Chapter 4

Propagation effects

Why channel modelling?

- The performance of a radio system is ultimately determined by the radio channel
- The channel models basis for
  - system design
  - algorithm design
  - antenna design etc.
- Trend towards more system interaction with channel

  - MINO (Multiple In Multiple Out)

  - UWB (Ultra Wide Band)

  - 4G

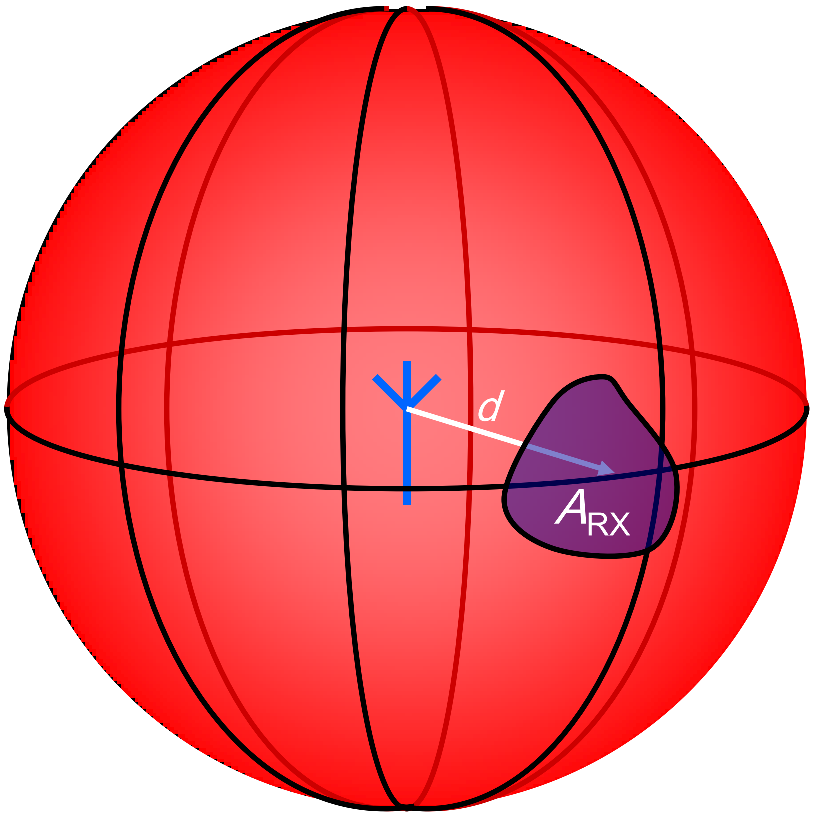
Without reliable channel models, it is hard to design radio systems that work in *real* environments.

THE RADIO CHANNEL
It is more than just a loss

- Some examples:
  - behavior in time/place?
  - behavior in frequency?
  - directional properties?
  - bandwidth dependency?
  - behavior in delay?

A major technical advance in wireless communications has been to utilize these channel problems to an advantage which can be implemented with the obvious assistance of computational horsepower, i.e., without computers it wouldn't have been possible.
If your handed lemons - make lemonade.

Free-space loss



If we assume RX antenna to be isotropic:

$$P_{RX} = \left(\frac{\lambda}{4\pi d} \right)^2 P_{TX}$$

Attenuation between two isotropic antennas in free space is (free-space loss):

$$L_{free}(d) = \left(\frac{4\pi d}{\lambda} \right)^2$$

LdB = 20 log f + 20 log d - 147.56 dB

{f in MHz, L in meters}

Free-space loss
Friis' law

Received power, with antenna gains G_{TX} and G_{RX}:

$$P_{RX}(d) = \frac{G_{RX} G_{TX}}{L_{free}(d)} P_{TX} = P_{TX} \left(\frac{\lambda}{4\pi d} \right)^2 G_{RX} G_{TX}$$

Inverse square relationship

Valid in the far field only

measurement point not near the transmitting antenna that is mathematically defined on the next slide - the Rayleigh Distance

$$P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{free|dB}(d) + G_{RX|dB}$$

$$= P_{TX|dB} + G_{TX|dB} - 10 \log_{10} \left(\frac{4\pi d}{\lambda} \right)^2 + G_{RX|dB}$$

recast as a log relationship (db) or Eq 4.7

if Gains dropped from equation

this leaves the free space loss factor (..)^2, the path loss $P_{RX}/P_{TX} = P_{out}/P_{in}$

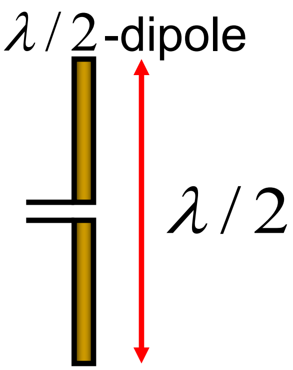
Free-space loss
What is far field?

Rayleigh distance:

$$d_R = \frac{2L_a^{\ 2}}{\lambda}$$

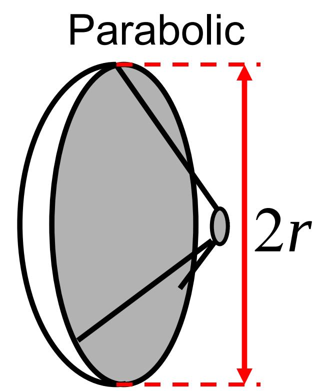
where L_a is the largest dimesion of the antenna. In practical terms this means d >> λ and d >> La

The effective area of the dish antenna is the area projected on the red line minus the blockage caused by the feed point and its supports



$$L_a = \lambda/2$$

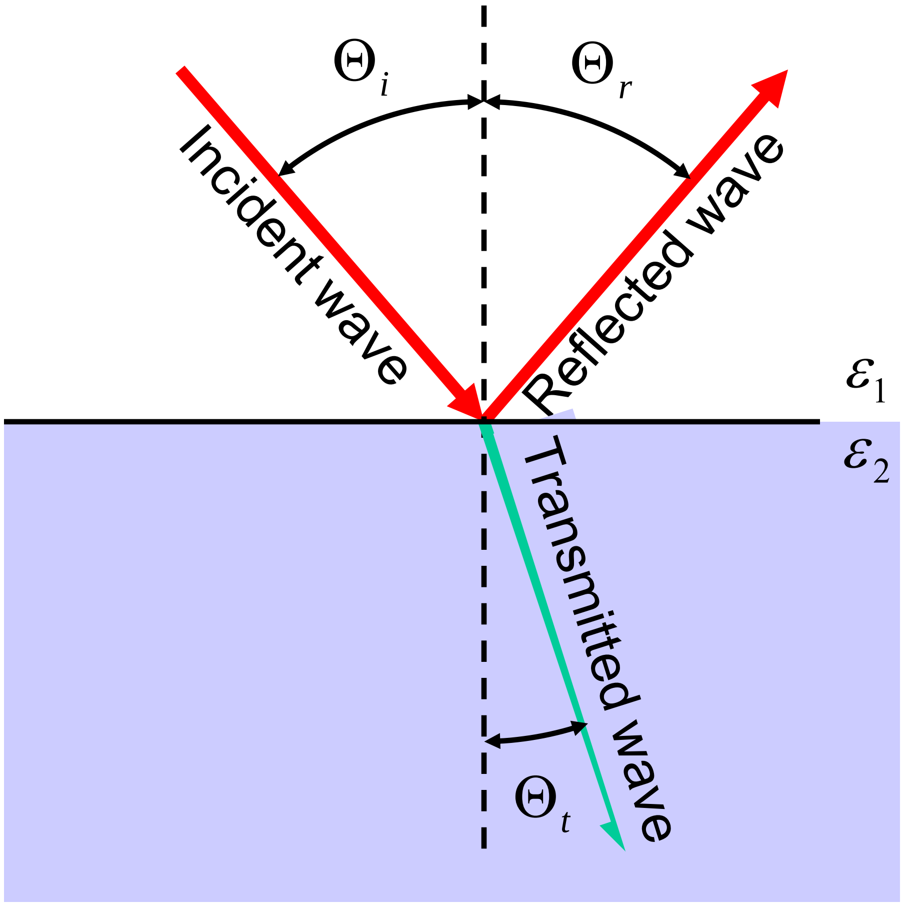
$$d_R = \lambda/2$$



$$L_a = 2r$$

$$d_R = \frac{8r^2}{\lambda}$$

Reflection and transmission (1)



Brewster Angle - angle at which no reflection occurs in the medium of origin, which only occurs for vertical (i.e. parallel) polarization (see slide 85). For air : water interface, the Brewster angle is 53 degrees for light.

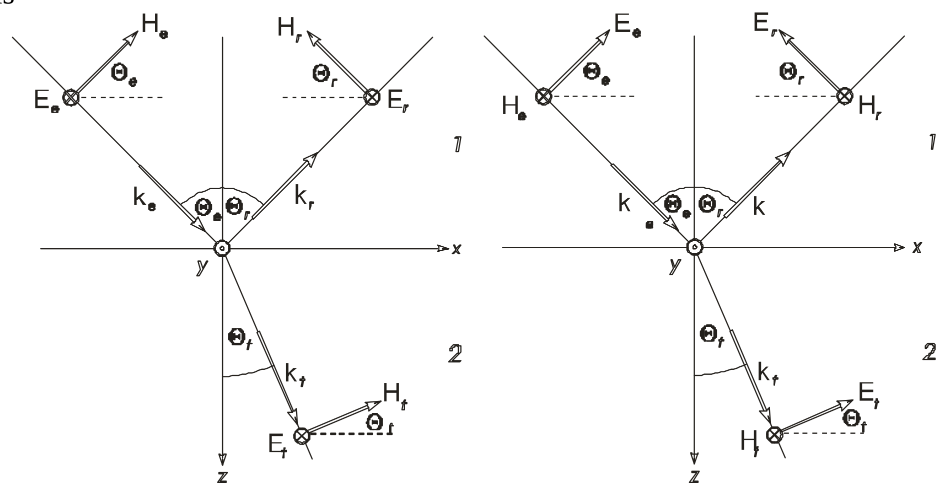
When source is "low" to the medium ($\Theta_i > 53^o$ for the air/water interface) it is all reflected, no energy directed into the second medium (water). However for waves that are reflected there is a phase shift of 180^o (reflection coefficient = -1) as Θ_i --> 90^o which is important in wireless systems when ground-reflected waves are considered.

Reflection and transmission (2)

- Snell's law
  - Reflection angle $\Theta_r = \Theta_e$
  - Transmission angle $\frac{\sin\Theta_t}{\sin\Theta_e} = \frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}}$ relative dielectric constant of material in farad/meter textbook formulation uses a complex dielectric constant
- Transmission and reflection: distinguish TE and TM waves

Horizontal Polarization where the electric field is parallel to the surface

TE TM



Vertical Polarization (TM) where the magnetic field component is parallel to the surface

Reflection and transmission (3)

Reflection Coefficient

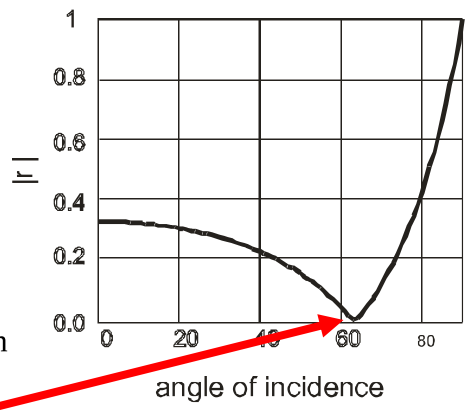
$$\rho_{TM} = \frac{\sqrt{\varepsilon_2}\cos\Theta_e - \sqrt{\varepsilon_1}\cos(\Theta_t)}{\sqrt{\varepsilon_2}\cos\Theta_e + \sqrt{\varepsilon_1}\cos(\Theta_t)}$$

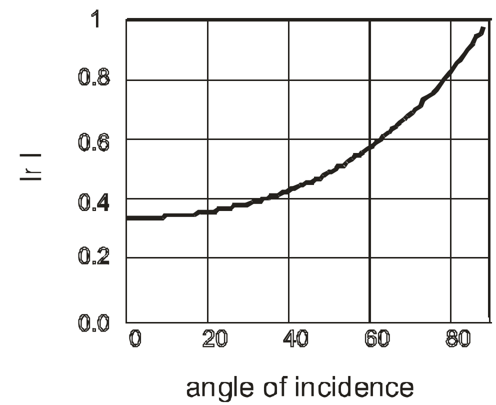
$$\rho_{TE} = \frac{\sqrt{\varepsilon_1}\cos(\Theta_e) - \sqrt{\varepsilon_2}\cos(\Theta_t)}{\sqrt{\varepsilon_1}\cos(\Theta_e) + \sqrt{\varepsilon_2}\cos(\Theta_t)}$$

TM-waves

TE-waves

Magintude

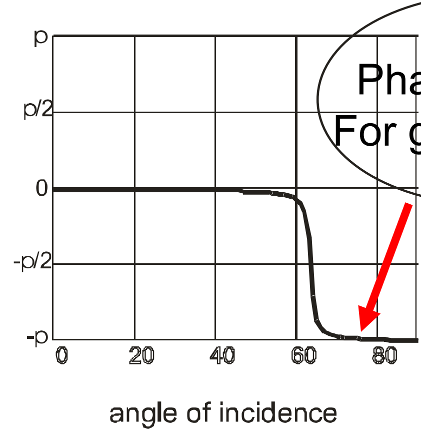




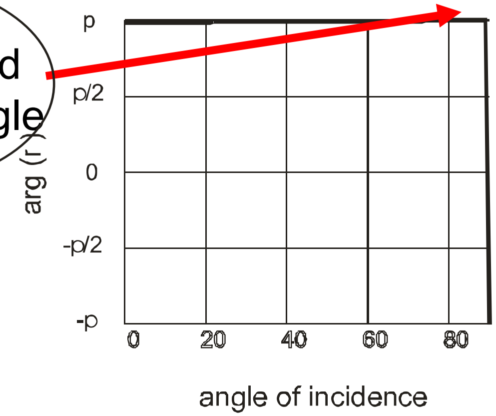
Only occurs for vertical polarization

Brewster angle

Phase

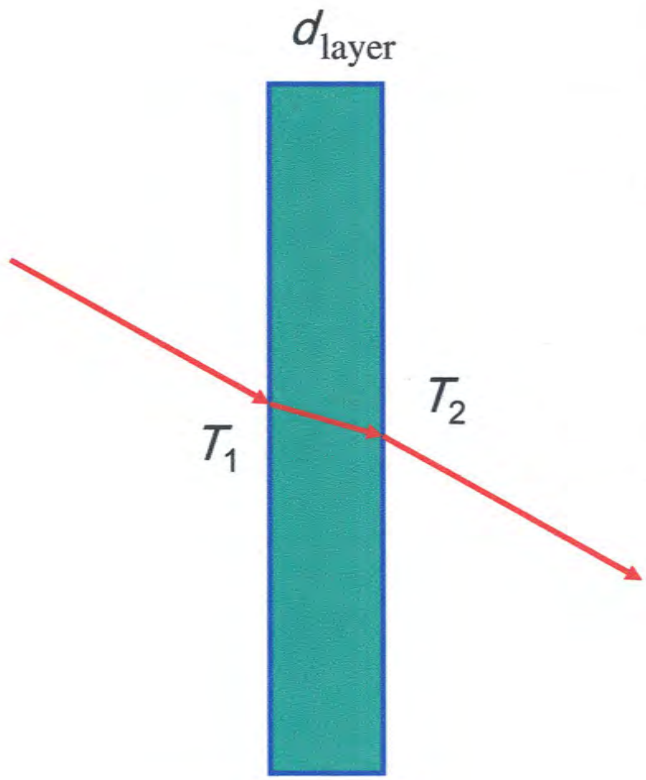


Phase inverted For grazing angle



Both waves have a magnitude of 1 and a phase shift of 180^0 as the glazing incidence approaches 90^0 - a ground reflected wave

Transmission through a wall – layered structures



Total transmission coefficient

$$T = \frac{T_1 T_2 e^{-j\alpha}}{1+\rho_1\rho_2 e^{-2j\alpha}}$$

T1 transmission coefficient of the wave from air into the wall

T2 transmission coefficient from the wall into air

total reflection coefficient

$$\rho = \frac{\rho_1+\rho_2 e^{-j2\alpha}}{1+\rho_1\rho_2 e^{-2j\alpha}}$$

with the electrical length of the wall (dielectric)

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\varepsilon_1}\, d_{layer} \cos(\Theta_t)$$

d_{layer} is the geometrical length of the layer

This doesn't apply to Millimeter waves (30 - 300 GHz) which don't penetrate much of anything since dielectrics have losses at these high frequencies

The d^{-4} law

- For the following scenario

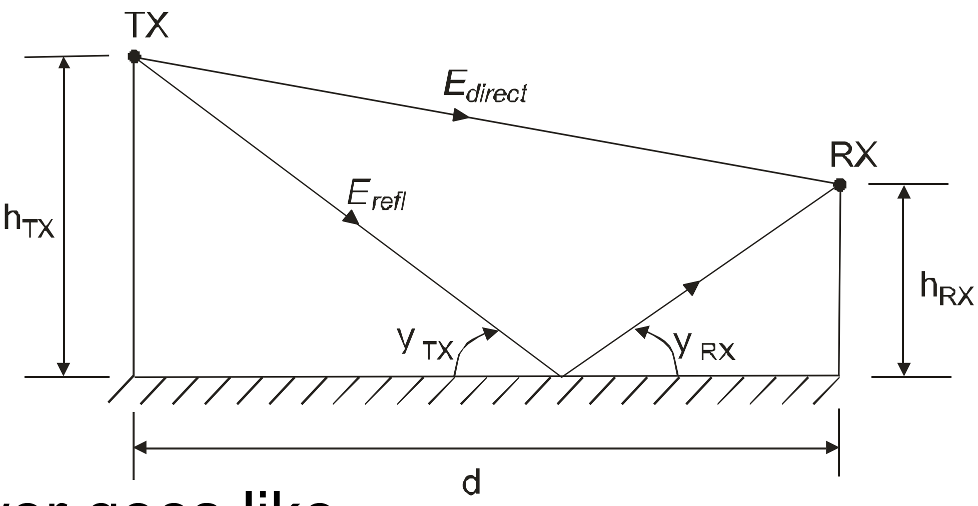


Figure shows that there is a direct wave and a ground-reflected wave for this 'simplified' transmission scenario.

The d^{-4} law is NOT a universal description of a wireless channel just a case to show that n = -4 is mathematically possible

- the power goes like

$$P_{\mathrm{RX}}(d) \approx P_{\mathrm{TX}} G_{\mathrm{TX}} G_{\mathrm{RX}} \left(\frac{h_{\mathrm{TX}} h_{\mathrm{RX}}}{d^2} \right)^2 .$$

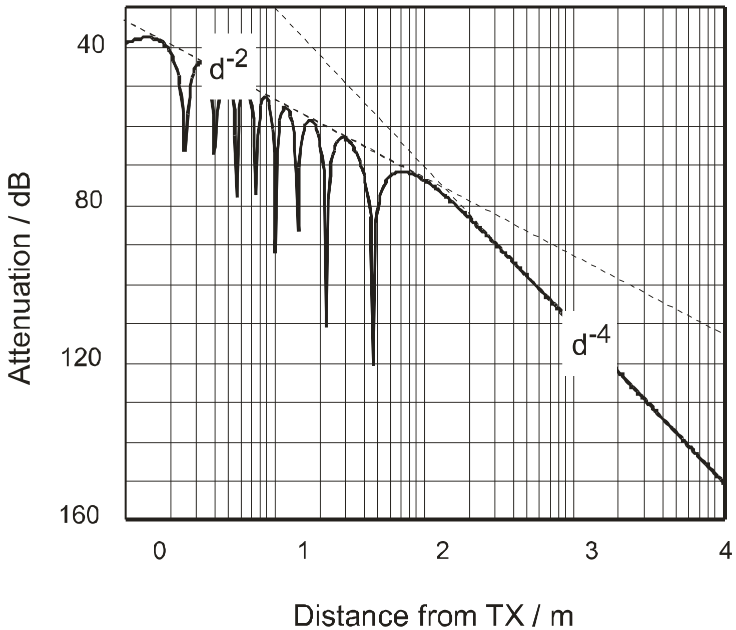
The nominal equation used in the wireless communications industry. The break point is the transition from d-2 to d-4 for the model (next slide). The Equation is derived in Appendix 4.A obviously for a nominal ranges of antenna heights

- for distances greater than

$$d_{\mathrm{break}} \gtrsim 4 h_{\mathrm{TX}} h_{\mathrm{RX}} / \lambda$$

The received power can be related to a receiver input voltage as well as to an induced E-field (volts) at the receiver antenna. This is based on the intrinsic impedance of free space (377 ohms), the power flux density and the receiver antenna modeled as a matched resistive load to the receiver.

The d^{-4} law (continued)



Simple Breakpoint Model

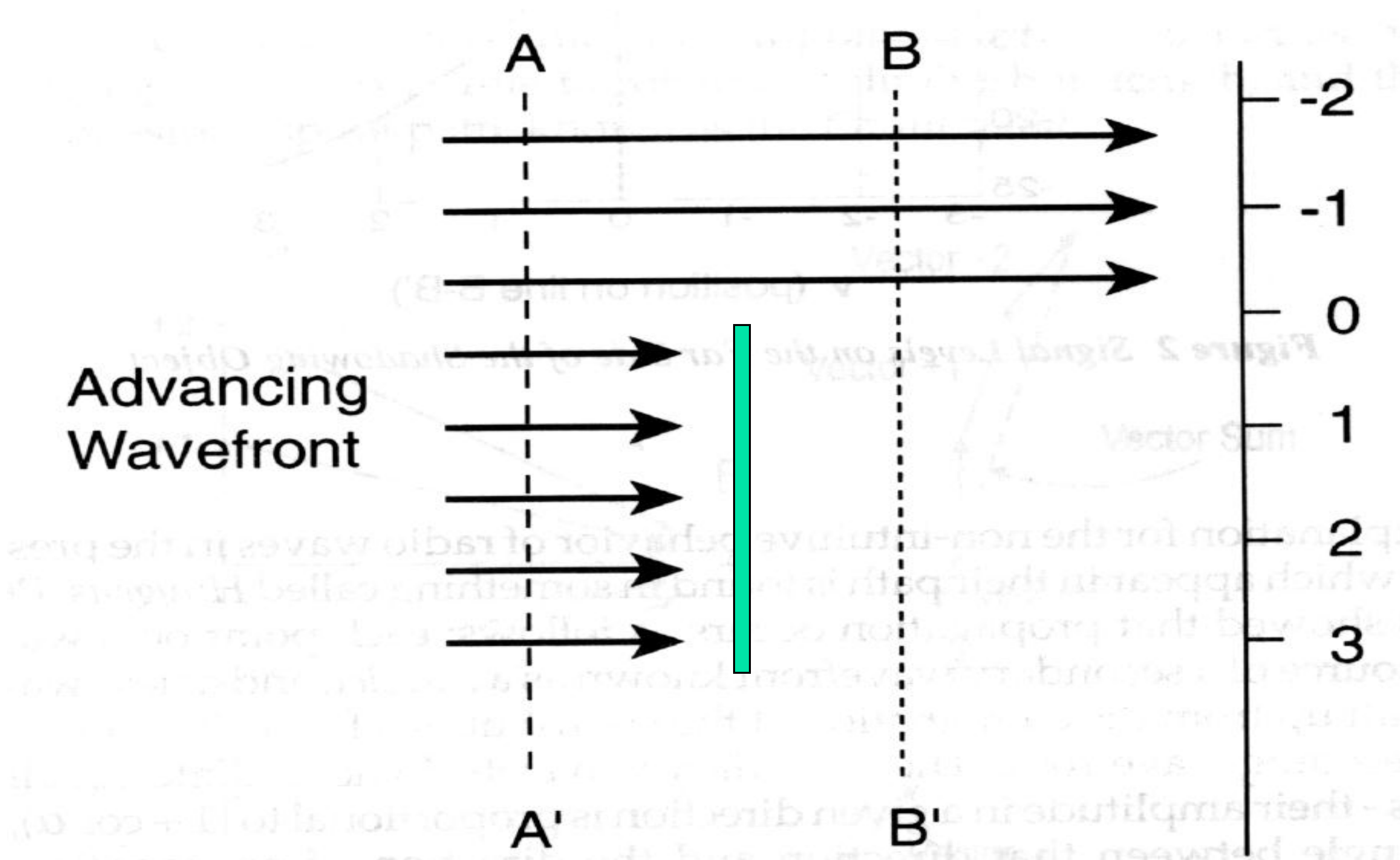
1. For distances d < dbreak, the received power is proportional to d-2
2. Figure shows that for d > dbreak the power is proportional to d-4
3. In the real world this is more like 1.5 < n < 5.5 thus n = 4 is at best a mean value of various environments
4. The transition between n = 2 and n = 4 is never at a specific point
5. The model doesn't take into account a second breakpoint when n > 6 which is best explained by the curvature of the earth which is an obvious constraint on LOS communications which normally applies for f > 100 MHz

Diffraction and Fresnel Zones

Material Related to Chapter 4

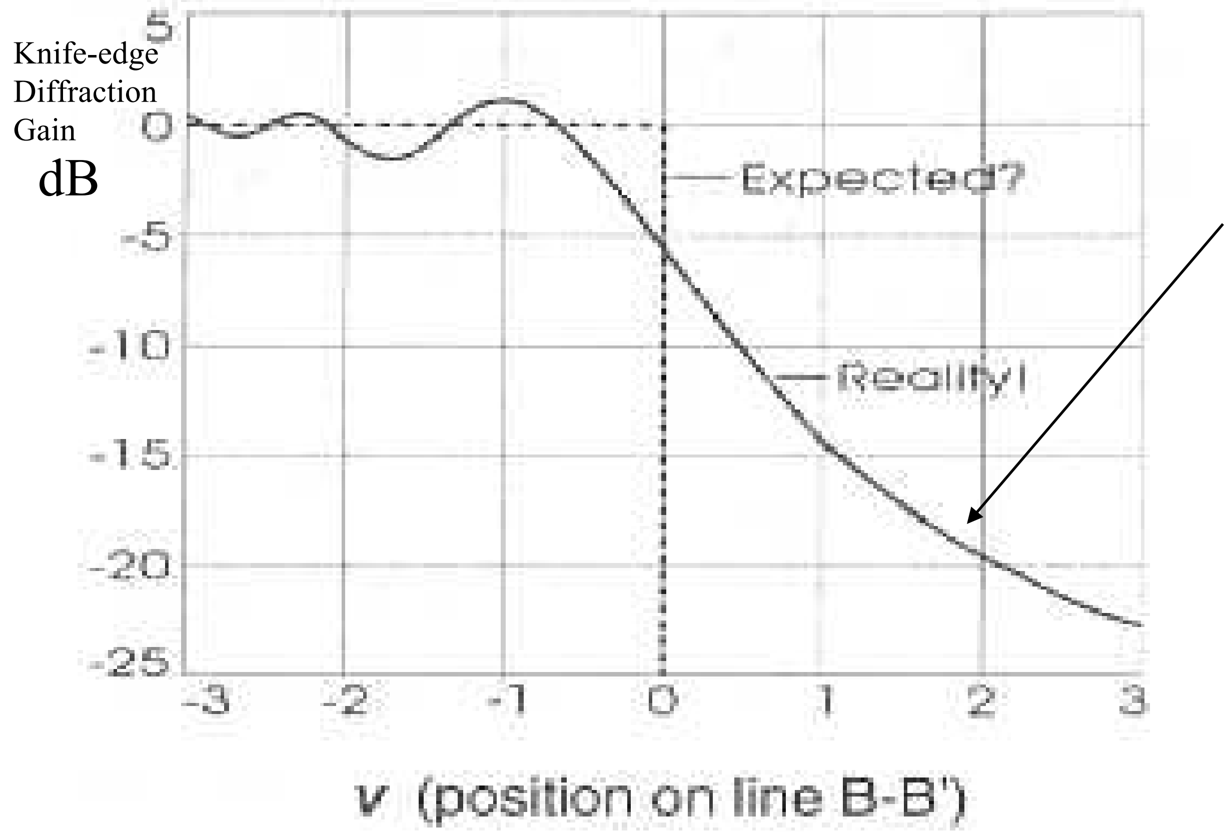
Textbook Pages 55 - 59

Wavefront Encountering an Obstacle



Consider the obstacle shown in green to be a knife-edge of known height (0 to 3) and infinite width - into and out of the paper (your looking at the side)

Blockage Signal Levels

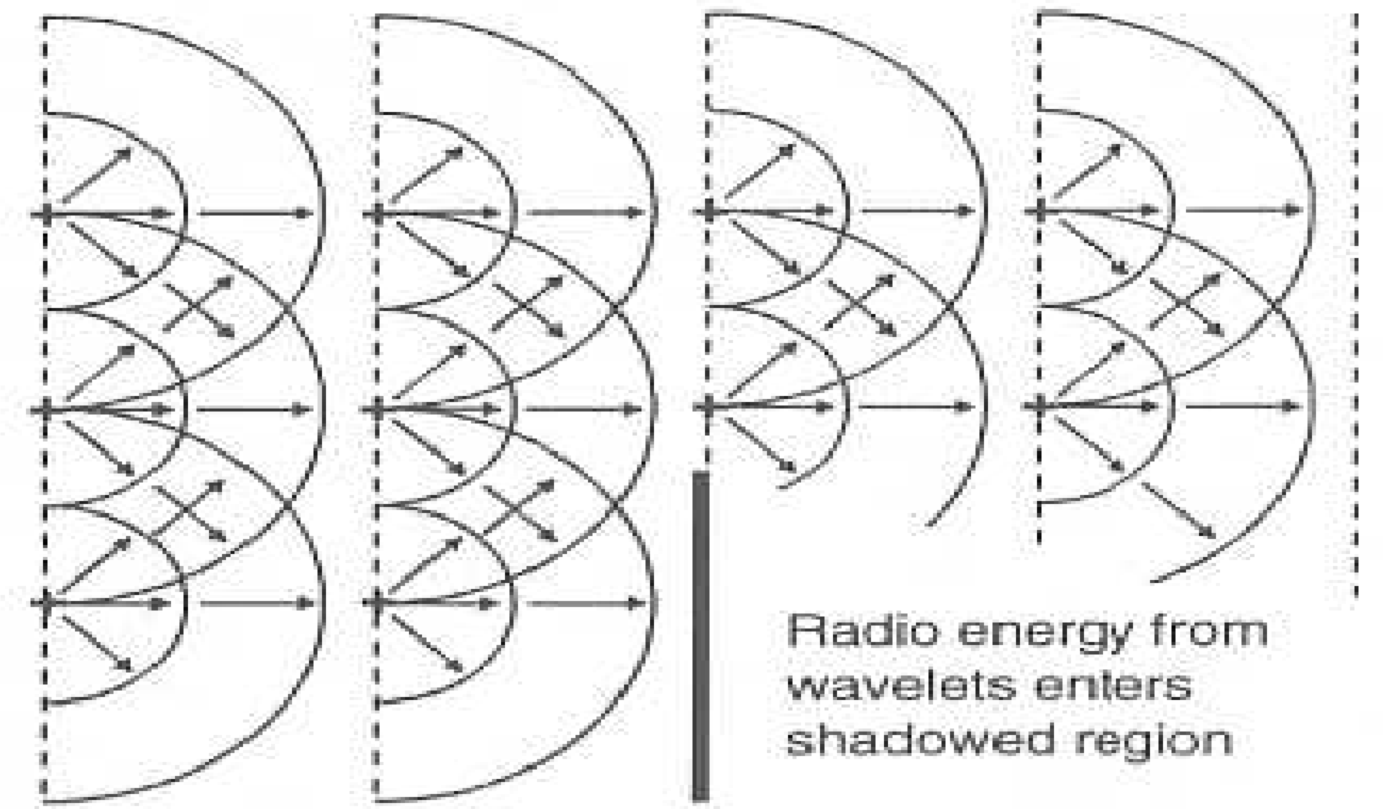


Note leakage of signal into blocked/shadowed area (0-3) but also that the field strength above the **top of the obstacle** (0 to -2) is also disturbed.

ν is the dimensionless Fresnel-Kirchoff diffraction parameter. The graph shows the loss in dB due to knife-edge diffraction, a graphical solution for finding the Fresnel integral $F(\nu_F)$

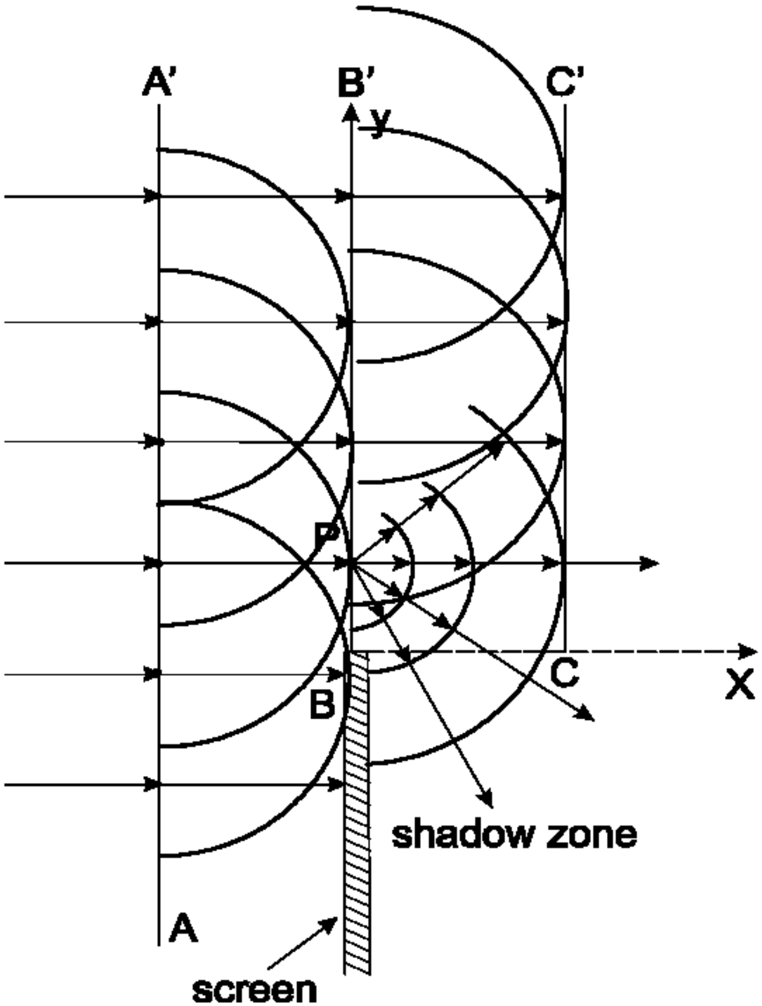
Signal Levels on the Far Side of the Shadowing Object

Huygens' Principle



Representation of Radio Waves as Wavelets

Diffraction, Huygen's principle



Is it a wave or a particle (a point source emanating vector components)?

Major advances in diffraction and scattering theory were an outcome of stealth technology.

Result (E_{TOTAL}) at specific point is the superposition of the spherical waves, both constructive and desctructive interference

Page 55 in textbook - see errata regarding Eq 4.27

Fresnel Zones

- To visualize what happens to radio waves when they encounter an obstacle, we have to develop a picture of the wavefront after the obstacle as a function of the wavefront just before the obstacle
- How much space around the direct path between the transmitter and receiver should be clear of obstacles including the ground?
  - Objects within a series of concentric circles around the line of sight between transceivers have constructive/destructive effects on communication
- A radio path has first *Fresnel zone clearance* if no objects capable of causing significant diffraction penetrate the corresponding ellipsoid

Fresnel Zones

The zones represented by each successive path length from T to R are n times the 1/2 wavelength greater than the direct LOS

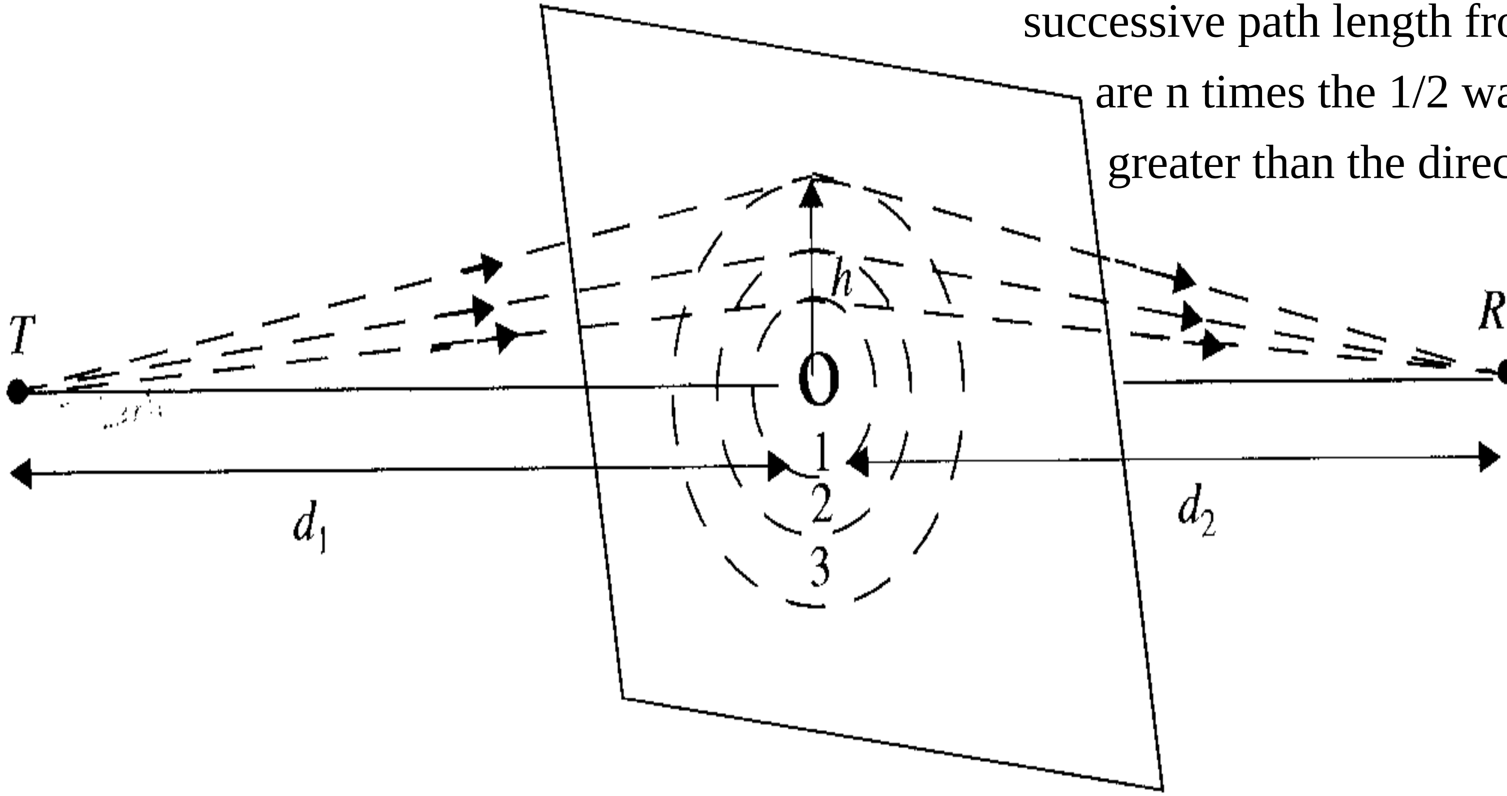
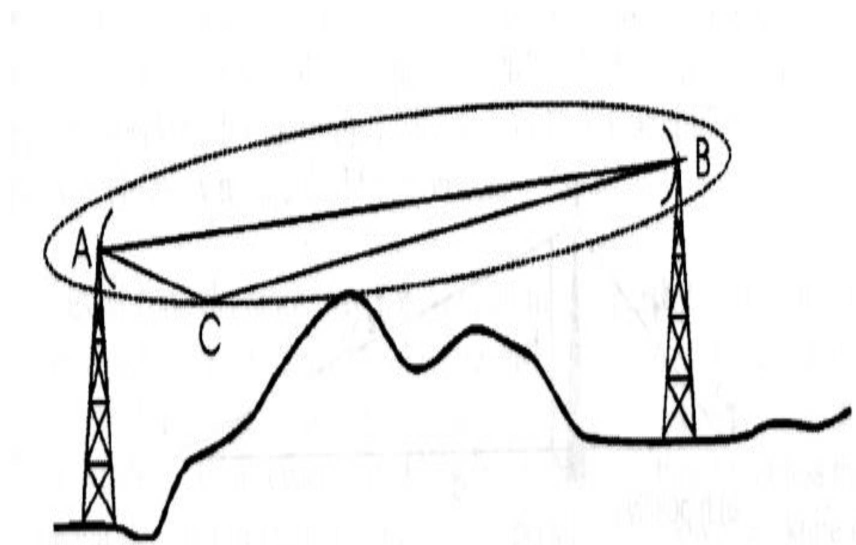


Figure 4.11 Concentric circles which define the boundaries of successive Fresnel zones.

Fresnel Zone for a Radio Link

- Assume that there is one obstacle in the Fresnel Zone, then we can look at the resultant wavefront at destination B (receiver in this case)
- Both blockage from the obstacle and passing near the obstacle impacts the received signal
- The resultant vector addition of ALL the Huygens' components is near the free space magnitude (i.e., magnitude with no obstacle)



For points along the direct path, radius of first Fresnel zone (most serious interference region):

$$R = \sqrt{\frac{\lambda S D}{S + D}}$$

S = obstacle distance from transmitter mountain peak D = obstacle distance from receiver mountain peak

Fresnel Zone Formulation

- $R_m = 17.3\ [\ S_{km}D_{km}\ /\ (f_{GHz}\{S_{km} + D_{km}\})]^{1/2}$

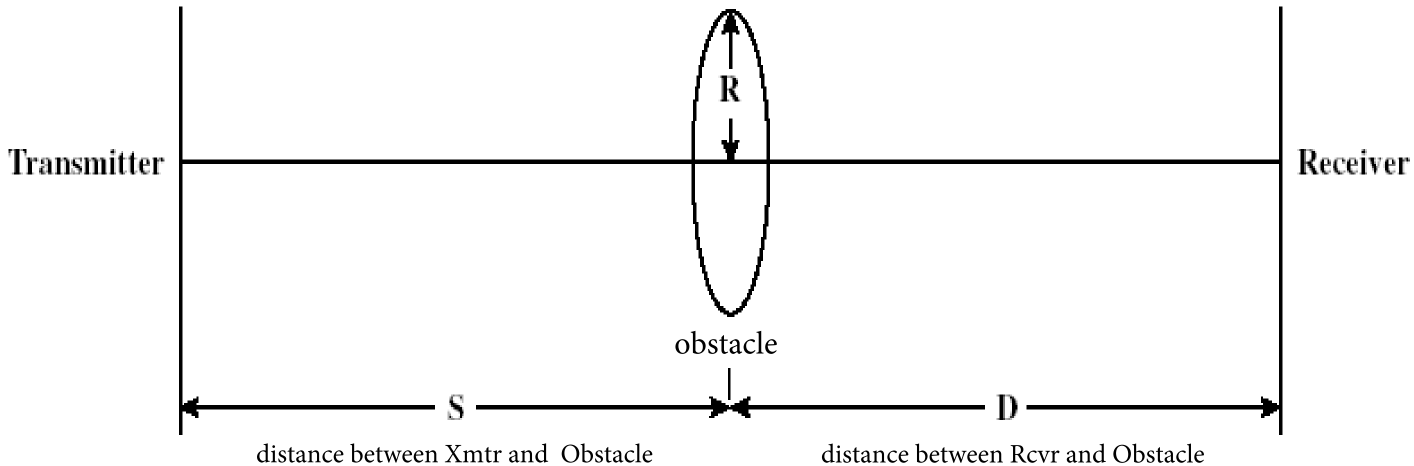
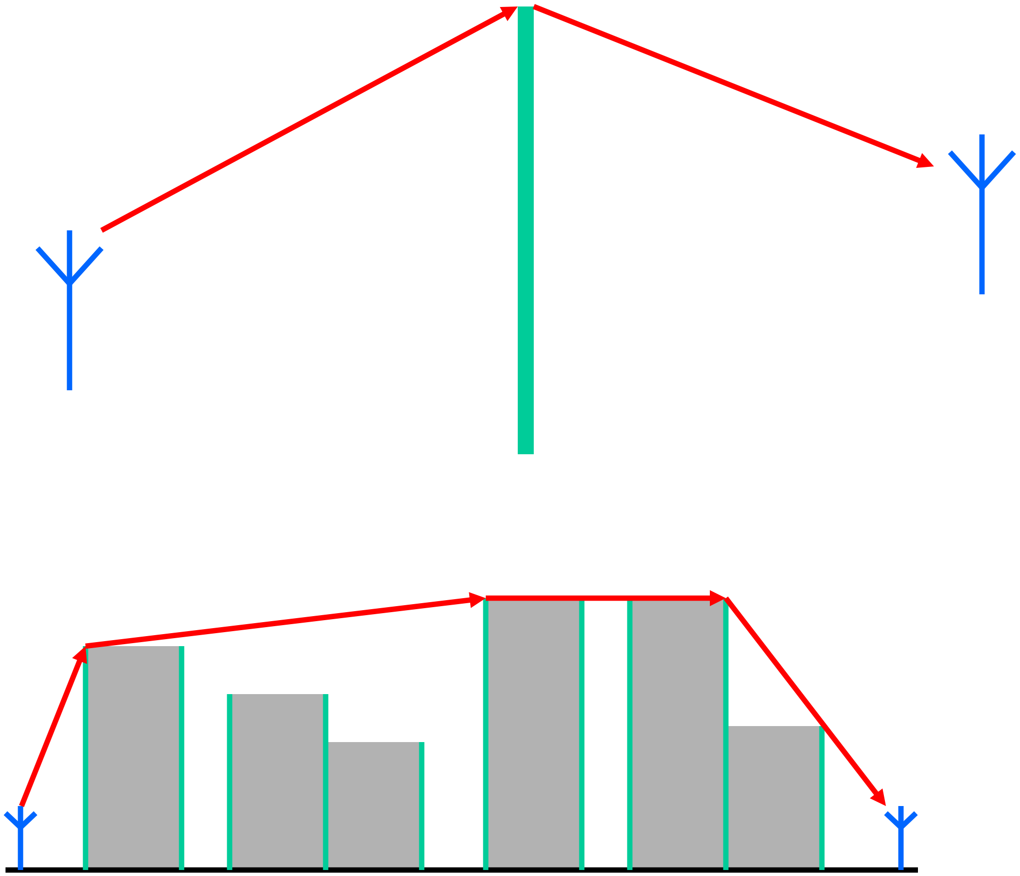


Figure 11.10 The First Fresnel Zone

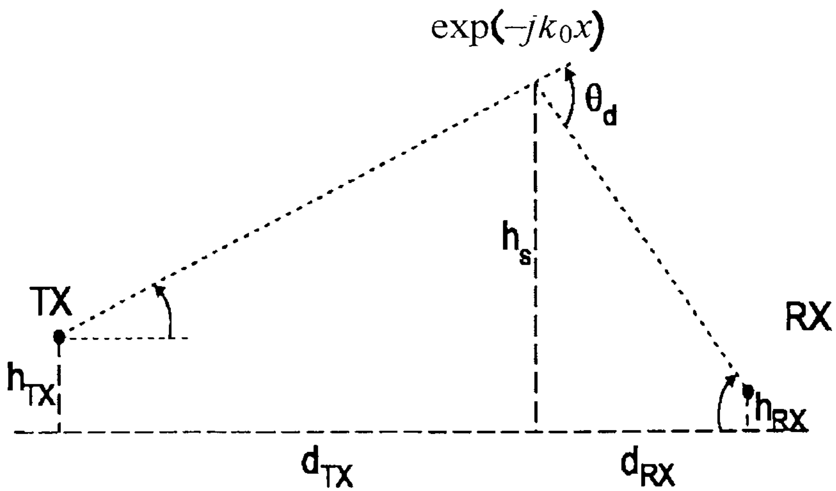
Note different units for R, S, D and f used for this simplified formula

Diffraction



1. Single or multiple edges
2. Makes it possible to go around corners or behind obstacles
3. Object doesn't even need to be in the direct LOS to impact the RF wave
4. Less pronounced when the wavelength is small (frequency is large) compared to the object

Diffraction Coefficient



Total field

$$E_{\text{total}} = \exp(-jk_0x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}}F\left(\nu_F\right)\right)$$

Fresnel integral

The Fresnel integral is defined

$$F\left(\nu_F\right) = \int_0^{\nu_F} \exp\left(-j\pi\frac{t^2}{2}\right)dt.$$

with the Fresnel parameter

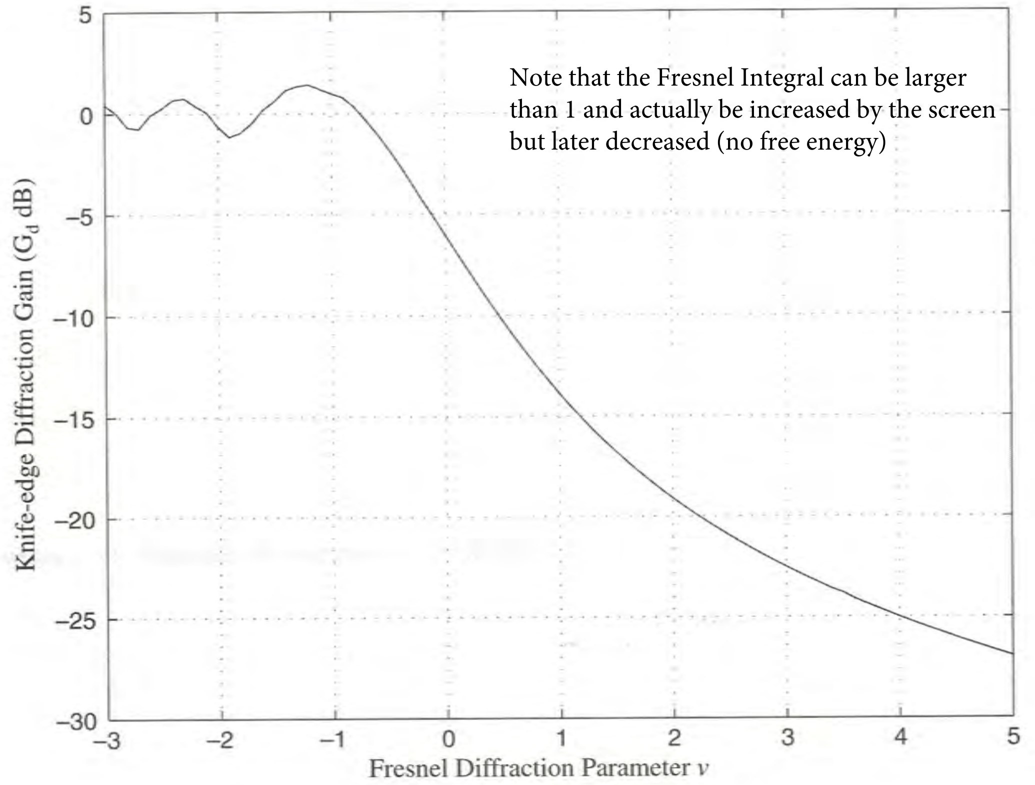
$$\nu_F = \theta_d\sqrt{\frac{2dtx\,drx}{\lambda(dtx+drx)}}$$

Eq 4.30 Page 57

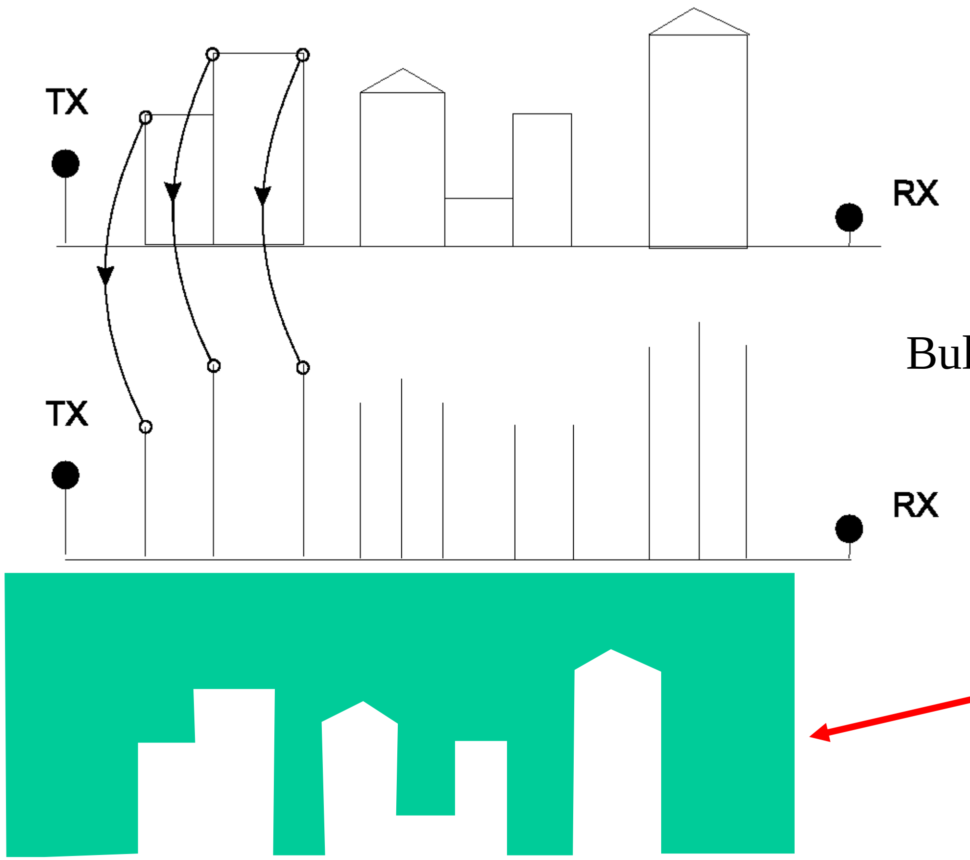
θ_d in radians

θ_d = arctan [(h_s - h_{TX})/d_{TX}] + arctan [(h_s - h_{RX})/d_{RX}]

The Fresnel integral can be approximated using graphical or tabular numerical solutions for values of the Fresnel parameter.


Note that the Fresnel Integral can be larger than 1 and actually be increased by the screen but later decreased (no free energy)
Knife-edge Diffraction Gain (G_d dB)
Fresnel Diffraction Parameter v
5
0
−5
−10
−15
−20
−25
−30
−3
−2
−1
0
1
2
3
4
5

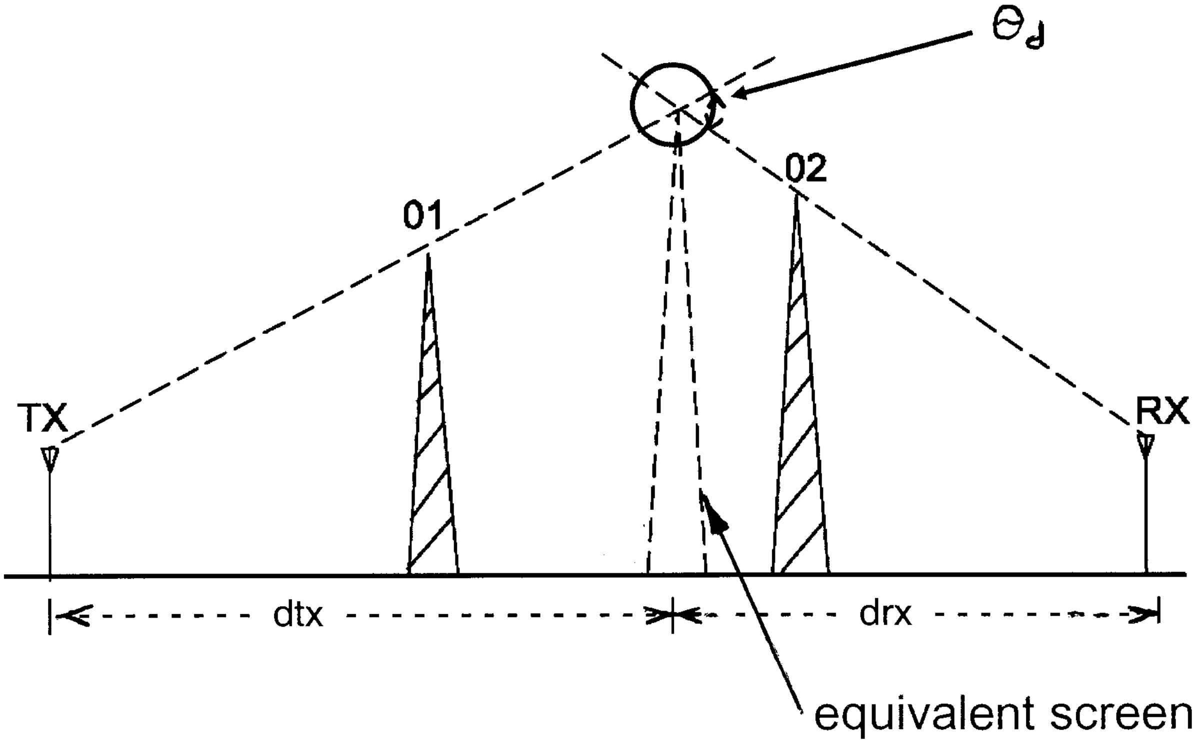
Diffraction in real environments



Bullington's Method - Chapter 4 Page 59

validity region

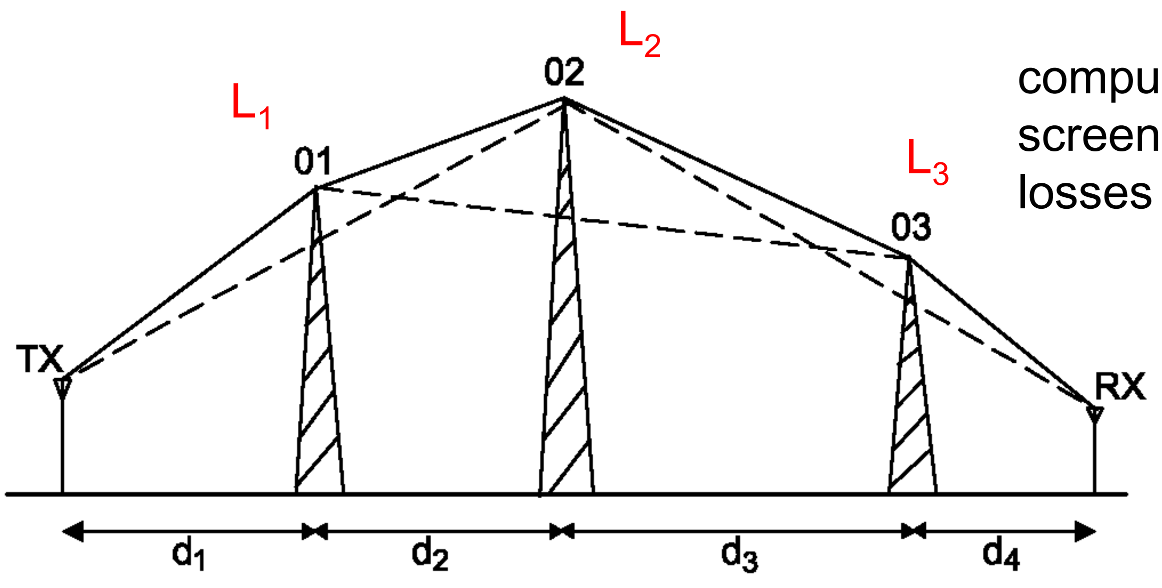
Diffraction – Bullington's method



$$E_{total} = \exp(-jk_0x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}}F\left(v_F\right)\right) \qquad v_F = \Theta_d\sqrt{\frac{2dtx\,drx}{\lambda(dtx+drx)}}$$

Eq 4.29 on page 56 for angle in radians

Diffraction – Epstein-Petersen Method



compute diffraction loss for each screen separately and add the losses

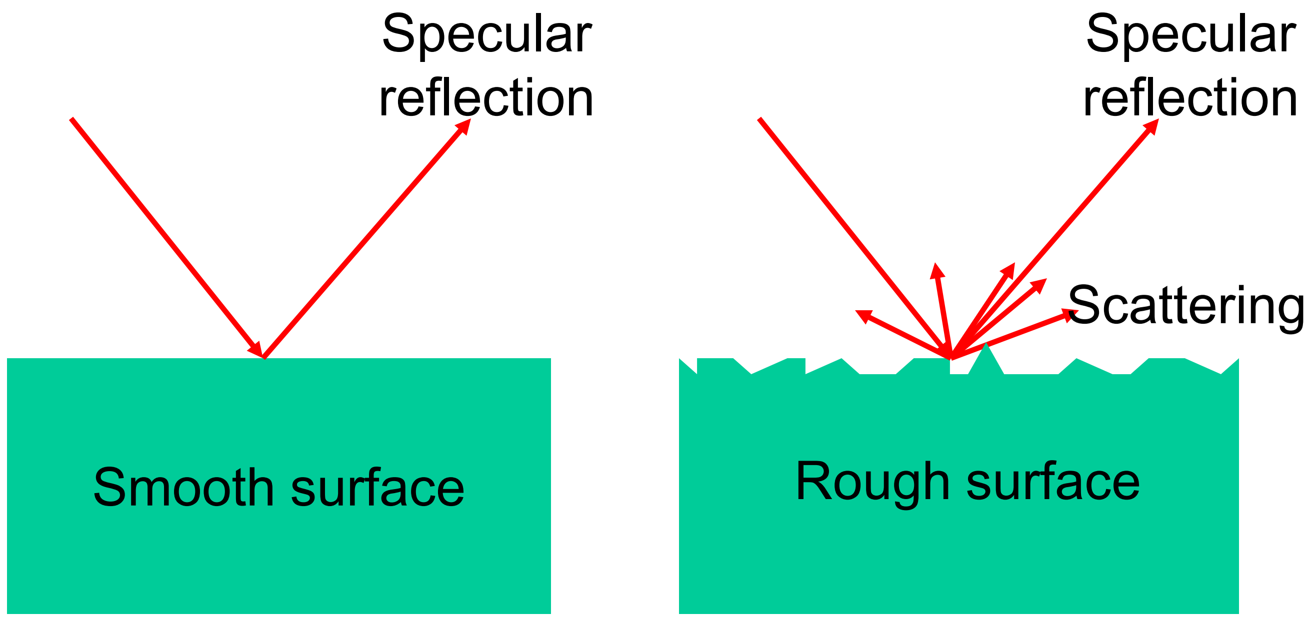
$$L_{tot}=L_1+L_2+L_3$$

More accurate than Bullington's Method but still an approximation caused by the far-field assumption.

See page 63 for a comparison of the various methods and a descriptive of the simple, semi-empirical modified ITU model.

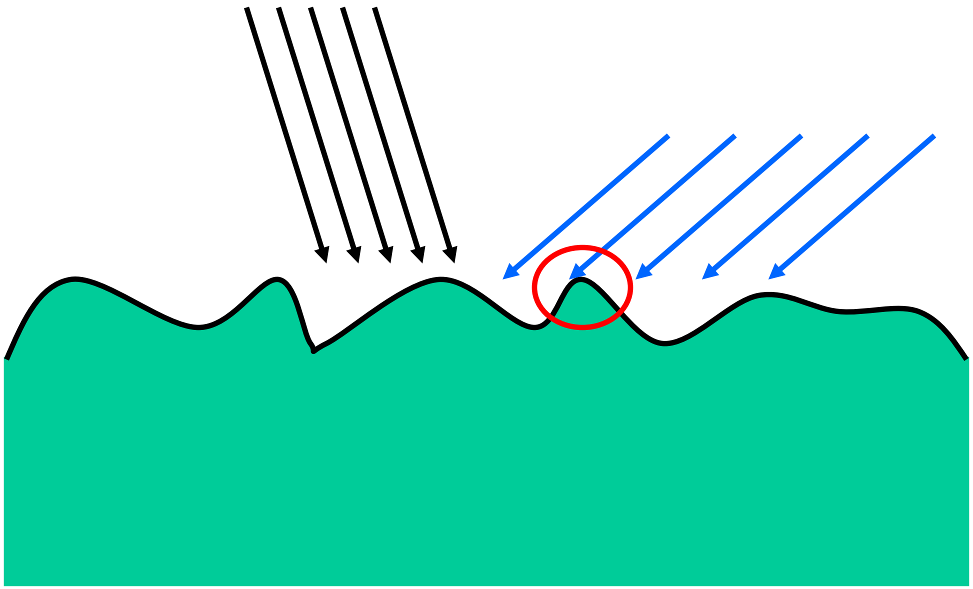
Use of all models requires using a tool like Matlab

Scattering



Impacts wireless communications, theory was an outcome of radar stealth technology.

Kirchhoff theory – scattering by rough surfaces



Note that for angle of incidence near zero (grazing incidence), the reflection becomes specular --> smooth surface (   ) is known as the Rayleigh roughness

for Gaussian surface distribution

$$\rho_{\text{rough}} = \rho_{\text{smooth}} \exp\left[-2\left(k_0 \sigma_{\text{h}} \sin\psi\right)^2\right]$$

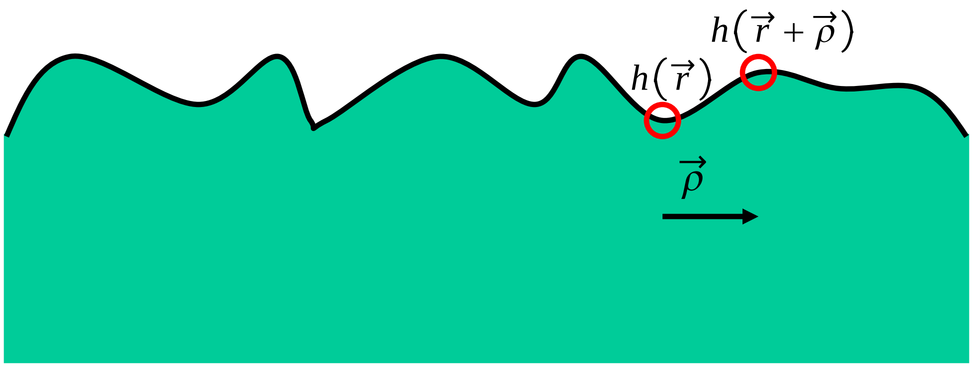
angle of incidence

standard deviation of height

only dependent on these 2 parameters

Pertubation theory – scattering by rough surfaces

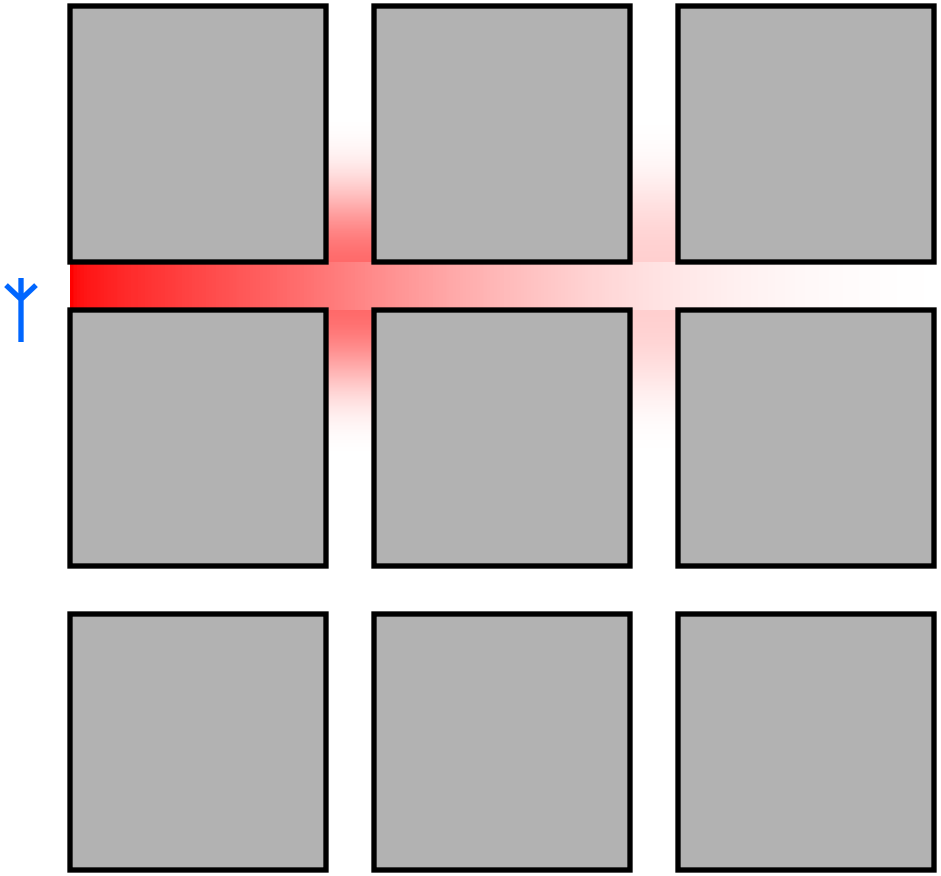
$$\sigma_h^2 W(\vec{\rho}) = E_{\vec{r}}\{h(\vec{r})h(\vec{r}+\vec{\rho})\}$$



Uses both the probability density function (pdf) of the surface height (like Kirchhoff Theory) and the spatial correlation function - how much does the height vary as we move along the surface? Allows shadowing of points on the surface unlike Kirchhoff

More accurate than Kirchhoff theory, especially for large angles of incidence and "rougher" surfaces

Waveguiding



Waveguiding effects often result in lower propagation exponents

$1.5 < n < 5$

This means lower path loss along certain street corridors

Impacts come from lossy materials, non-continuous walls, very rough surfaces and waveguides that are not empty but filled with metallic (cars) and dielectric (people)

Atmospheric Absorption

- Radio waves at frequencies above 10 GHz are subject to molecular absorption
  - Peak of water vapor absorption at 22 GHz
  - Peak of oxygen absorption near 60 GHz
- Favorable windows for communication:
  - From 28 GHz to 42 GHz
  - From 75 GHz to 95 GHz
- Millimeter waves are generally considered to be from 30 to 300 GHz. These frequencies are an area of great interest for 5G wireless systems; however, the signals hardly penetrate anything which will probably lead to utilizing mesh networks for system connectivity

Effect of Rain

- Attenuation due to rain
  - Presence of raindrops can severely degrade the reliability and performance of communication links
  - The effect of rain depends on drop shape, drop size, rain rate, and frequency
- Estimated attenuation due to rain:

$$A = aR^b$$

- *A* = attenuation (dB/km)
- *R* = rain rate (mm/hr)
- *a* and *b* depend on drop sizes and frequency

Effects of Vegetation

- Trees near subscriber sites can lead to multipath fading
- The tree canopy multipath effects are diffraction and scattering
- Measurements in orchards found considerable attenuation values when the foliage is within 60% of the first Fresnel zone
- Multipath effects highly variable due to wind since the leaves, tree limbs, …. move in the wind in addition to the time of the year (season – path loss is generally lower during the winter)