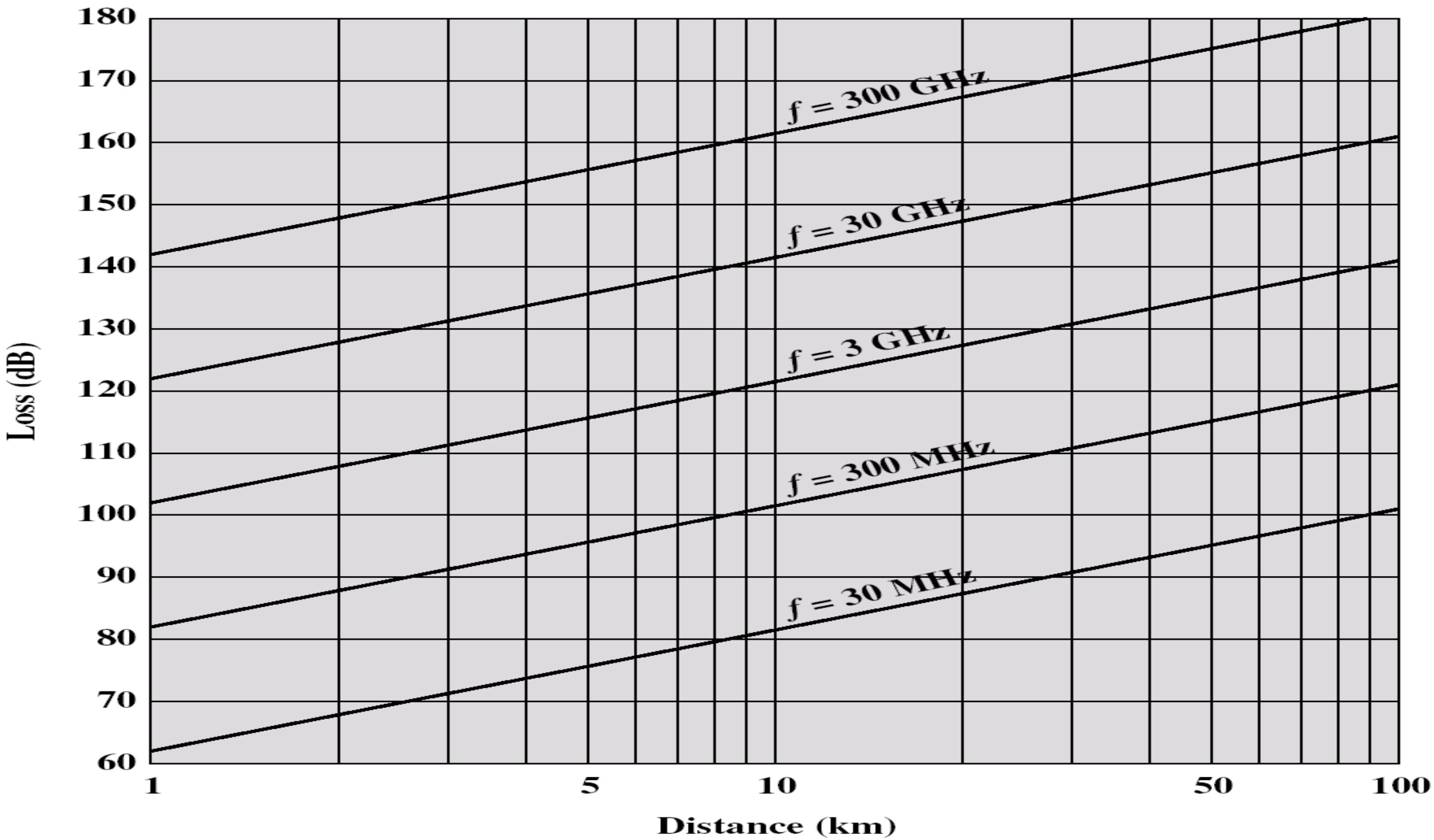
$$L_{dB} = 10\log\frac{P_t}{P_r} = 20\log\left(\frac{4\pi d}{\lambda}\right)$$

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

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

using f in Hz
and d in meters

Free Space Loss (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 **Not in dB**
  - G_r = gain of receiving antenna
  - A_t = effective area of transmitting antenna (aperture)
  - A_r = effective area of receiving antenna
  - d and λ in meters, f in Hz

Free Space Loss

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

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

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

Remember that L = - G

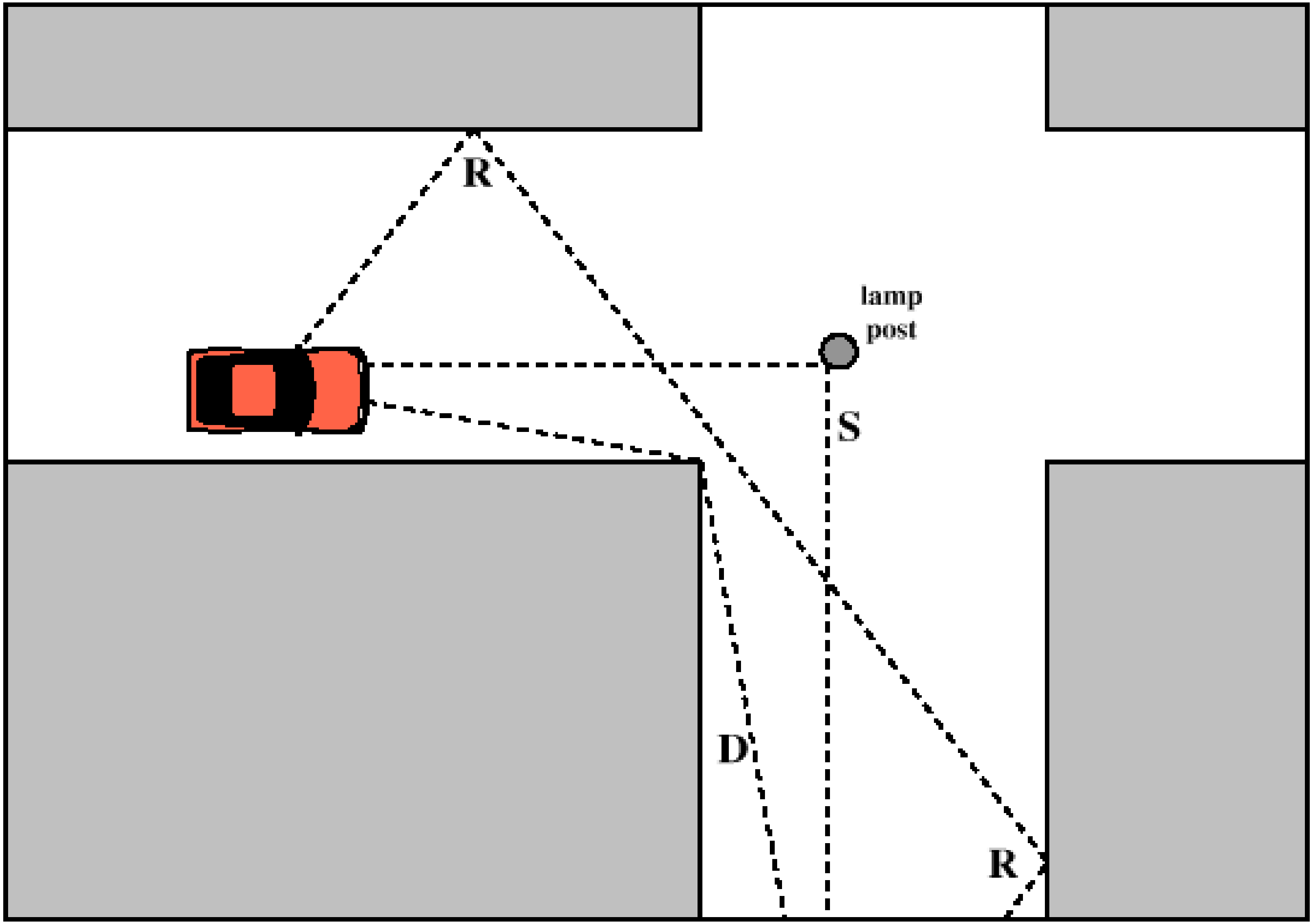
Normally don't use these equations since antenna gains are usually given in dB which are just algebraically added to the path loss in dB.

Other Impairments (most notable for VHF and above)

- Atmospheric absorption – water vapor and oxygen contribute to attenuation (microwave)
- Multipath – obstacles reflect signals so that multiple copies with varying delays are received (shadow fading – obstruction of signal by objects in the straight-line path)
- Refraction – bending of radio waves as they propagate through the atmosphere

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 the wavelength of the radio wave (signals received without a direct line-of-sight)
- Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less (difficult to predict)
- If there isn't a clear LOS, multipath can be the primary means of signal reception so it is not always a negative attribute.



Sketch of Reflection (R), Scattering (S) and Diffraction (D) Propagation Mechanisms in a non-LOS case

Types of Fading

- Fast fading (usually movement over very short distances)
- Slow fading (movement in excess of wavelengths; environment)
- Flat fading (or non-selective fading, constant fading over entire signal frequencies, e.g., path loss)
- Selective fading (e.g., dependent on frequency, unequal over the frequencies associated the signal)
- Rayleigh fading (multiple indirect paths, e.g., no LOS, thus multipath components dominate, worst-case scenario, can be the dominant factor in an outdoor environment, special case of Rician distribution.)
- Rician fading (direct LOS path and a number of weaker indirect paths/small-scale fading – multipaths such as found in an indoor environment. As the dominant LOS becomes weaker, e.g. fades away, the composite signal degenerates from a Rician distribution to a Rayleigh distribution.

Slow or Small-Scale Fading

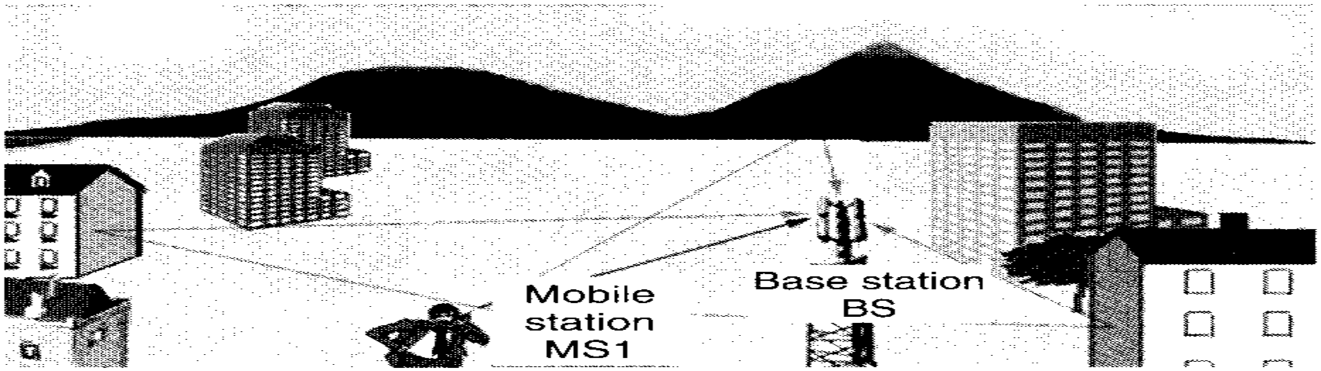
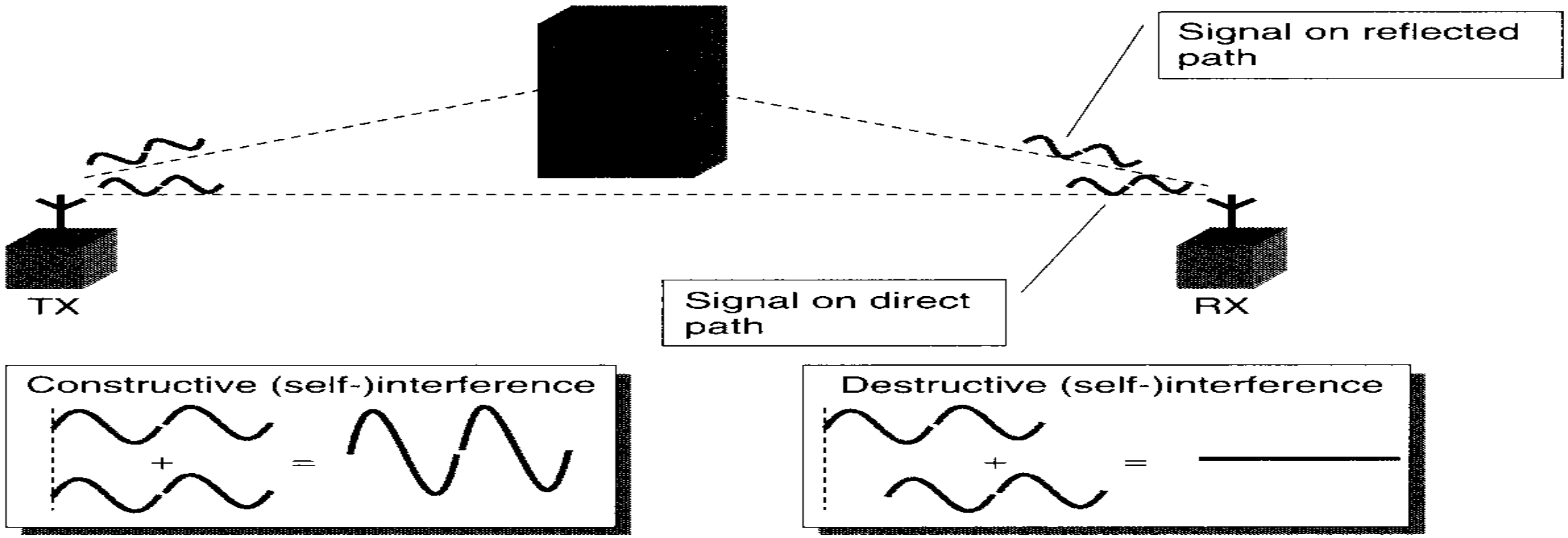
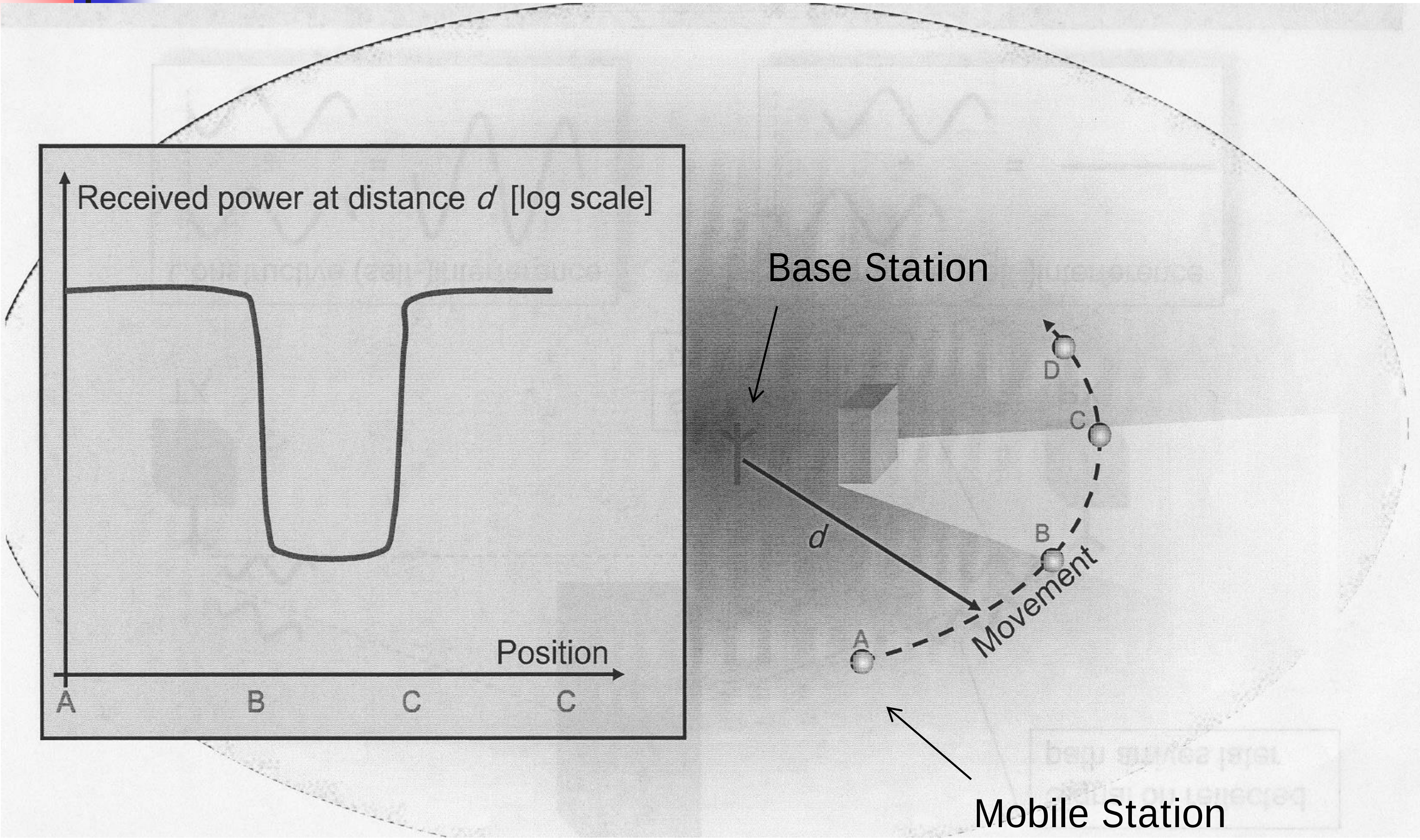


Figure 2.1 Multipath propagation.



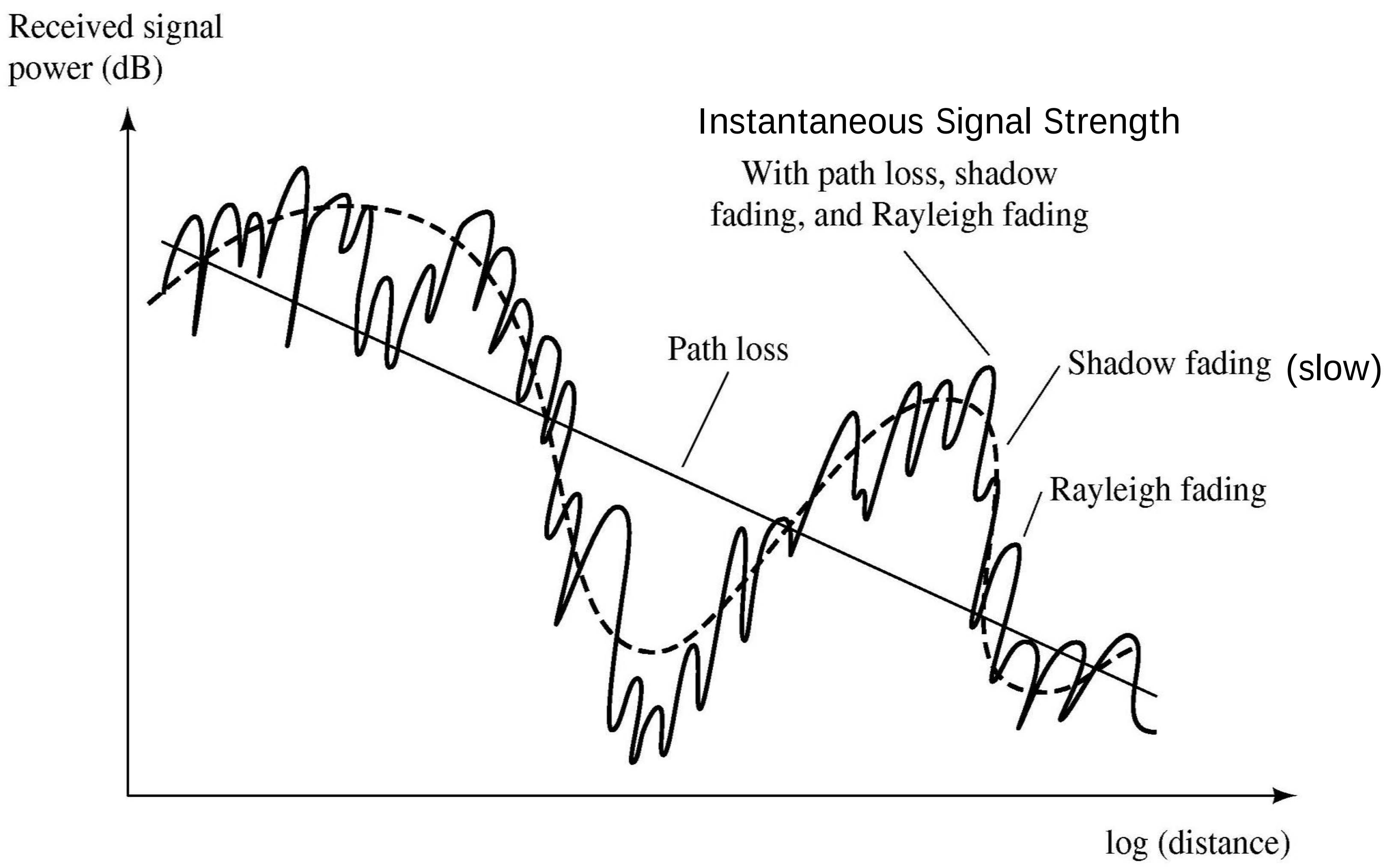
Slow or Large-Scale Fading



Consequences of Fading

- Error probability is dominated by probability of being in a fading low point (dip)
- Error probability decreases only linearly with increasing SNR
- Fighting the effects of fading becomes mandatory for wireless equipment design
- Deterministic modeling of a channel at each point in the path is very difficult
- Statistical modeling of propagation and system behavior - a far more common means of characterization
- Empirical determination: On site testing (*"Can you hear me now?"*)

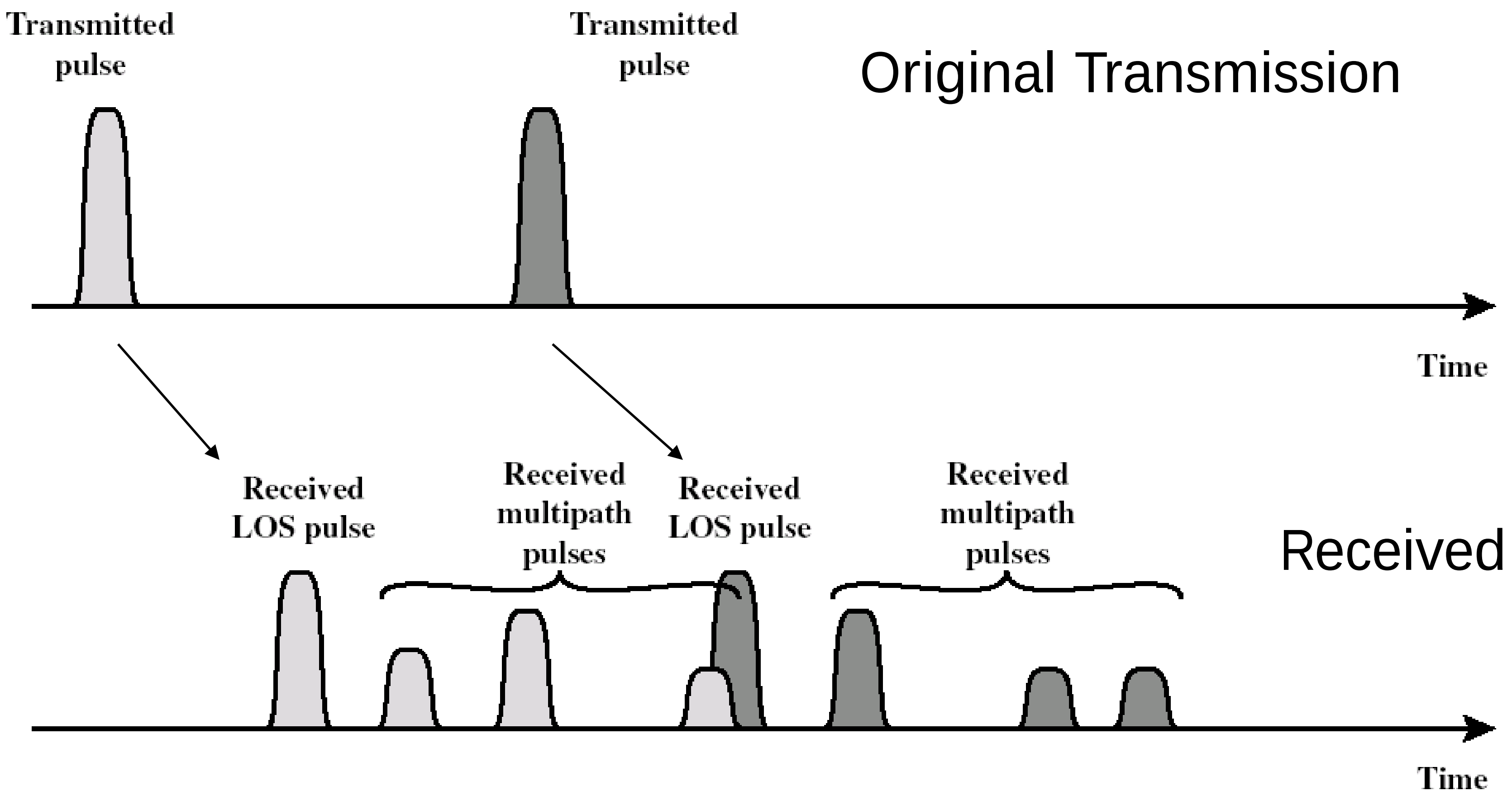
Wireless RF Environment



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) (especially digital)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit, e.g., modulation pulses are spread in time into the adjacent symbols. The modulation bandwidth exceeds the coherence bandwidth of the channel.
  - This is the major obstacle to high speed data transmission over wireless channels.

Intersymbol Interference (ISI)



Error Compensation Mechanisms

- Forward error correction (coding)
- Adaptive equalization
- Diversity techniques
- All three categories are used to combat error rates in a wireless communications system
- Good technical reference: Chapter 7 in Rappaport's *Wireless Communications* textbook

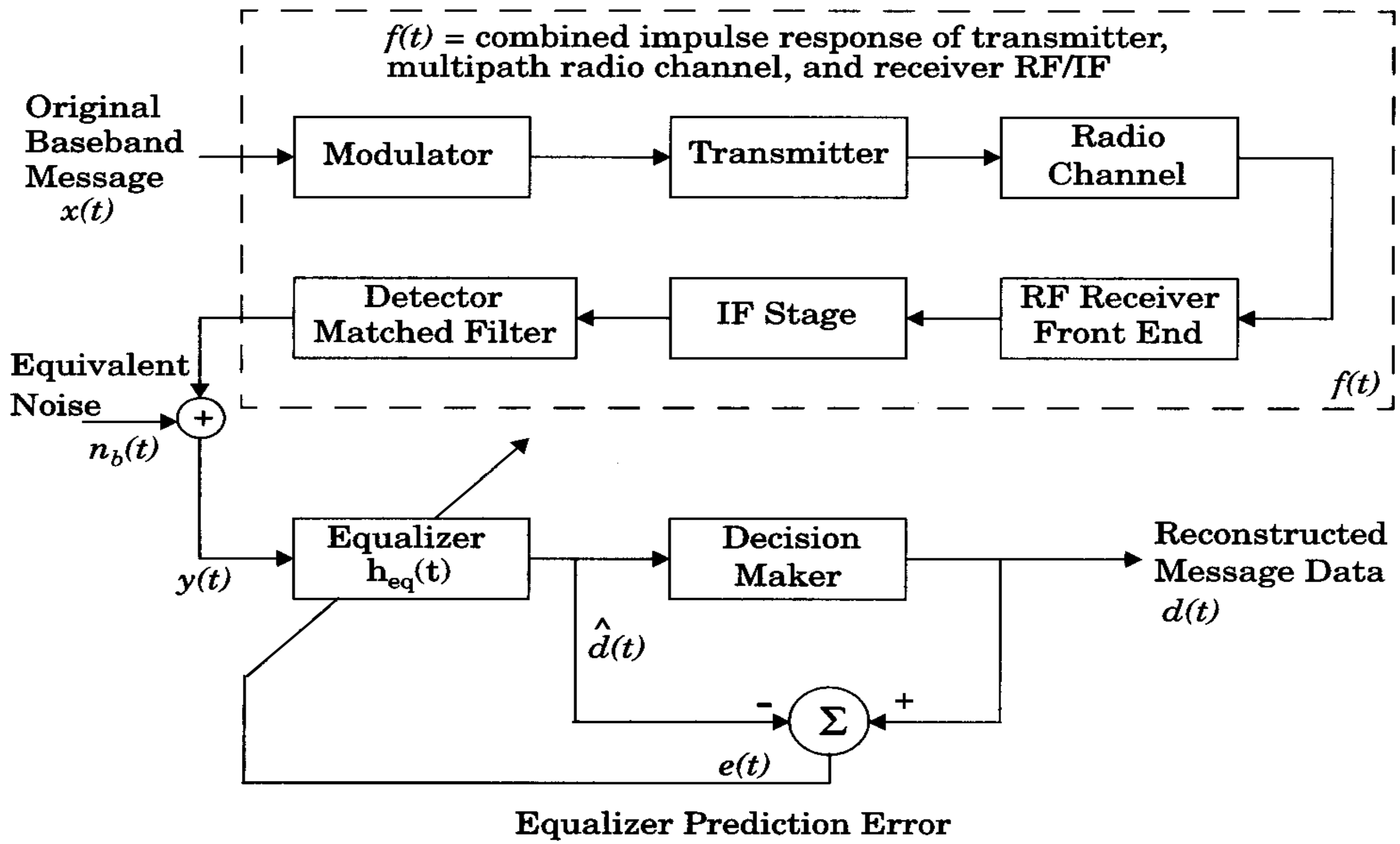
Forward Error Correction

- Transmitter adds error-correcting code to data
  - 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 shows an error, receiver attempts to determine the bits in error and correct.
- Requires high levels of data redundancy (2 →3 times)
- Backward Error Correction: an ACK/NAK protocol like the old AX.25 protocol. When the receiver sends a NAK to the transmitter, it results in a request to retransmit, possibly many times (which means time delays or even a time out/loss of the connection).

Adaptive Equalization (the lemonade maker)

- Can be applied to transmissions that carry analog or digital information in a channel with time varying characteristcs.
  - Analog voice or video
  - Digital data, digitized voice or video
- Used to combat intersymbol interference (ISI), a major obstacle, created by multipath within time dispersive channels
- Involves ‘restoring’ dispersed symbol energy back into its original time interval
- Techniques
  - Lumped analog circuits
  - Sophisticated digital signal processing algorithms (usually adaptive, processor based techniques)
  - Linear Equalization Circuits implemented with DSP

Block Diagram of a Simplified Communications System Using a Receiver Adaptive Equalizer

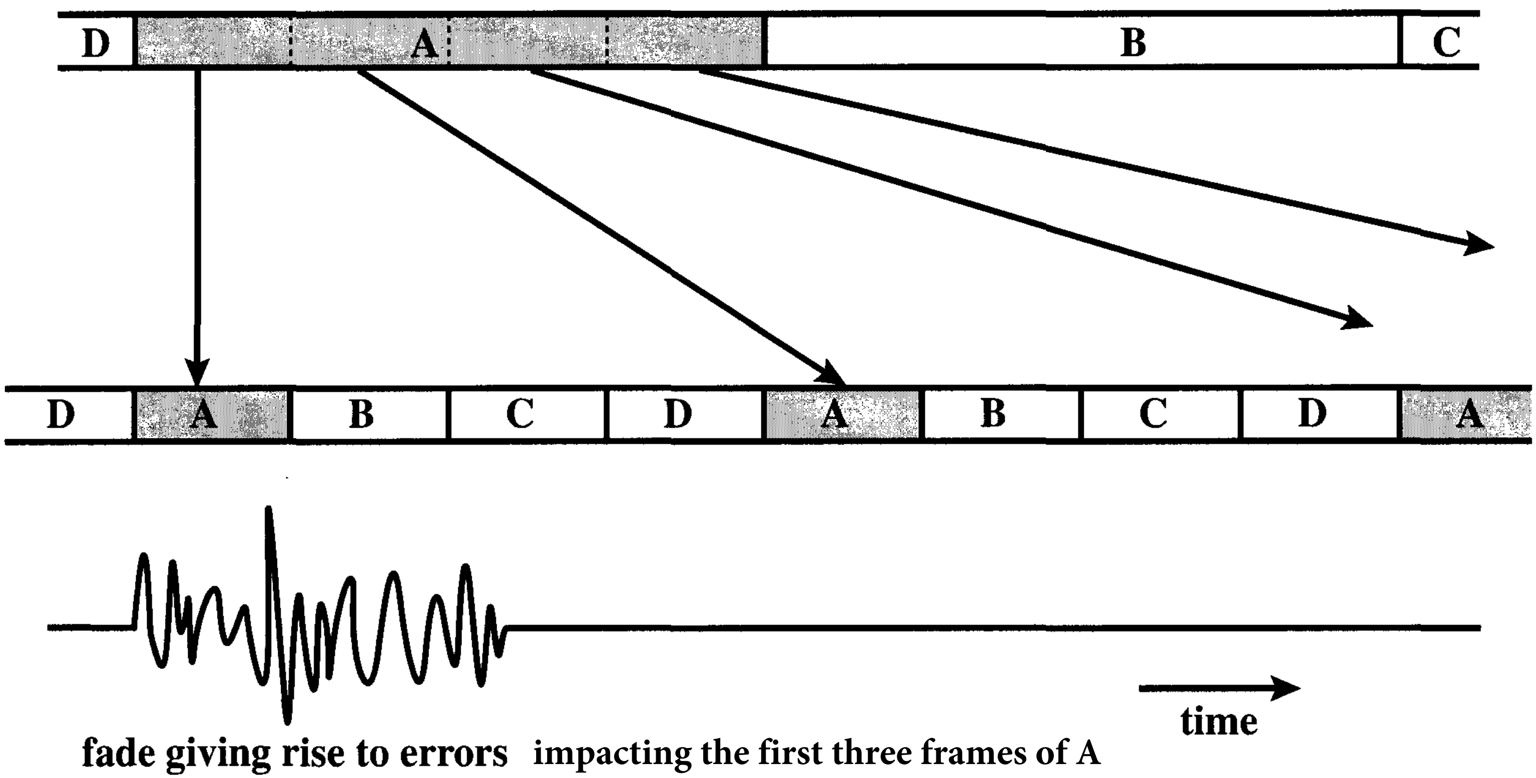


Diversity Techniques

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

Interleaving Data to Spread the Effects of Error Bursts
(Time Diversity)

greatly improves error correcting techniques since the number of contiguous errors is reduced



A Hobby Gone Amok at K5RG

7-30 MHz Log
Periodic in 1985

Erection of 40 Meter Beam

3 element 40 M Beam &
UHF/VHF Log Periodic