

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: $c = 3 \times 10^8$ 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.

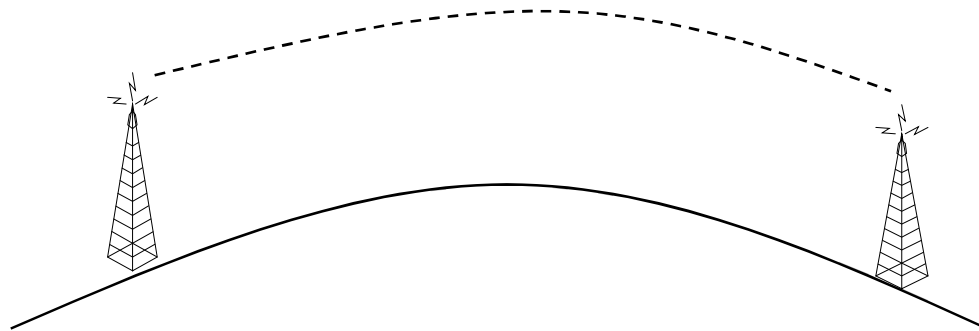
Basics

- 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 ($\Delta f \ll f$)
 - 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

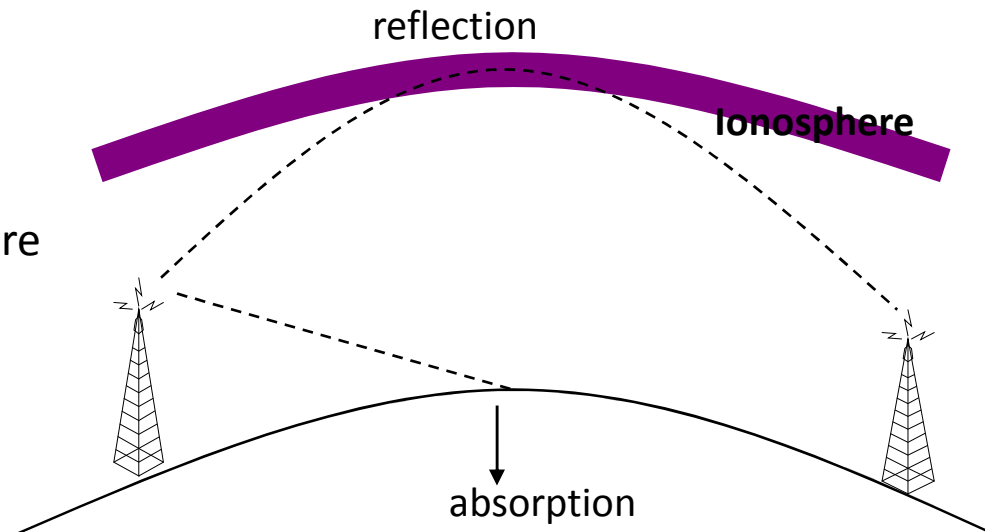
- Radio waves are
 - Easy to generate
 - Can travel long distances
 - Can penetrate buildings
 - They are both used for indoor and outdoor communication
 - They are omni-directional: can travel in all directions
 - They can be narrowly focused at high frequencies (greater than 100MHz) using parabolic 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 off obstacles (they can also be absorbed by rain)
 - » They are subject to interference from other radio wave sources

Basics - Propagation



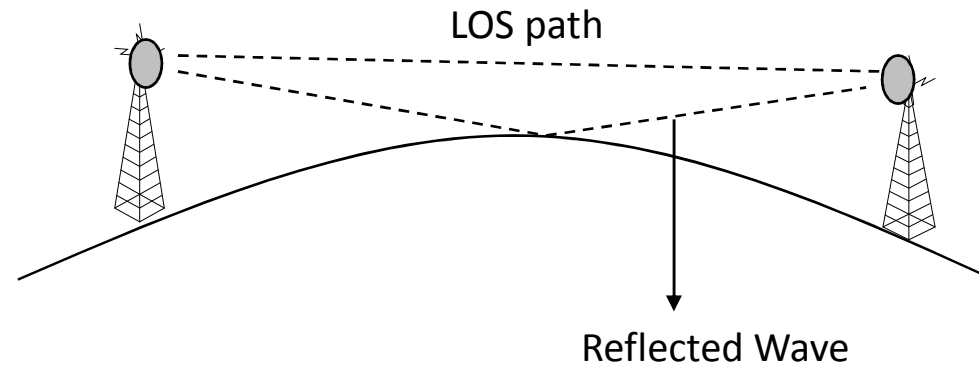
At **VLF, LF, and MF** bands, radio waves follow the ground. AM radio broadcasting uses MF band

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 $10\log(100/1) = \underline{20\text{dB}}$.

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:
 - $Tx_power(dBm) = 10\log(100W/1mW) = 10\log(100W/0.001W)$
 $= 10\log(100,000) = \underline{50dBm}$

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:
 - $\text{Tx_power(dBW)} = 10\log(100\text{W}/1\text{W}) = 10\log(100) = \underline{20\text{dBW}}$.

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
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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:

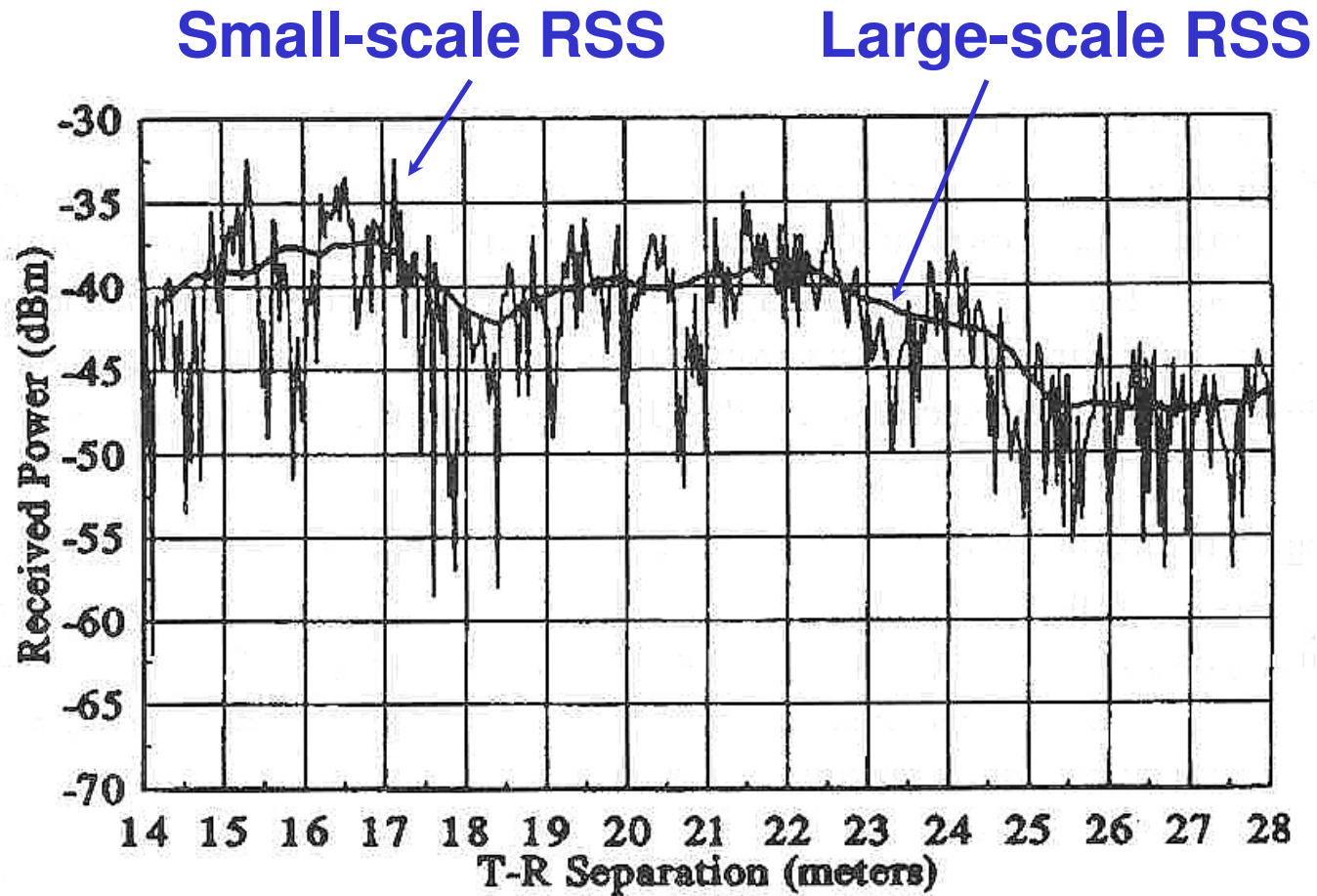
1) Predict magnitude and rate (speed) of RSS fluctuations over short distances and/or time durations

- “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
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Radio Signal Propagation



Radio Signal Propagation

◆ Wireless Link

- Line of Sight (LOS)
- Obstructed (OBS)

◆ Basic Propagation Mechanisms

- Free space
 - Reflection
 - Diffraction
 - Scattering
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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:

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

- $d^2 \rightarrow$ 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

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

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:

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

where η_o : free-space wave impedance = $120\pi = 377 \Omega$
 A_e : effective aperture of antenna = $G\lambda^2 / 4\pi$

Reflection

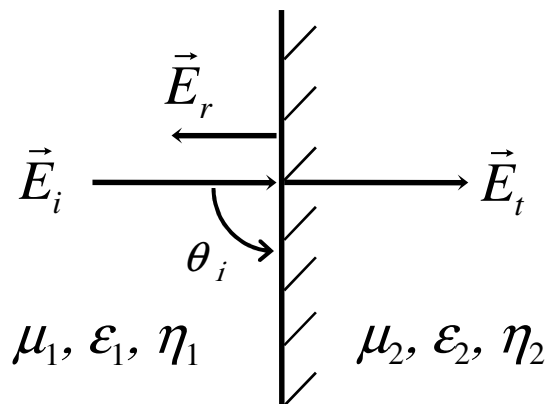
- ◆ Reflections → occur when RF energy incident upon boundary between two materials (e.g air/ground) with different electrical characteristics (μ , ϵ , σ)
 - ◆ Reflecting surface must be **large** relative to λ of RF energy
 - ◆ Reflecting surface must be **smooth** relative to λ of RF energy
 - “Specular”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

◆ Fresnel reflection coefficient $\rightarrow \Gamma$

- 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 $\rightarrow \theta_i = \theta_r$

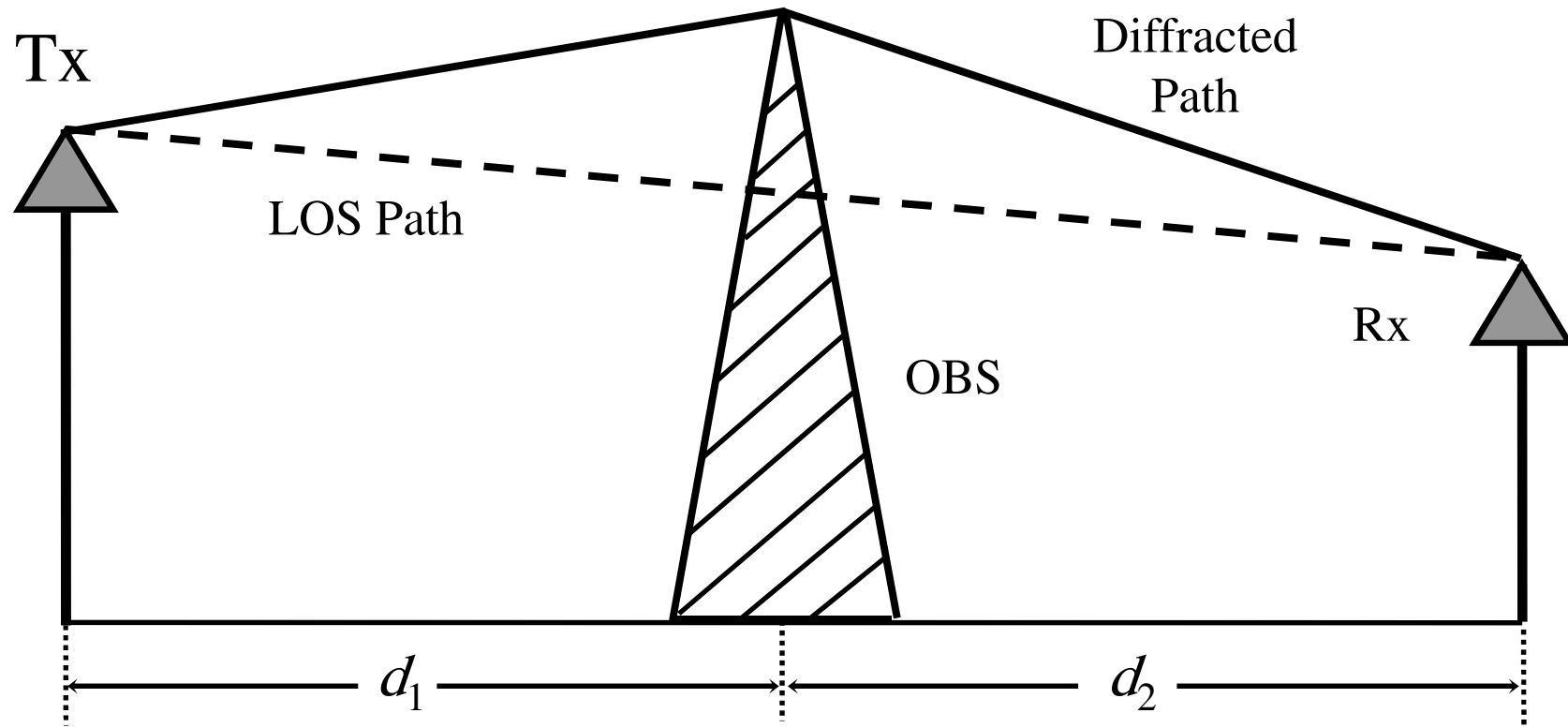
$$|\vec{E}_r| = \Gamma |\vec{E}_i| \quad \text{and} \quad |\vec{E}_t| = (1 + \Gamma) |\vec{E}_i|$$

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 →

$$R_n \approx \sqrt{\frac{n \lambda d_1 d_2}{d_1 + d_2}}$$

where

$$n = 1, 2, 3 \dots \text{ and}$$

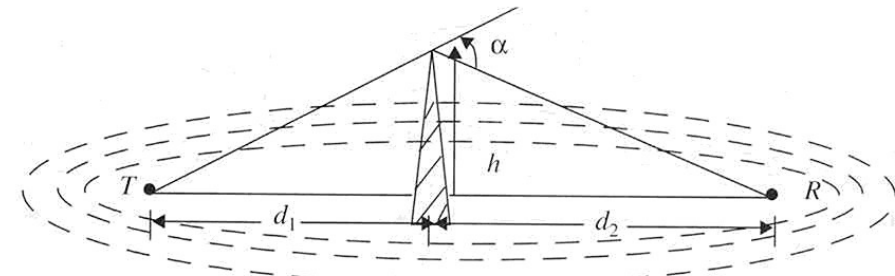
$$\theta_{\Delta} = \lambda/2, \lambda, 3\lambda/2 \dots \text{ or}$$

$$\theta_{\Delta} = \pi, 2\pi, 3\pi \dots$$

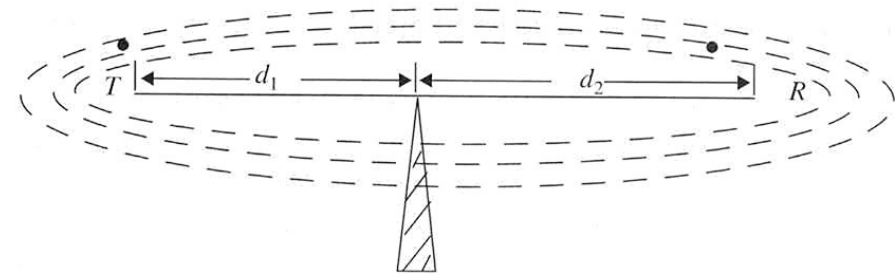
- ◆ If OBS does **NOT** block energy in 1st Fresnel zone then diffraction **loss** is negligible
 - ◆ LOS microwave links use 55% of R_1 as minimum clearance requirement
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Fresnel Zone Clearance

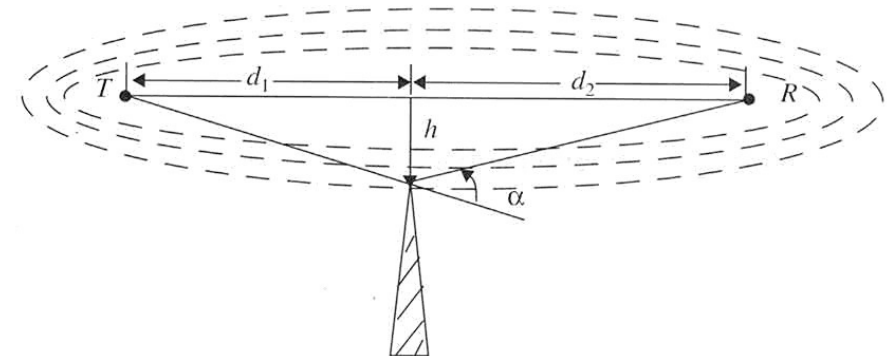
Fig. 4.12, pg. 130



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



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



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

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

Diffraction

◆ Diffraction models

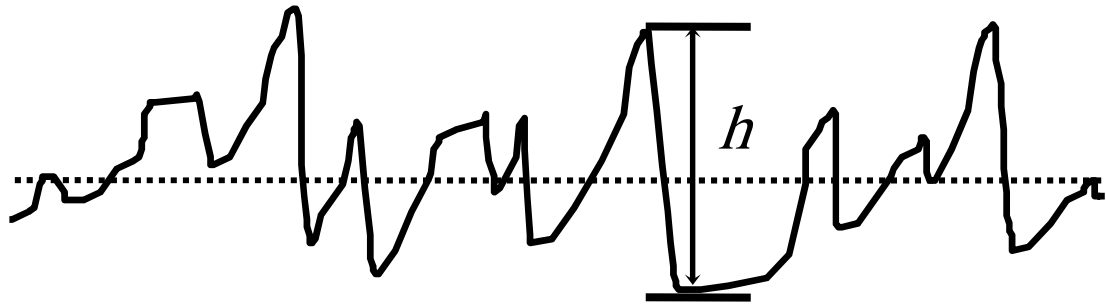
- Predict signal attenuation caused by buildings and/or hilly terrain
- Can't provide exact estimates as physical situation is too complex to solve precisely
- Signal power at any location also determined by other propagation mechanisms as well

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

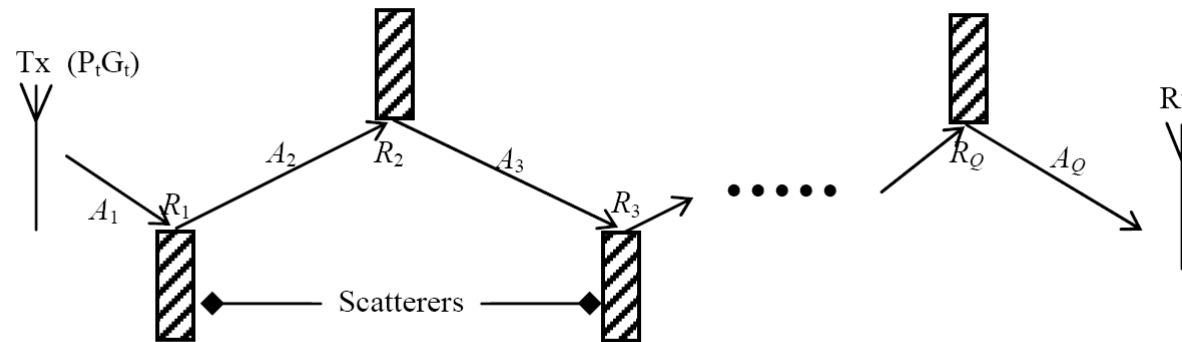


Figure 34: Path-loss due to shadowing.

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

- ◆ Empirical *PL* models are OK but **NOT** as good as making actual field measurements