Antennas and Propagation

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Textbook: Wireless Communications and Networks, William Stallings, Prentice Hall

Outline

- Antennas
- Propagation Modes
- Line of Sight Transmission
- Fading in Mobile Environment and Compensation

Decibels

- The Decibel Unit:
  - Standard unit describing transmission gain (loss) and relative power levels
  - Gain: N(dB) = 10 log(P_2/P_1)
  - Decibels above or below 1 W: N (dBW) = 10 log($P_2/1W$)
  - Decibels above or below 1 mW: N(dBm) = 10log($P_2/1mW$)
- Example:
  - P = 1mW => P(dBm) = ?; P(dBW) = ?
  - P = 10mW => P(dBm) = ?   ; P(dBW) = ?

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

Basics of Radio-waves Propagation

- Radiowave propagation:
  - Radiowaves: electromagnetic waves
  - Signal energy: electrical field (E) and magnetic field (H)
  - E and H are sinusoidal functions of time
  - The signal is attenuated and affected by the medium

- Antennas
  - Form the link between the guided part and the free space: couple energy
  - Purpose:
    - Transmission: efficiently transform the electrical signal into radiated electromagnetic wave (radio/microwave)
    - Reception: efficiently accept the received radiated energy and convert it to an electrical signal

Radiation Patterns

- Radiation pattern
  - Graphical representation of radiation properties of an antenna
  - Depicted as two-dimensional cross section
  - Distance from the antenna to each point on the radiation pattern is proportional to the power radiated from the antenna in that direction
- Beam width (or half-power beam width)
  - Measure of directivity of antenna
- Reception pattern
  - Receiving antenna's equivalent to radiation pattern

Types of Antennas

- Theoretical reference antenna (isotropic radiator):
  - A point in space radiating with equal power in all directions
  - Points with equal power are located on a sphere with the antenna in the center
- Real antennas exhibit directive effects:
  - Types: omnidirectional (dipole) or directional (pencil beam)
  - Simplest antenna:
    - Dipole (or Hertzian dipole) of length $\lambda/4$ or $\lambda/2$
  - Directional antennas may be more useful:
    - To cover a highway, valley, satellite beam
  - Parabolic antenna
    - Beamwidth at 5m diameter is 0.35

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

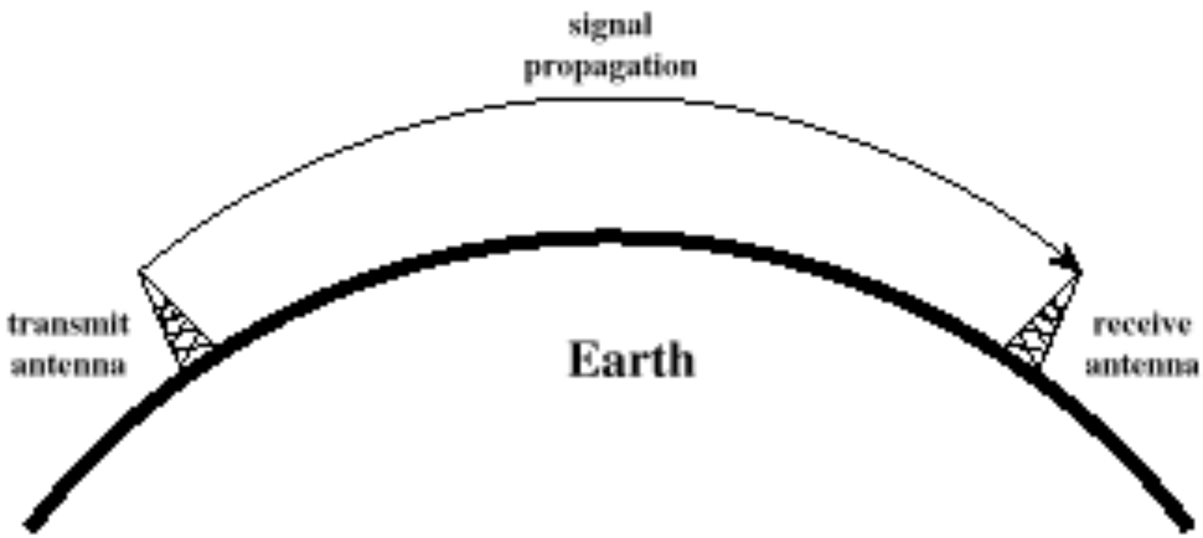
$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

  – Effective area:
    - Isotropic: $\lambda^2/(4\pi)$
    - Half-wave dipole: $1.64\lambda^2/(4\pi)$
        – power gain vs. istropic 1.64
    - Parabolic: 0.56 A where A is the face area
        – power gain vs. istropic $7A/\lambda^2$
        – E.g., Parabolic antenna of diameter 2m @ 12GHz => *Ae*? *G*?
        – > G = 35.186 = 45.46 dB

Propagation Modes

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

Ground Wave Propagation



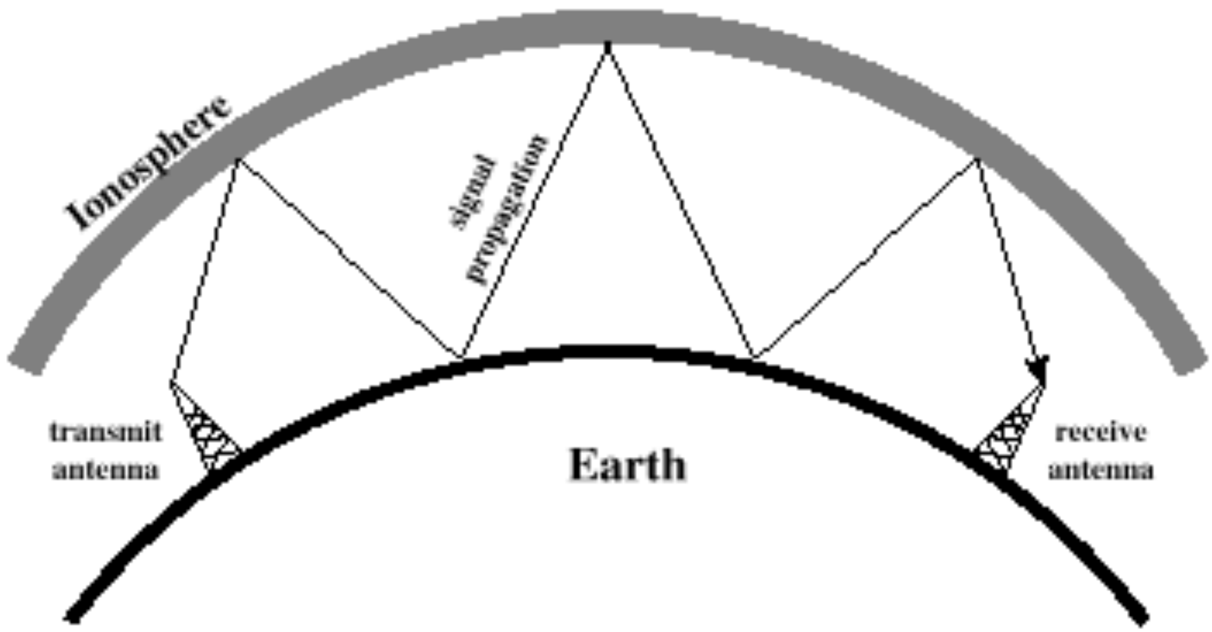
Reasons:

- Induced currents slows the wavefront
- Diffraction

Ground Wave Propagation

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

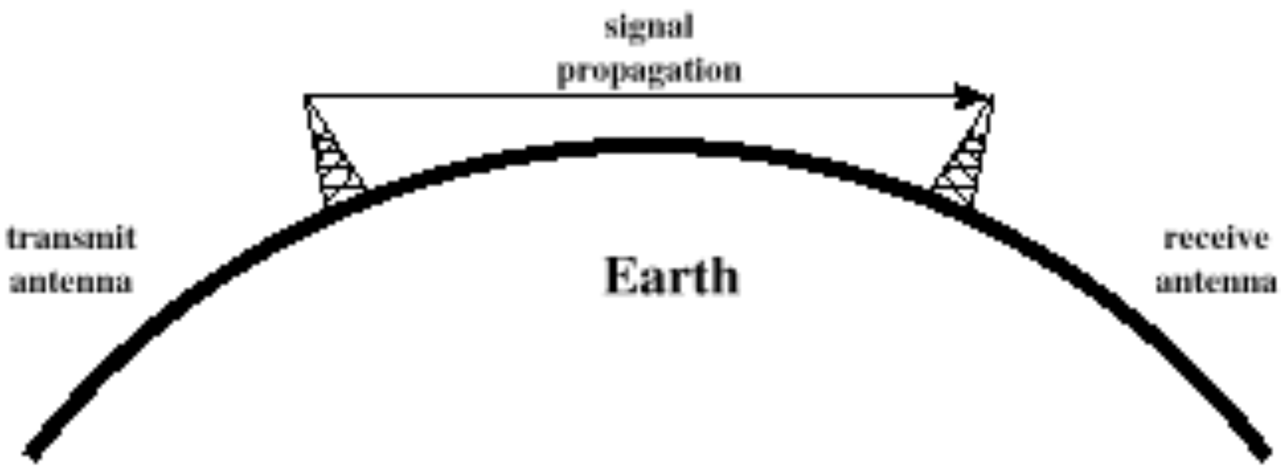
Sky Wave Propagation



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
- Works below 30 MHz

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 (earth diameter 12734 Km)

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

- 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
- Example:
  - – h1 = 100m, h2 = 0 => 41km
  - – If h2 = 10m => h1 = 46.2m

LOS Wireless Transmission Impairments

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

Attenuation (Pathloss)

- 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)
- What is the loss (dB) when distance is doubled?

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 Kelvin (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

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

E.g., T = 290K, N_0= 4 10^{-21}W/H = -204dbW/H

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

$$\frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S}{\mathrm{k}TR}$$

- 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

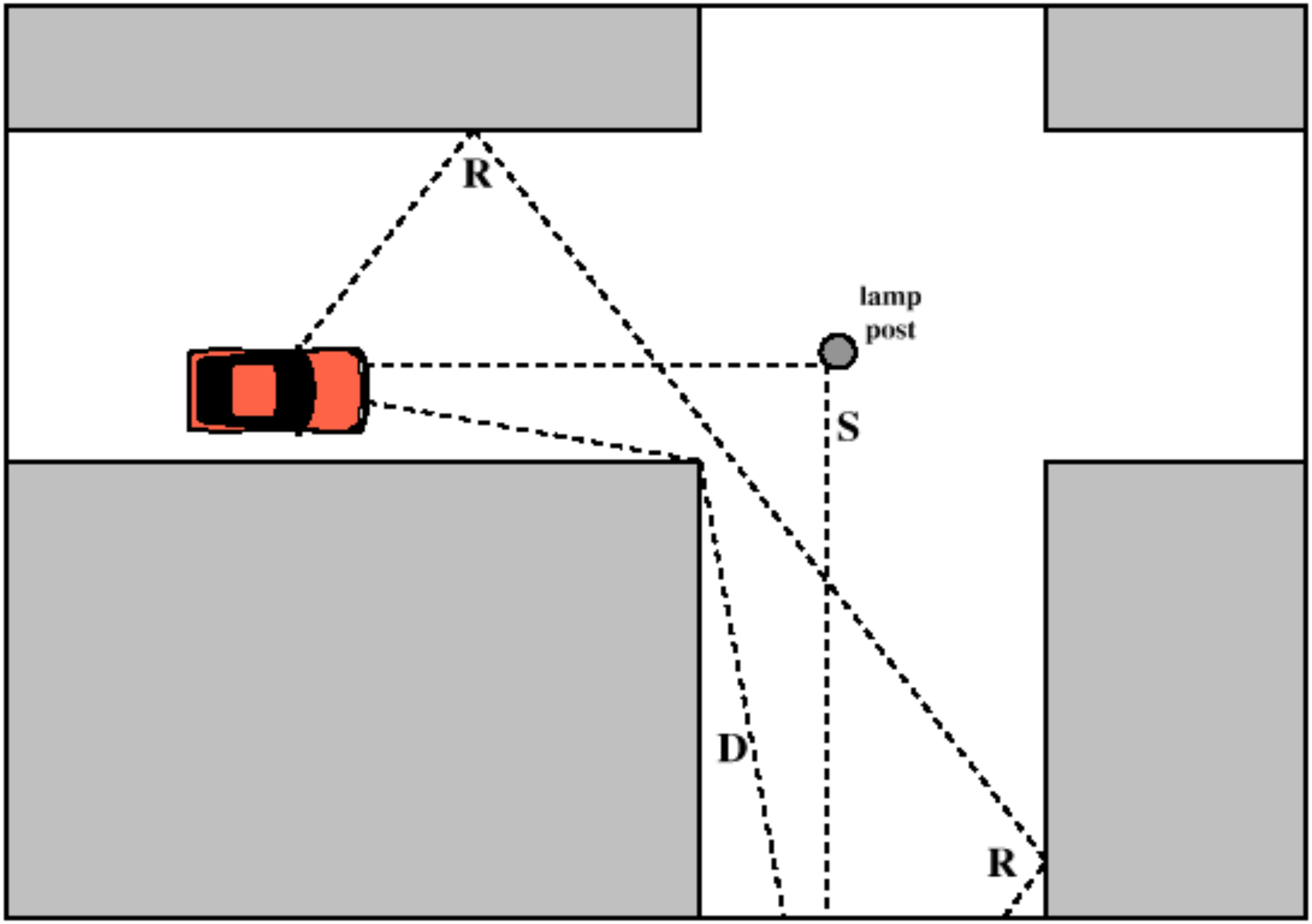


Figure 5.10 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

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
- Channels:
  - Additive White Gaussian Noise (AWGN)
  - Rayleigh fading (due to multipath, no LOS)
  - Rician fading (LOS + Rayleigh fading)

Radio Propagation

- Large scale path loss + small-scale fading
- Large scale path loss
  - Outdoor propagation
    - Long distance
    - Takes into account terrain profile (e.g., mountains, hills, large buildings, etc.)
  - Indoor propagation (inside buildings)
    - Distances covered are much smaller and the environment is more variable
    - Increasing interest due to PCS and WLAN
    - Classified as line-of-sight (LOS) or obstructed (OBS)
- Small-scale fading: multi-path

Path Loss Models

- Log-distance path loss model: average path loss

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0})$$

Environment	Path Loss Exponent n
Free space	**2**
Urban area PCS	**2.7 to 3.5**
Shadowed urban PCS	**3 to 5**
In building LOS	**1.6 to 1.8**
Obstructed in building	**4 to 6**
Obstructed in factories	**2 to 3**

- Log-normal shadowing (signal level at a specific distance have Gaussian distribution)

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma \qquad \Pr(X_\sigma > x) = \frac{1}{\sigma 2\pi}\int_x^\infty e^{\frac{-u^2}{2\sigma^2}} du$$

Path Loss Models of Outdoor

- Okumura-Hata empirical model:
  - Valid for *f* from 150MHz to 1500 MHz. For urban area:

$$L_u = 69.55 + 26.16\log f - 13.82\log h_b - A(h_m) + (44.9 - 6.55\log h_b)\log d$$

  - f: freq, h_b: BS height, h_m: mobile height, d: BS-MS distance
  - For a small to medium sized city:

$$A(h_m) = (1.1\log f - 0.7)h_m - (1.56\log f - 0.8)$$

  - For a large city:

$$A(h_m) = 8.29(\log 1.54 h_m)^2 - 1.1 \quad f\,or - f \le 300MHz$$

$$A(h_m) = 3.2(\log 11.75 h_m)^2 - 4.97 \quad f\,or - f \ge 300MHz$$

  - For suburban area:

$$L_{su} = L_u - 2\left[\log\frac{f}{28}\right]^2 - 5.4$$

  - For rural area:

$$L_{ru} = L_u - 4.78[\log f]^2 - 18.33\log f - 40.94$$

Other Path Loss Models

- Euro-COST Extension of Okumura-Hata to PCS (f>1500MHz):

$$L_u = 46.3 + 33.9\log f - 13.82\log h_b - A(h_m) + (44.9 - 6.55\log h_b)\log d + C_M$$

  - C_M = 0dB (medium and suburban), 3dB (metropolitan)
- Walfish and Bertoni Model
  - Integrates effect of diffraction on rooftops

Path Loss Models for Indoor

- Partition losses (same floor with soft or hard partitions)
  - Uses estimation of path loss for each material at working frequency
- Partition losses between floors
  - Uses estimates of path loss
- Ericsson Multiple breakpoint model:
  - 4 breakpoints, range of path-loss: $[PL_{min}, PL_{max}]$
- Log-distance path loss:
  - $PL(dB) = PL(d_0) + 10\, n \log(d/d_0) + X_\sigma$
  - n depend on surrounding environment, X_σ is a normal random variable with standard deviation σ
- Attenuation factor model (average path loss): SF: single floor, FAF: floor attenuation factor, MF: multiple floor
  - $PL(dB) = PL(d_0) + 10\, n_{SF} \log(d/d_0) + FAF\ (dB) = PL(d_0) + 10\, n_{MF} \log(d/d_0)$
- Buildings penetration: depends on building height, number of windows, etc.
- Ray tracing using Geographical Information System (GIS) databases

Small Scale Fading Models

- Multi-path fading:
  - Multiple reflections from various objects: multiple path => multiple phase shifts
  - Signal strength may vary by as much as 30-40dB in hostile environments when the receiver moves by only a fraction of λ
  - Main effects:
    - Rapid change in signal strength over a small travel distance
    - Random frequency modulation due to varying Doppler shifts on different multi-path signals
    - Time dispersion (echoes) caused by multipath propagation

Small Scale Fading (Cont'd)

- Factors:
  - Multipath propagation: multiple version of the signal with different shifts that may add or subtract
  - Speed of the mobile: the relative speed between the mobile and BS results in random frequency modulation due to different incidence angles of paths
  - Speed of surrounding objects
  - Transmission bandwidth of the signal versus channel bandwidth (coherence bandwidth)
- Characteristics:
  - Long-term fading x short-term fading: $s(t) = m(t)r(t)$

Fading Statistics

- Doppler shift: $f_d = (v/\lambda) \cos \theta$
  - θ is the angle between the radio wave propagation axis and the mobile trajectory
- Level crossing rate (LCR):
  - Average number of times per second that the signal envelope crosses the level in a positive direction
- LCR and level crossing duration are important for estimating fading rate and duration => designing error control codes:
  - $\rho = R$(Specified level)/R_{rms} ; f_m: max Doppler shift

=>

  - Average fade duration: $$\tau = \frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}}$$

$$N_T = \sqrt{2\pi} f_m \rho e^{-\rho^2}$$

Bit Error Rate

- Bit Error Rate (BER): rate of bit errors
- Estimating the BER is very important: it determines the packet loss (Frame Error Rate: FER)
- Bit Error Rate is a function of the received energy per bit
- Estimating path loss statistics allows to estimate the BER
- Shannon's Theorem (AWGN):
  - A channel with a given SNR has maximum capacity: $C = W \log(1 + SNR)$
  - There exist a coding scheme that allows to achieve the channel capacity

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