Wireless Communications

Lecture 3

Mobile Propagation Models
Large-Scale Path Loss

Basics

- When electrons move, they create electromagnetic waves that can propagate through the space
- Number of oscillations per second of an electromagnetic wave is called its frequency, f, measured in Hertz.
- The distance between two consecutive maxima is called the wavelength, designated by λ.

Basics

- By attaching an antenna of the appropriate size to an electrical circuit, the electromagnetic waves can be broadcast efficiently and received by a receiver some distance away.
- In vacuum, all electromagnetic waves travel at the speed of light: $c = 3\times10^8$ m/sec.
- In copper or fiber the speed slows down to about 2/3 of this value.
- Relation between f, λ , c: $\lambda f = c$

Basics

- We have seen earlier the electromagnetic spectrum.
- The radio, microwave, infrared, and visible light portions of the spectrum can all be used to transmit information
  - By modulating the amplitude, frequency, or phase of the waves.

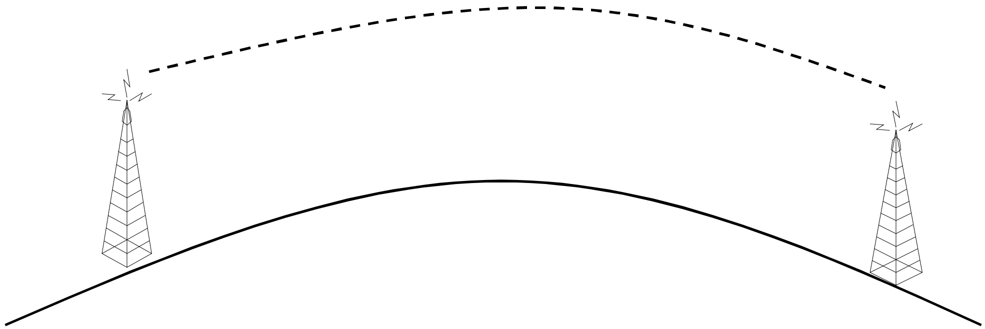
Basics

- We have seen wireless channel concept earlier: it is characterized by a frequency band (called its bandwidth)
- The amount of information a wireless channel can carry is related to its bandwidth
- Most wireless transmission use narrow frequency band ($\Delta f << f$)
    - Δf: frequency band
    - f: middle frequency where transmission occurs
- New technologies use spread spectrum techniques
    - A wider frequency band is used for transmission

Basics - Propagation

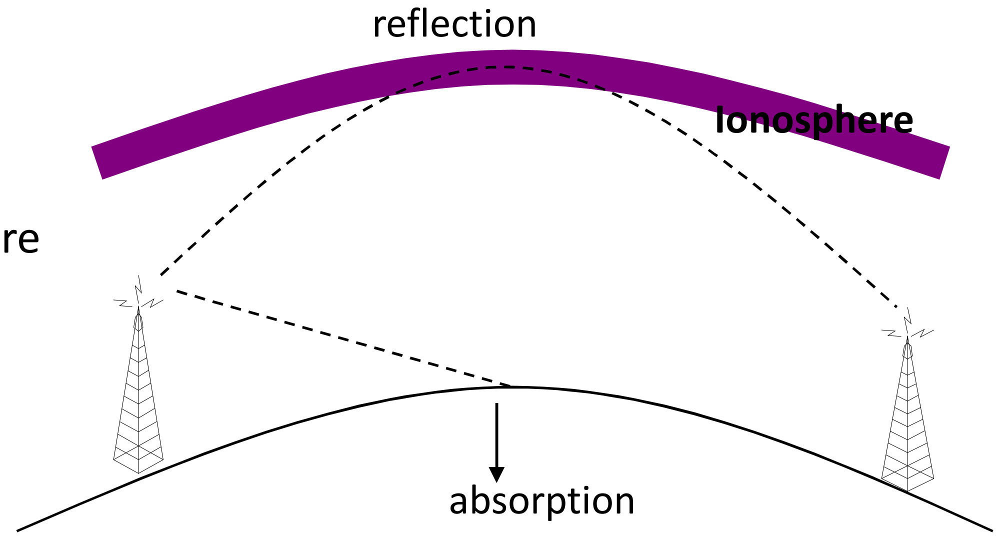
- Radio waves are
  - Easy to generate
  - Can travel long distances
  - Can penetrate buildings
  - They are both used for indoor and outdoor communication
  - They are omni-directional: can travel in all directions
  - They can be narrowly focused at high frequencies (greater than 100MHz) using parabolic antennas (like satellite dishes)
  - Properties of radio waves are frequency dependent
    - » At low frequencies, they pass through obstacles well, but the power falls off sharply with distance from source
    - » At high frequencies, they tend to travel in straight lines and bounce of obstacles (they can also be absorbed by rain)
    - » They are subject to interference from other radio wave sources

Basics - Propagation



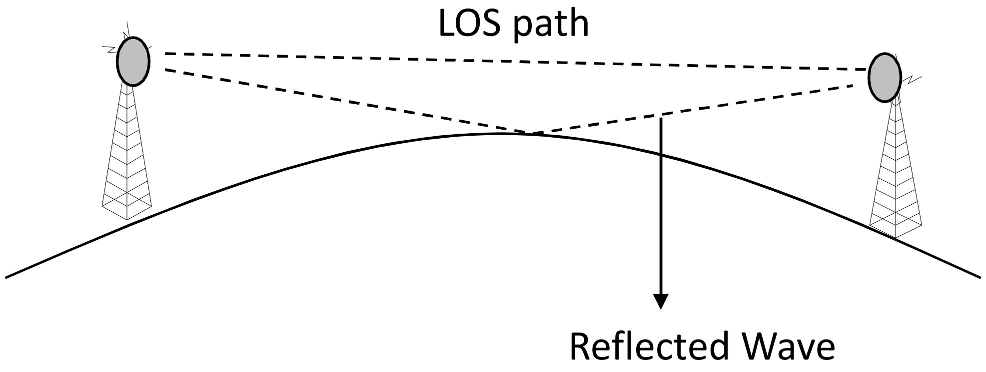
At **VLF, LF, and MF** bands, radio waves follow the ground. AM radio broadcasting uses MF band

At **HF** bands, the ground waves tend to be absorbed by the earth. The waves that reach ionosphere (100-500km above earth surface), are refracted and sent back to earth.



Basics - Propagation

VHF Transmission



-**Directional antennas are used**
-**Waves follow more direct paths**
- LOS: Line-of-Sight Communication
- Reflected wave interfere with the original signal

Basics - Propagation

- Waves behave more like light at higher frequencies
    - Difficulty in passing obstacles
    - More direct paths
- They behave more like radio at lower frequencies
    - Can pass obstacles

What is Decibel (dB)

- What is dB (decibel):
  - A logarithmic unit that is used to describe a ratio.
    - Let say we have two values P1 and P2. The difference (ratio) between them can be expressed in dB and is computed as follows:
      - 10 log (P1/P2) dB
    - Example: transmit power P1 = 100W,
      received power P2 = 1 W
        - » The difference is 10log(100/1) = <u>20dB</u>.

dB

- dB unit can describe very big ratios with numbers of modest size.
  - See some examples:
    - Tx power = 100W, Received power = 1W
      - Tx power is 100 times of received power
      - Difference is 20dB
    - Tx power = 100W, Received power = 1mW
      - Tx power is 100,000 times of received power
      - Difference is 50dB
    - Tx power = 1000W, Received power = 1mW
      - Tx power is million times of received power
      - Difference is 60dB

dBm

- For power differences, dBm is used to denote a power level with respect to 1mW as the reference power level.
    - Let say Tx power of a system is 100W.
    - Question: What is the Tx power in unit of dBm?
    - Answer:
        - Tx_power(dBm) = 10log(100W/1mW) = 10log(100W/0.001W) = 10log(100,0000) = <u>50dBm</u>

dBW

- For power differences, dBW is used to denote a power level with respect to 1W as the reference power level.
    - Let say Tx power of a system is 100W.
    - Question: What is the Tx power in unit of dBW?
    - Answer:
        - Tx_power(dBW) = 10log(100W/1W) = 10log(100) = <u>20dBW</u>.

Wireless Issues

- Problems Unique to **Wireless** (not wired) systems:
  - Interference from other service providers
    - Out-of-band non-linear Tx emissions
  - Interference from other users (same network)
    - CCI due to frequency reuse
    - ACI due to Tx/Rx design limitations & large # users sharing finite BW
  - Shadowing
    - Line of Sight (LOS) obstructions cause areas of weak RSS
  - Fading
    - Multipath reflections cause destructive interference @ Rx
    - Mobile Rx in motion influences rate of fading

Wireless Issues

** Mobile Radio Channel (MRC) has unique problems that limit performance of wireless systems ***

- Wired Channel → stationary & predictable
- Wireless Channel → random & unpredictable
    - Must be characterized in a statistical fashion
    - Field measurements often needed to characterize radio channel performance

Radio Signal Propagation

- Two basic goals of propagation modeling:

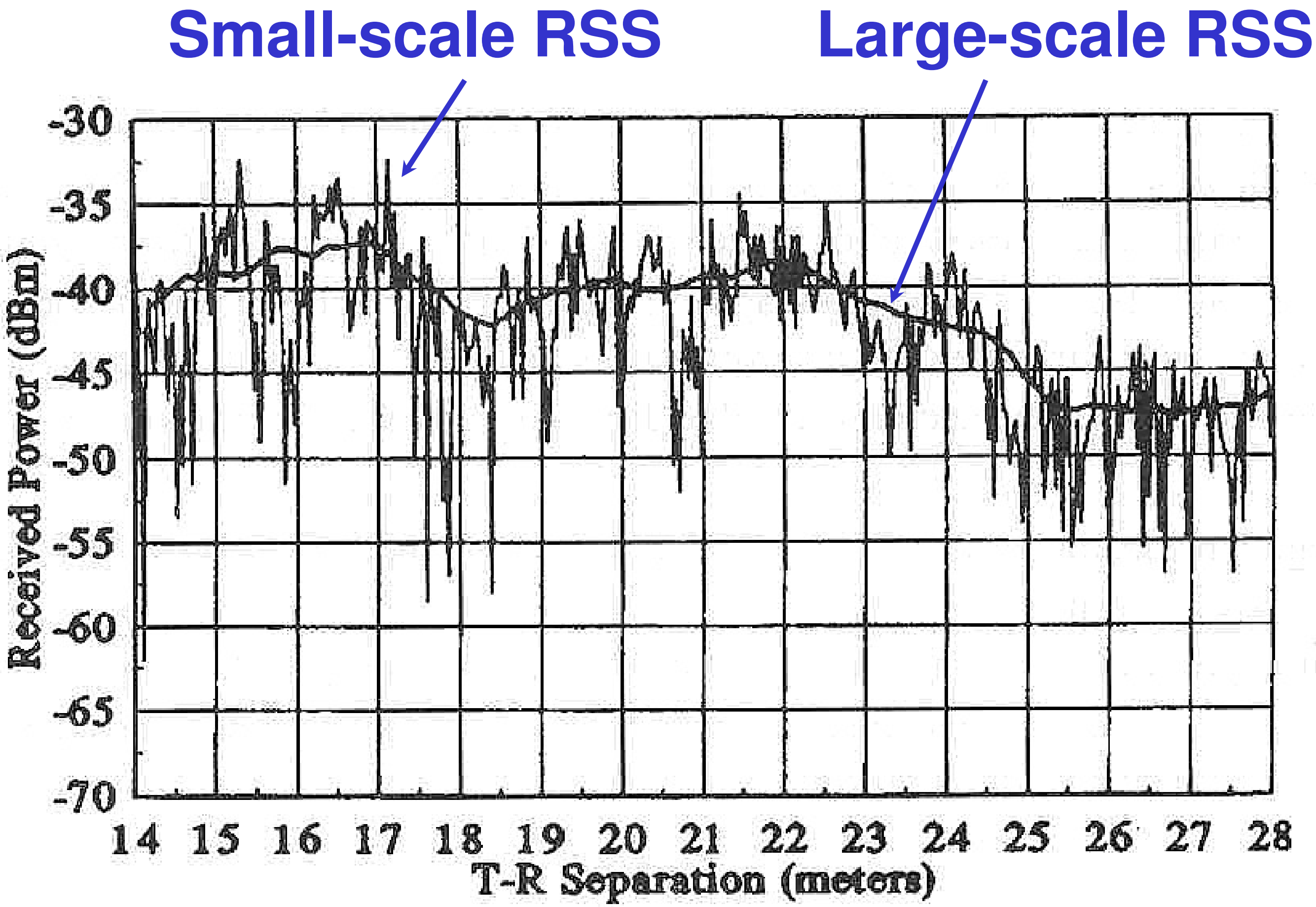
  1) Predict magnitude and rate (speed) of RSS fluctuations over short distances and/or time durations

  - "Short" → typically a few λ or seconds!!
  - RSS can vary by 30 to 40 dB!!
  - **Small-scale** RSS fluctuations → **fading** (next chapter)

  2) Predict **average** RSS for given Tx/Rx separation

  - Characterize RSS over distances from 20 m to 20 km
  - **Large-scale** models
  - Needed to estimate coverage area of base station

Radio Signal Propagation


Small-scale RSS

Large-scale RSS

Radio Signal Propagation

- Wireless Link
  - Line of Sight (LOS)
  - Obstructed (OBS)
- Basic Propagation Mechanisms
  - Free space
  - Reflection
  - Diffraction
  - Scattering

Radio Signal Propagation

- Free-Space Signal Propagation
  - Clear & unobstructed LOS path → satellite and fixed microwave
  - Friis transmission formula → Rx power (P_r) vs. Tx-Rx separation (d)

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

where P_t = Tx power (W)

G = Tx or Rx antenna gain (unitless)

→ relative to isotropic source

→ far-field of antenna

λ = wavelength = c/f (m)

L = system losses (antennas, T.L., atmosphere, etc.)

→ unitless

→ $L = 1$ for zero loss

Large Scale Path Loss

- **Free-Space** Path Loss (PL) in dB:

$$\boxed{PL(dB) = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right)}$$

  - d^2 → power law relationship
    - » P_r decreases at rate of 20 dB/decade
    - » e.g. P_r is 20 dB smaller @ 1 km vs. 100 m

Large Scale Path Loss

- Close in reference point (d_o) used in large-scale models

$$P_r(d) = P_r(d_o)\left(\frac{d_o}{d}\right)^2 \quad \text{for} \quad d > d_o > d_f$$

where d_f: far-field distance of antenna = $2D^2/\lambda$

D: largest linear dimension of antenna

d_o: typically 100 m for outdoor systems
and 1 m for indoor systems

Large Scale Path Loss

- Relating power to $\vec{E}$ field strength:

$$\boxed{P_r(d) = \left| \vec{E}(d) \right|^2 \left(\frac{A_e}{\eta_o} \right)}$$

where η_o : free-space wave impedance = 120π = 377 Ω

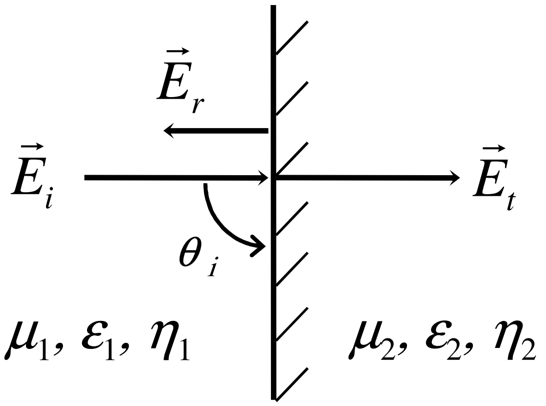
A_e : effective aperture of antenna = $G\lambda^2/4\pi$

Reflection

- Reflections → occur when RF energy incident upon boundary between two materials (e.g air/ground) with different electrical characteristics (μ, ε, σ)
- Reflecting surface must be **large** relative to λ of RF energy
- Reflecting surface must be **smooth** relative to λ of RF energy
  - "Specular" reflection
- Important reflecting surfaces for mobile radio:
  - Earth (ground)
  - Concrete streets
  - Buildings
  - Walls/windows
  - Water (lakes, rivers, etc.)

Reflection

- Fresnel reflection coefficient → Γ
  - Describes magnitude of **reflected** RF energy
  - Depends upon material properties, polarization, & angle of incidence
- Consider boundary between two materials:



$\vec{E}_i$: incident field
$\vec{E}_r$: reflected field
$\vec{E}_t$: transmitted field
θ_i : angle of incidence = 90°

Snell's Law → $\theta_i = \theta_r$

$$\left|\vec{E}_r\right| = \Gamma\left|\vec{E}_i\right| \quad \text{and} \quad \left|\vec{E}_t\right| = (1+\Gamma)\left|\vec{E}_i\right|$$

Reflection

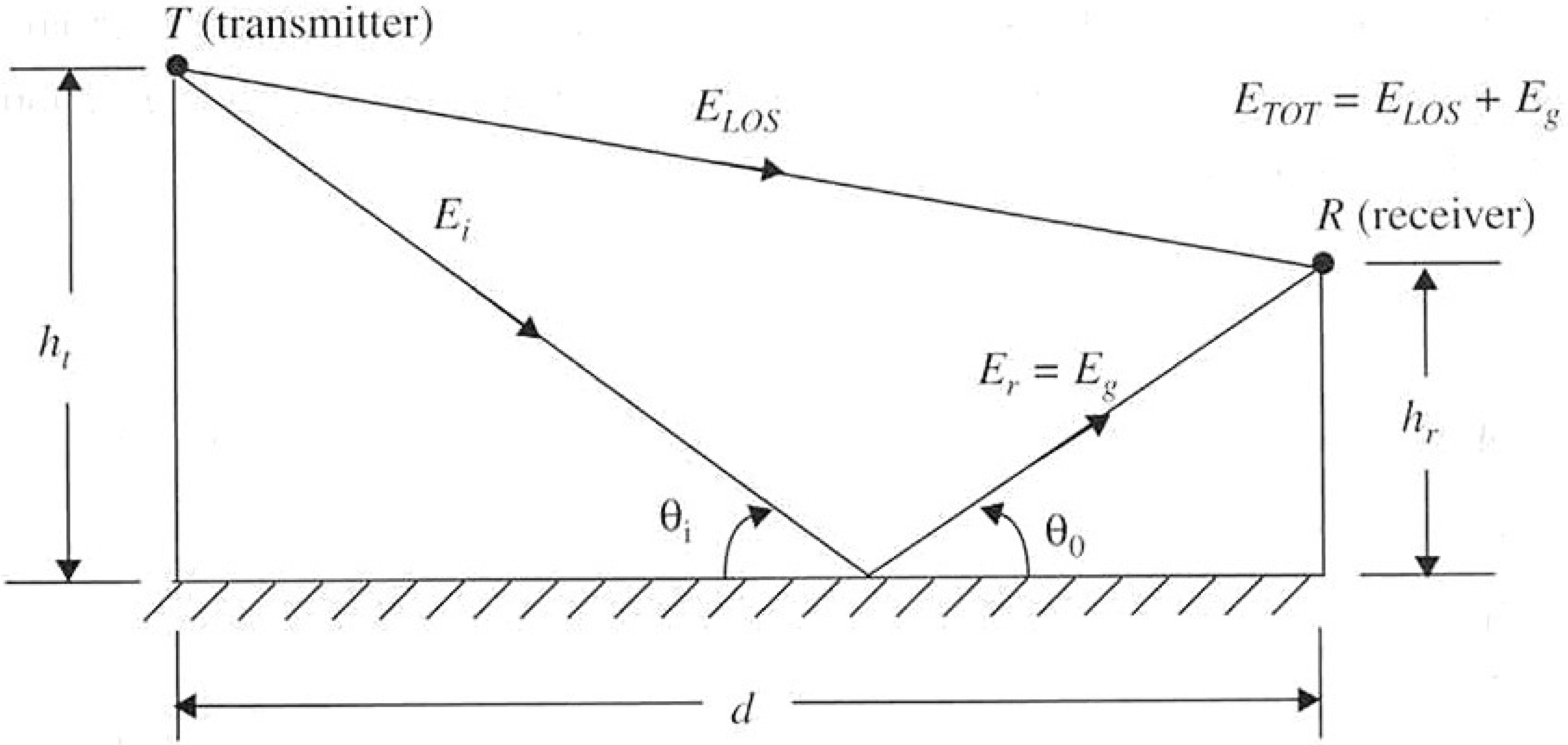
- Fresnel Reflection Coefficient → $\Gamma = \dfrac{\eta_2 - \eta_1}{\eta_1 + \eta_2}$
  - η = wave impedance = $\sqrt{\mu / \varepsilon}$
  - Γ is a measure of the **discontinuity** between material properties
  - For free space :
    - » $\varepsilon = \varepsilon_o = 8.85 \cdot 10^{-12}$ F/m & $\mu = \mu_o = 4\pi \cdot 10^{-7}$ H/m
    - » $\eta = \eta_o = \sqrt{\mu_o / \varepsilon_o} = 377\ \Omega$
  - For most materials $\mu \approx \mu_o$ so that Γ depends largely on dielectric constant ε
  - $\varepsilon = \varepsilon_o\, \varepsilon_r + j\, \varepsilon'$ where
    - » ε_r : relative dielectric constant
    - » ε' : imaginary component

Reflection

- Imaginary component, ε′, of dielectric constant
  - ε′ = 0 for “lossless” dielectric
  - ε′ ≠ 0 for “lossy” dielectric → transmitted energy undergoes attenuation due to absorption
    - » Important for quantifying signal penetration thru walls/floors and into buildings
- General Γ formulas 4.19–4.20 take into account polarization and angle of incidience (θ_i)
  - **For small θ_i → | Γ | approaches 1 → ≈ total reflection**
  - For conductors (metals) → | Γ | = 1

Ground Reflection

Fig. 4.7, pg. 121



Ground Reflection Model

◆ Ground Reflection (2-Ray) Model

- $\vec{E}_{TOT}$ results from **combination** of direct LOS path and ground reflected path
- $\vec{E}_{TOT} = \vec{E}_{LOS} + \vec{E}_g$
- Let E_o be $|\vec{E}|$ at reference point d_o then

$$\vec{E}(d,t) = \left(\frac{E_o d_o}{d}\right) \cos[\omega_c (t - d/c)] \quad \text{(V/m)} \quad \text{for} \quad d > d_o$$

- Let direct path → $d = d'$ and reflected path → $d = d''$ then

$$\vec{E}_{TOT}(d,t) = \left(\frac{E_o d_o}{d'}\right) \cos[\omega_c (t - d'/c)] \; + \; \Gamma \left(\frac{E_o d_o}{d''}\right) \cos[\omega_c (t - d''/c)]$$

Ground Reflection Model

- Let direct path → $d = d'$ and reflected path → $d = d''$ then

$$\vec{E}_{TOT}(d,t) = \left(\frac{E_o d_o}{d'}\right)\cos[\omega_c(t - d'/c)] \quad + \quad \Gamma\left(\frac{E_o d_o}{d''}\right)\cos[\omega_c(t - d''/c)]$$

- For large Tx–Rx separation : $\theta_i \rightarrow 0$ and $\Gamma = -1$
- **Constructive/destructive interference** can occur depending on phase difference between direct and reflected *E* fields
- **Phase difference** θ_Δ due to **path length difference**, $\Delta = d'' - d'$, between $\vec{E}_{LOS}$ and $\vec{E}_g$!!

Ground Reflection Model

- For $d >> \sqrt{h_t h_r}$
  - $|\vec{E}_{TOT}(d)| = \frac{4\pi E_o d_o h_t h_r}{\lambda d^2}$ and
  - $P_r \approx \frac{P_t G_t G_r (h_t h_r)^2}{d^4}$
- d^4 vs. d^2 for free space !!
- $P_r \propto 1/d^4$ or **40 dB/decade**

Ground Reflection

- Two-ray path loss model:

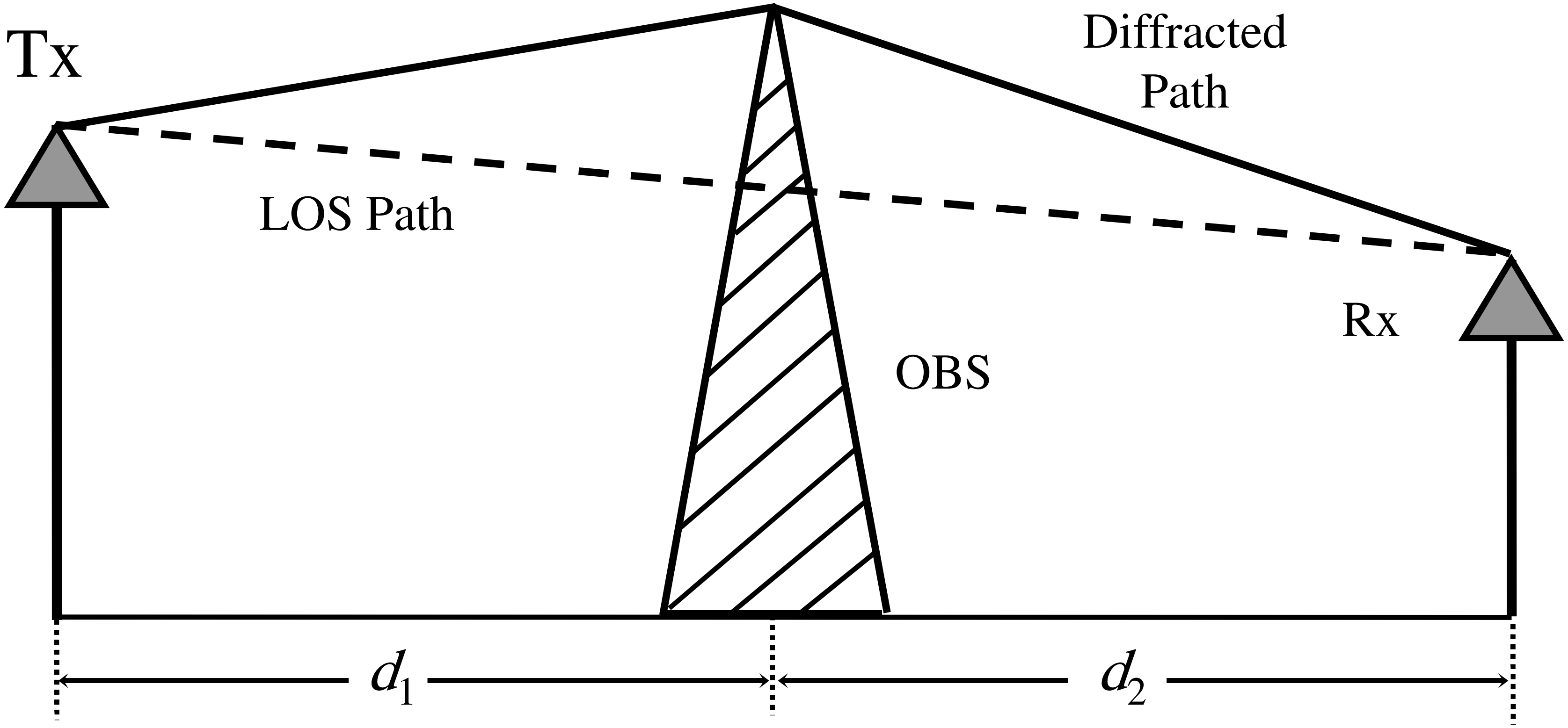
$$PL\,(\text{dB}) = 40\log d - [10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r]$$

- For $\theta_\Delta = \pi = 180° \rightarrow d = 4\,h_t h_r / \lambda$
  - Vertical height difference between LOS & reflected path @ reflection point corresponds to first "Fresnel Zone"
    - » Fresnel zone clearance used to determine if path is LOS or obstructed for point-to-point microwave systems

Diffraction

- Fresnel Zones
  - Zones where phase difference between direct LOS path and diffracted path alternately provide constructive or destructive interference to total Rx signal
  - Diffraction loss occurs when EM energy from secondary waves is blocked by an obstruction → blockage from energy in Fresnel zones

Diffraction



Diffraction

- Fresnel Zone radius → $\boxed{R_n \approx \sqrt{\frac{n\lambda\, d_1 d_2}{d_1 + d_2}}}$

  where

  $n = 1, 2, 3 \ldots$ and

  $\theta_\Delta = \lambda/2, \lambda, 3\lambda/2 \ldots$ or

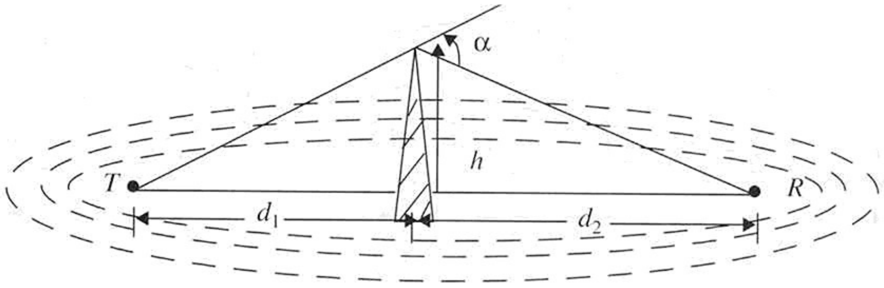
  $\theta_\Delta = \pi, 2\pi, 3\pi \ldots$

- If OBS does **NOT** block energy in 1st Fresnel zone then diffraction **loss** is negligible

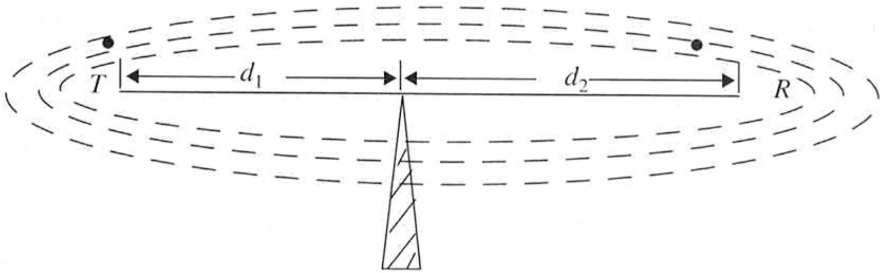
- LOS microwave links use 55% of R_1 as minimum clearance requirement

Fresnel Zone Clearance

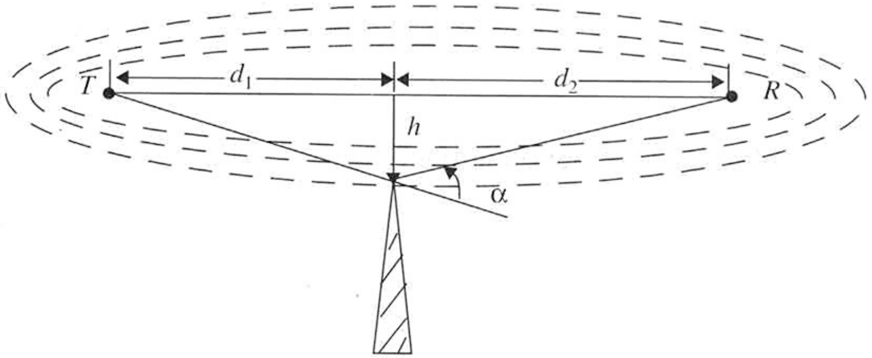
Fig. 4.12, pg. 130



(a) α and ν are positive, since h is positive



(b) α and ν are equal to zero, since h is equal to zero



(c) α and ν are negative, since h is negative

Figure 4.12 Illustration of Fresnel zones for different knife-edge diffraction scenarios.

Diffraction

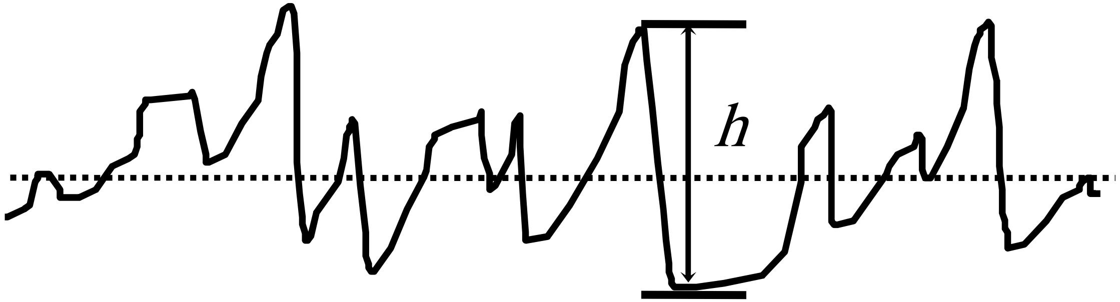
- ◆ Diffraction models
  - Predict signal attenuation caused by buildings and/or hilly terrain
  - Can’t provide exact estimates as physical situation is too complex to solve precisely
  - Signal power at any location also determined by **other** propagation mechanisms as well

Scattering

- RSS is often much **stronger** than that predicted by reflection/diffraction models
- EM wave incident upon rough or complex surface is **scattered** in **many** directions
  - Scattering caused by
    - Trees/bushes, lamp posts, towers, etc.
  - Flat surface → EM reflection (one direction)
  - Rough surface → EM scattering (many directions!)
  - In general → scattering is beneficial for mobile radio channel as it leads to stronger signals in OBS links

Scattering

- Rayleigh criteria for rough surface $h_c = \lambda / (8 \sin\theta_i)$



  - If $h < h_c$ → flat surface → reflection
  - If $h \geq h_c$ → rough surface → scattering

Path Loss Models

- Predict **average** large scale coverage using analytical and empirical (field data) methods
  - P_r @ Rx decreases **logarithmically** with distance
    - » 20 dB/decade for free space propagation
    - » 40 dB/decade for ground reflection model
  - $PL(d) = \left(\frac{d}{d_o}\right)^n$ where n : path loss exponent or
  - $\overline{PL}(dB) = PL(d_o) + 10\, n \log\left(\frac{d}{d_o}\right)$
    - » "bar" means **average** of many PL values at given value of d (Tx-Rx sep.)
    - » n depends on propagation environment

Path Loss Models

- Table 4.2, pg. 139 → “typical” values of n based on **measured** data

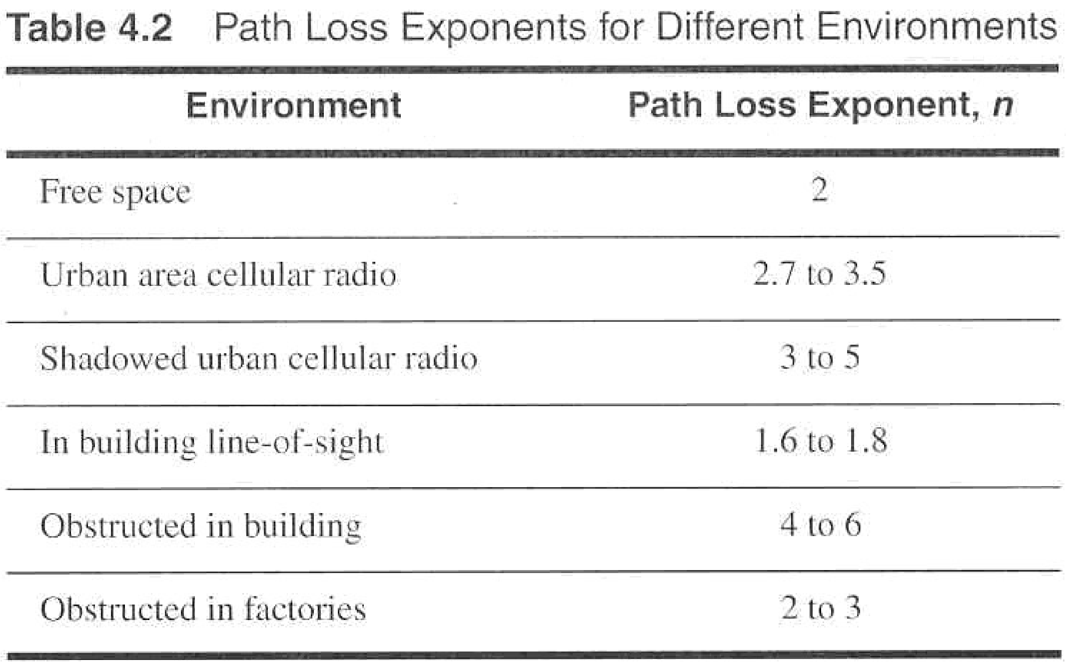


Table 4.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban 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

Shadowing

- Created via obstacles and tall buildings.
- Impacts different path profiles differently.
- Therefore, in general, their behavior can be explained using a random variable

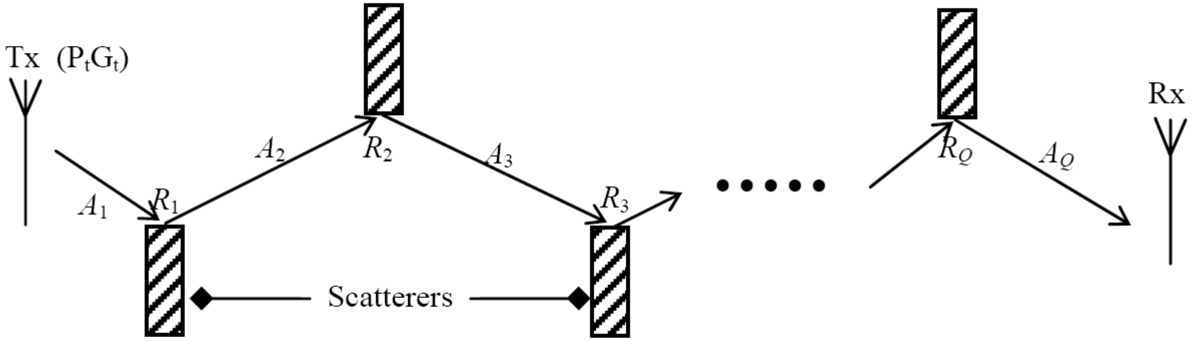


Figure 34: Path-loss due to shadowing.

Path Loss Models

- At any d the **measured** PL values vary drastically b/c of variations in surrounding environment
  - OBS vs. LOS, scattering, reflections, etc.
- Log-Normal Shadowing

$$\boxed{PL(dB) = PL(d_o) + 10\, n \log\left(\frac{d}{d_o}\right) + X_\sigma}$$

  - X_σ : zero mean Gaussian random variable (in dB) with SD = σ (dB)
  - Takes into account **random** RSS variations due to shadowing
  - Measurements verify this distribution
  - n & σ computed from measured data for different area types
  - Fig. 4.17, pg. 141

Path Loss Data

Best Fit Model

$n = 2.7$

$\sigma = 11.8$ dB

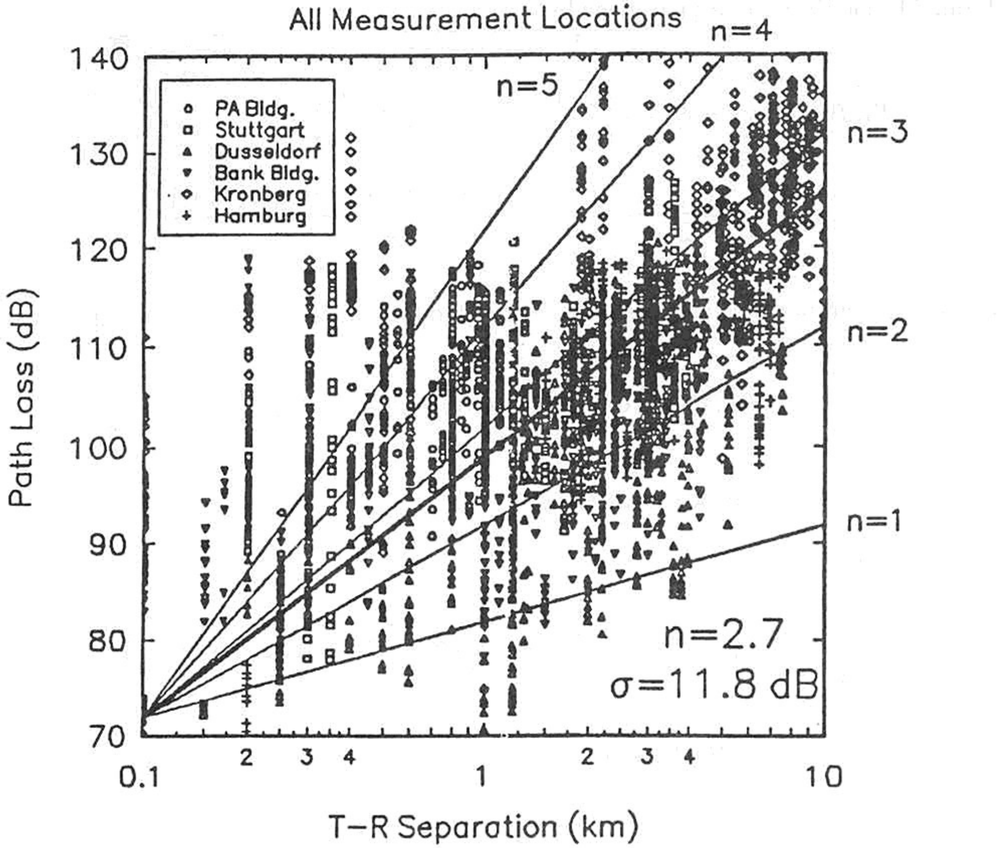


Figure 4.17 Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [from [Sei91] © IEEE].

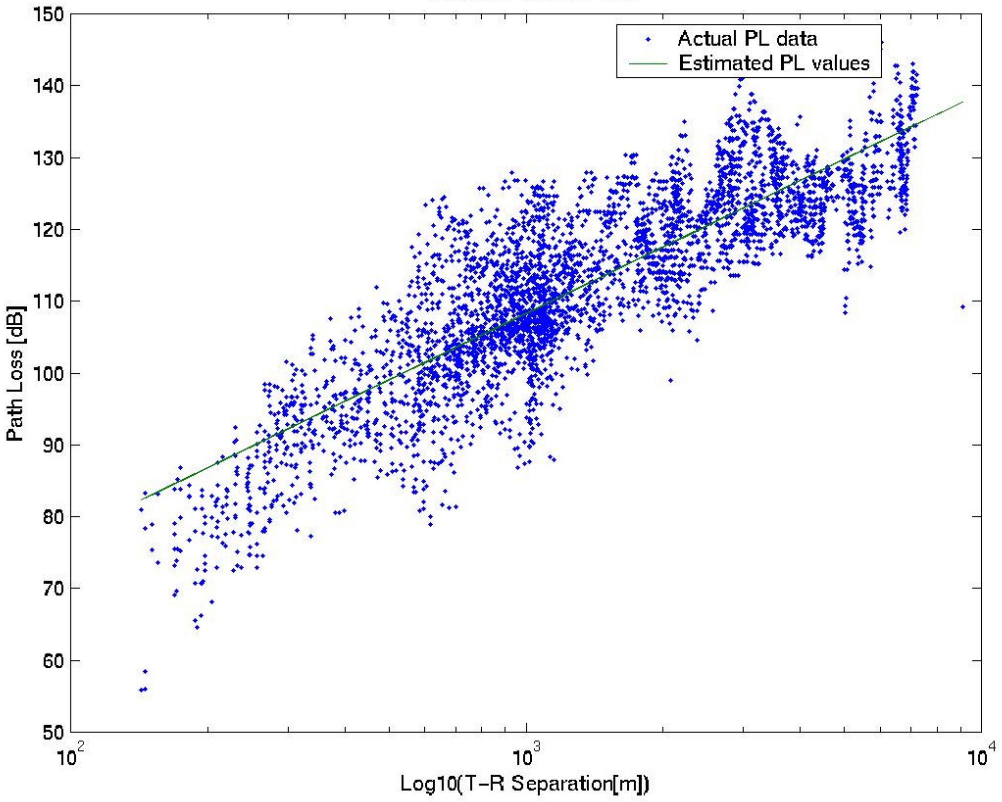
Path Loss Data

T-Mobile GSM Cell Kansas City, MO

Best Fit Model

$n = 3.1$

$\sigma = 7.0$ dB



Empirical Path Loss Models

- Best fit curves using extensive datasets of *PL* under variety of conditions
- Variables include frequency, distance, antenna heights, & various correction factors for terrain type

- Okumura Model
  - **urban** area prediction
  - f: 100 MHz to 2 GHz
  - d: 1 km to 100 km
  - widely used
  - simple and fairly accurate

Empirical Path Loss Models

- Hata Model
  - Based on Okumura with correction factors for city size & coverage area
  - Extended to include suburban and rural areas (unlike Okumura)
  - Valid for cell radius > 1 km
- Empircal *PL* models are OK but **NOT** as good as making actual field measurements

Outage Probability

◆ Outage Probability under Path Loss and Shadowing

- The probability that the received power at a given distance d, $P_r(d)$, falls below $P_{\min}$

$$P_{\text{out}}(P_{\min}, d) = p(P_r(d) < P_{\min})$$

$$\frac{P_r}{P_t} dB = 10\log_{10} K - 10n\log_{10}\frac{d}{d_0} - X_\sigma$$

$$p\left(P_r(d) \le P_{\min}\right) = 1 - Q\left(\frac{P_{\min} - \left(P_t + 10\log_{10} K - 10n\log_{10}(d/d_0)\right)}{\sigma_{X_{dB}}}\right)$$

Outage Probability

Example

- Find the outage probability at 150 m for a channel based on the combined path loss and shadowing model where the power received at 1 m is 21.54 dBm, $P_{\min} = -110.5$ dBm, n=3.71, and

$$\sigma_{X_{dB}} = 3.65dB$$

Cell Coverage