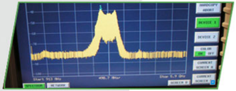


Radio Engineering

Lecture 2: Antennas and Propagation

Florian Kaltenberger

Summary of last lecture

- History of wireless communications
- Types of services and their requirements
- Technical challenges
  - Multipath propagation
  - Spectrum limitations
  - Limited Energy
  - User Mobility
- Link budgets
  - Decibel notation
  - Noise modeling
  - Antenna gain and EIRP
  - Path loss and fading margin
- Interference limited networks

Link Budget: Example (1)

Consider a mobile radio system with the following characteristics:

- Carrier frequency $f_c = 950$MHz,
- Bandwidth $B = 200$kHz,
- Operating temperature $T = 300$ K,
- Transmit power: $P = 30$ W,
- Antenna gains $G_{\text{TX}} = 10$ dB and $G_{\text{RX}} = 0$ dB,
- Cable losses at TX $L_{\text{TX}} = 5$ dB,
- Receiver noise figure $F = 7$ dB.
- The required operating SNR is 15 dB

Compute

- **the EIRP**
- **the RX sensitivity**

Link Budget: Example (2)

Assume the following propagation characterisitcs

- Path loss model[1]

$$PL(d) = \left(\frac{4\pi d}{\lambda}\right)^2 \quad 0 \leq d \leq d_{\text{break}}$$

$$PL(d) = PL(d_{\text{break}}) \left(\frac{d}{d_{\text{break}}}\right)^n \quad d > d_{\text{break}}$$

  with $d_{\text{break}} = 100\text{m}$.

- the fading margin is 12 dB.

What distance can be covered in for $n = 4$?

[1] Recall that $P_{\text{RX}}(d) = \frac{P_{\text{TX}}}{PL(d)}$ or $P_{\text{RX}}(d)|_{\text{dB}} = P_{\text{TX}}|_{\text{dB}} - PL(d)|_{\text{dB}}$

This lecture

4. Antennas and Propagation
   - Maxwell equations
   - Plane waves
   - Linear and circular polarization
   - Free space loss
   - Reflection and transmission
   - Diffraction
   - Scattering

Maxwell’s Equations

- Maxwell’s Equations fully describe the nature of electromagnetic waves
- They describe the relationship between variations of the electric field **E** and the vector magnetic field **H** in time and space within a medium
- All radio propagation mechanisms could be described, but in practice much too complicated

Maxwell's Equations

Theorem (Maxwell's Equations)

- *An electric field is produced by a time-varying magnetic field*
- *A magnetic field is produced by a time-varying electric field or by a current*
- *Electric field lines may either start and end on charges, or are continious*
- *Magnetic field lines are continuous*

Plane waves

- Many solutions to Maxwell's Equations exist
- They can all be described as a sum of plane waves

$$\mathbf{E} = E_0 cos(\omega t - kz)\mathbf{x}$$
$$\mathbf{H} = H_0 cos(\omega t - kz)\mathbf{y}$$

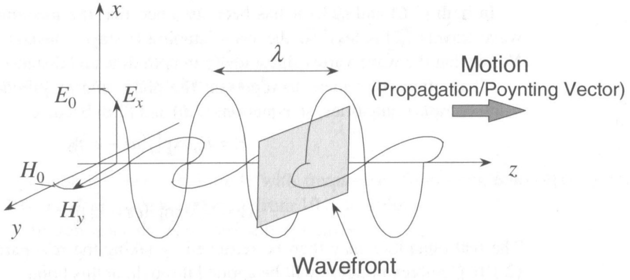


Figure 2.1: A plane wave

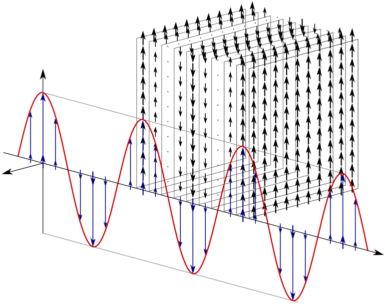
Linear and circular polarized plane waves (1)

- Alignment of the electric field vector relative to Poynting vector defines the polarization

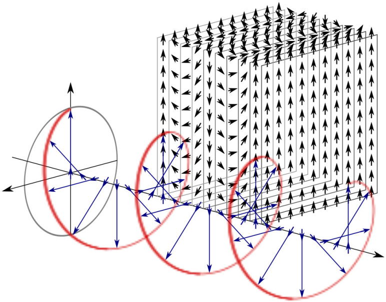
$$\mathbf{E} = E_x\mathbf{x} + E_y\mathbf{y}$$

- *Linearly polarized* waves: Electric field is parallel to x or y-axis
  - *vertical polarization:* $E_x = 0, E_y = E_0/\sqrt{2}$
  - *horizontal polarization:* $E_x = E_0/\sqrt{2}, E_y = 0$
- *Circulary polarized* waves: Horizontal and vertical polarization combined with a 90° phase difference
  - *right-hand circular polarization:* $E_x = -E_0/\sqrt{2}, E_y = jE_0/\sqrt{2}$
  - *left-hand circular polarization:* $E_x = E_0/\sqrt{2}, E_y = jE_0/\sqrt{2}$

Linear and circular polarized plane waves (2)



Linearly polarized plane wave



Circularly polarized plane wave

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 interaction system-channel
  - MIMO
  - UWB

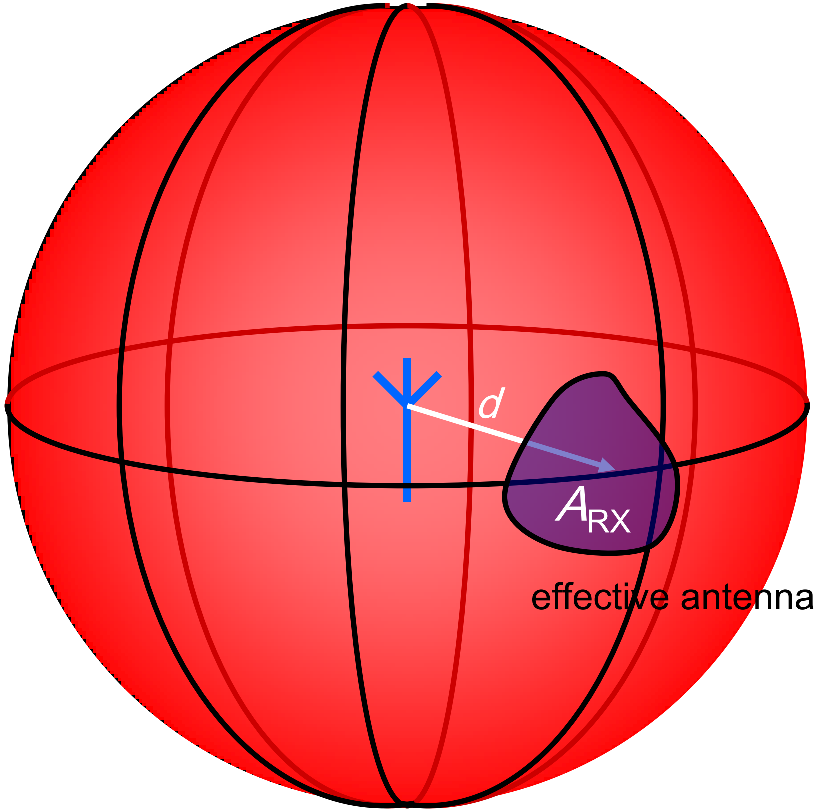
Without reliable channel models, it is hard to design radio systems that work well in *real* environments.

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?

BASIC PROPAGATION MECHANSISMS

Free-space loss



$$P_{RX}(d) = P_{TX} \underbrace{\frac{1}{4\pi d^2}}_{\text{Surface Sphere}} A_{RX}$$

$$G_{RX} = \frac{4\pi}{\lambda^2} A_{RX}$$

If we assume RX antenna to be isotropic:

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

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

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

Free-space loss
Friis' law

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

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

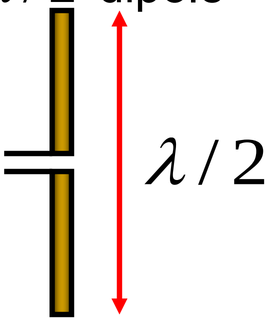
$$\Leftrightarrow$$

Valid in the far field only

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

Free-space loss
What is far field?

$\lambda/2$-dipole



$$L_a = \lambda/2$$

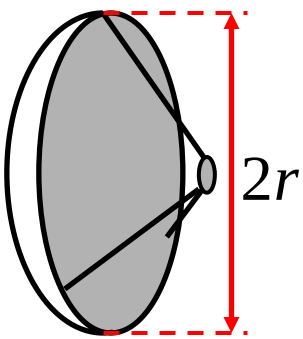
$$d_R = \lambda/2$$

Rayleigh distance:

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

where L_a is the largest dimesion of the antenna.

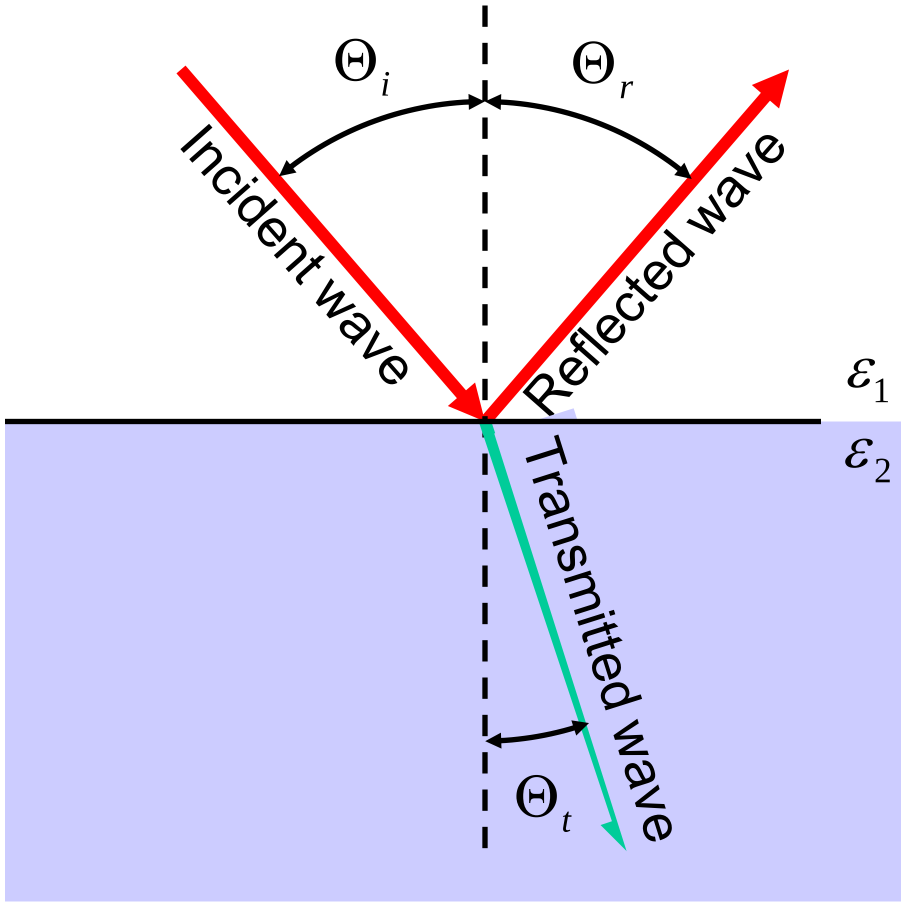
Parabolic



$$L_a = 2r$$

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

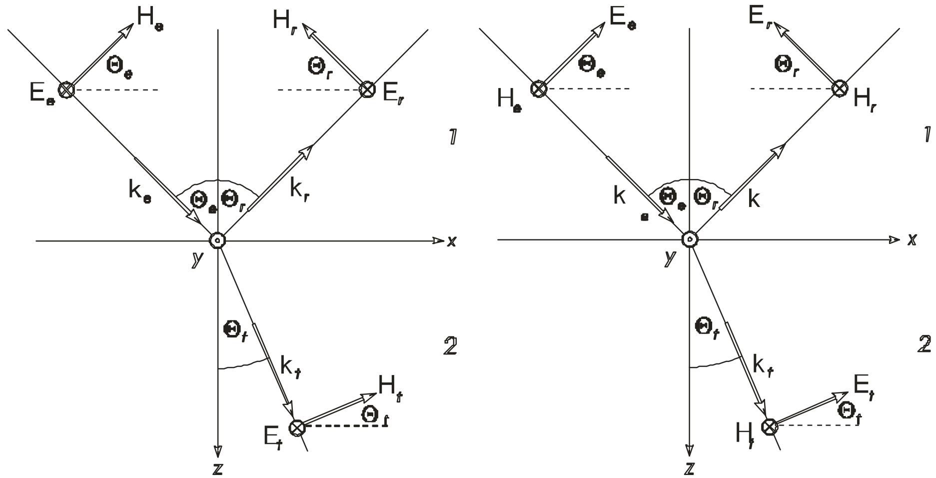
Reflection and transmission (1)



Reflection and transmission (2)

- Snell's law
  - Reflection angle $\Theta_r = \Theta_e$
  - Transmission angle $\dfrac{\sin\Theta_t}{\sin\Theta_e} = \dfrac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}}$
- Transmission and reflection: distinguish TE and TM waves

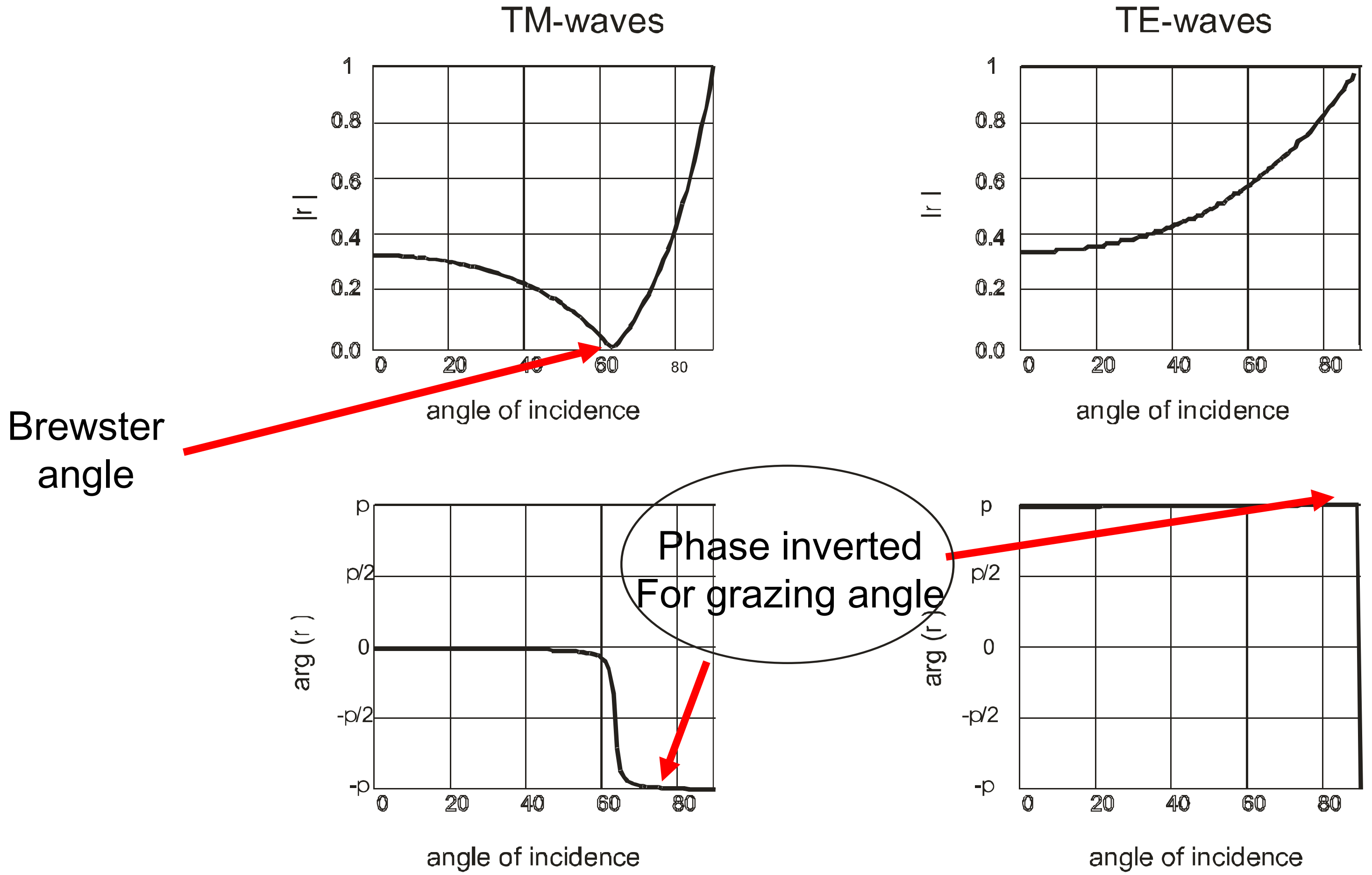
TE TM



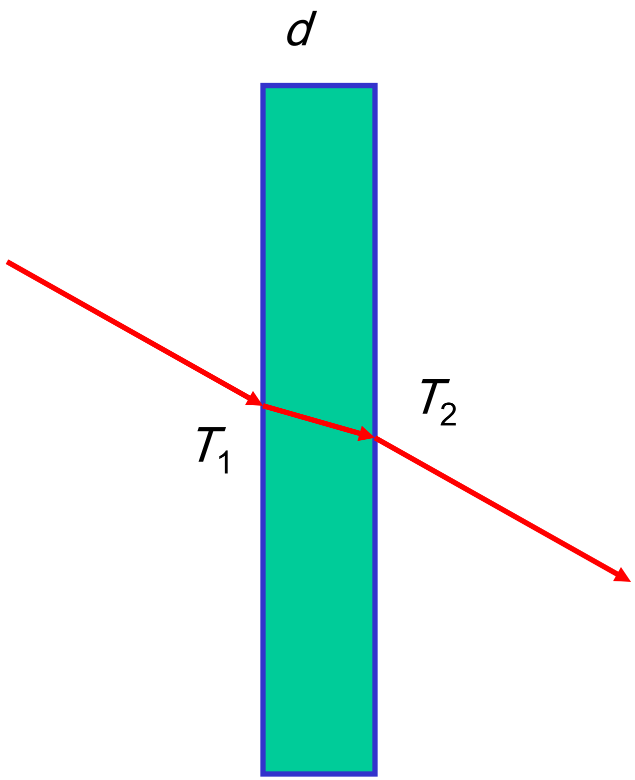
Reflection and transmission (3)

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

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



Transmission through a wall – layered structures



Total transmission coefficient

$$T = \frac{T_1 T_2 e^{-j\alpha}}{1+R_1 R_2 e^{-2j\alpha}}$$

total reflection coefficient

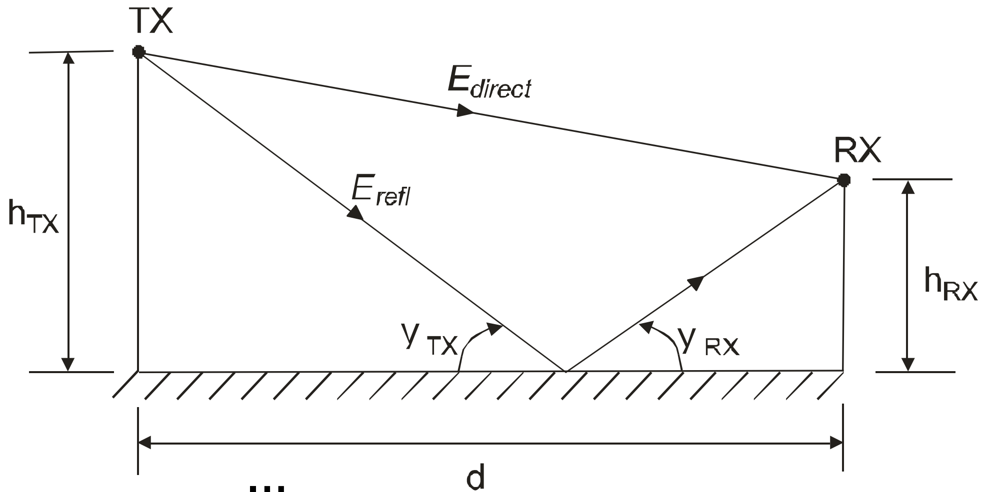
$$\rho = \frac{\rho_1+\rho_2 e^{-j2\alpha}}{1+\rho_1 \rho_2 e^{-2j\alpha}}$$

with the electrical length in the wall

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

The d^{-4} law (1)

- For the following scenario



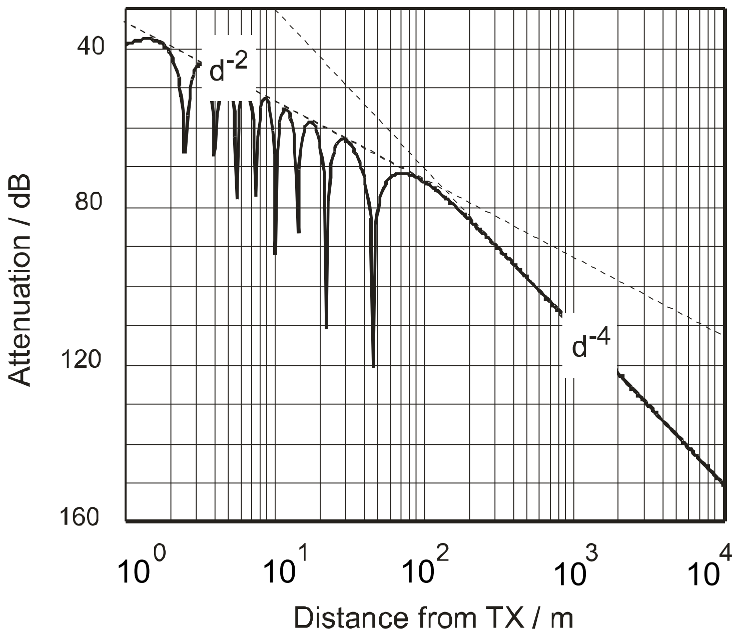
- the power goes like

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

- for distances greater than

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

The d^{-4} law (2)

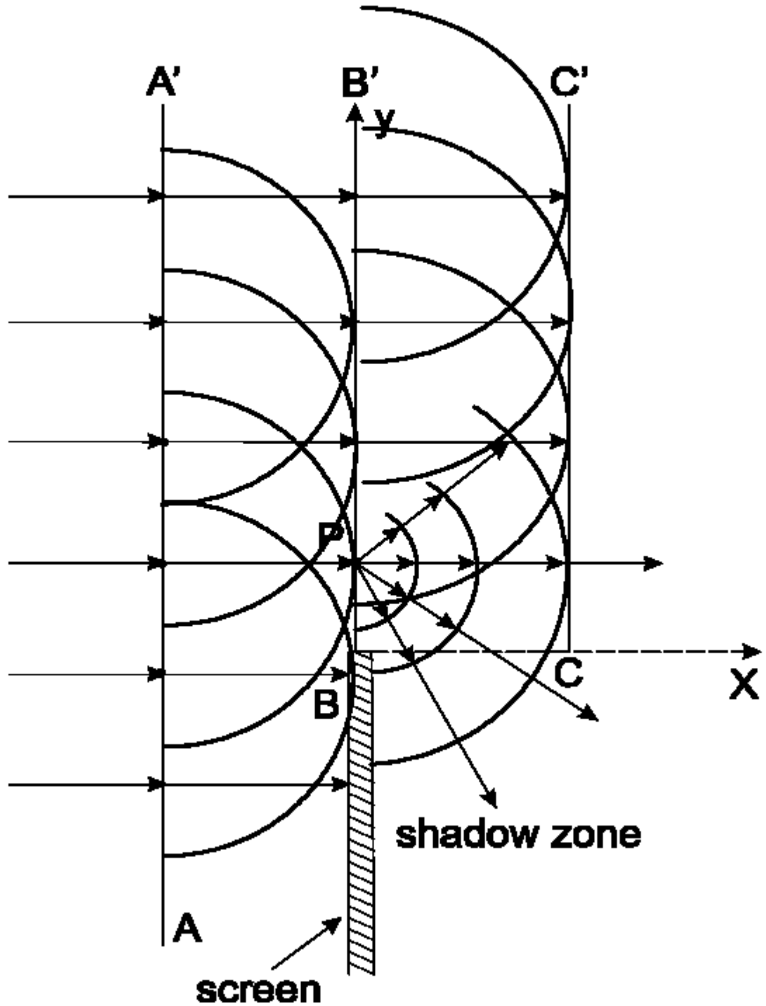


htx = 5m

hrx = 1.5m

fc = 900MHz

Diffraction, Huygen's principle



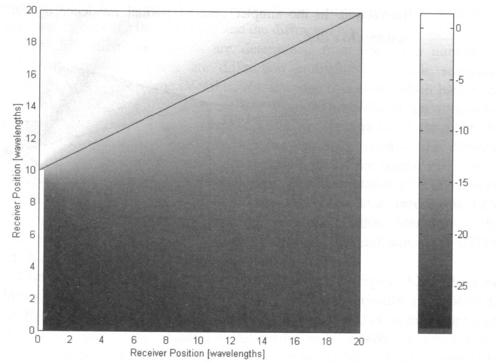
* Semi-infinite screen
* Each point of the wavefront can be considered as a source of a spherical wave
* Screen eliminates parts of the waves
* Constructive and destructive interference

Fresnel integral

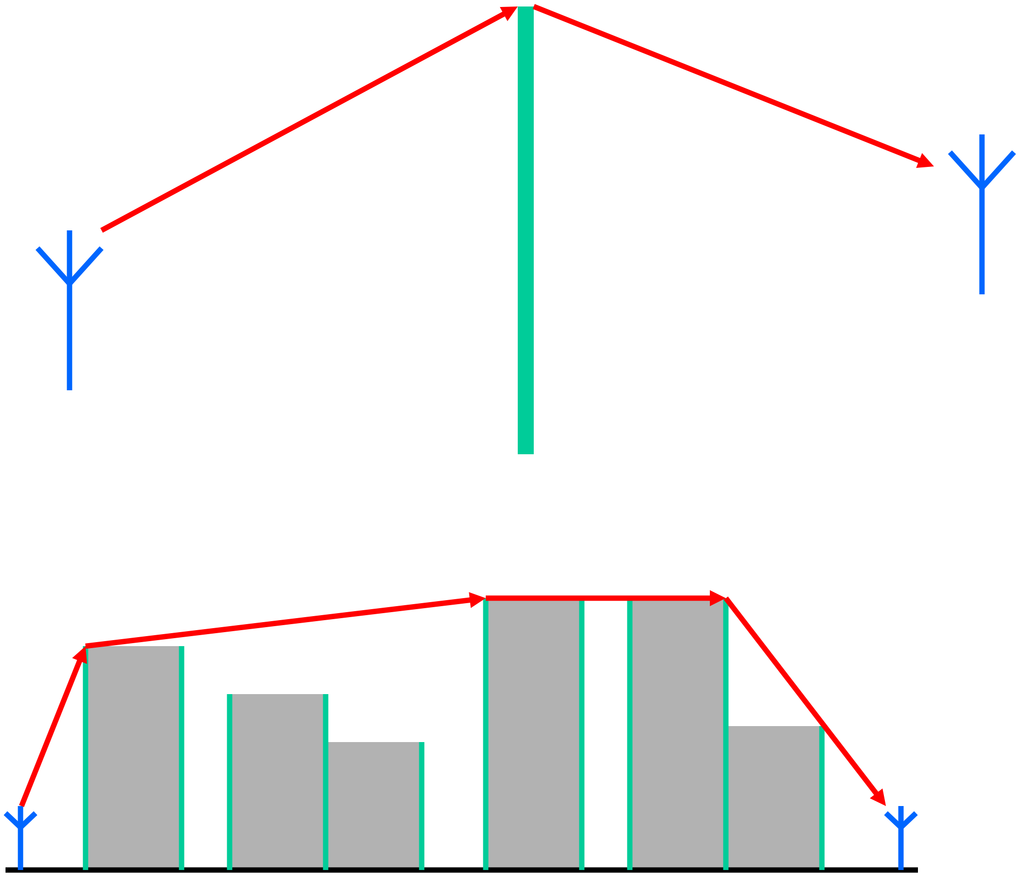
- The electric field (for $x \geq 0$) can be expressed as

$$E_{total} = exp(-jk_0 x)F(\nu_F)$$

where $\nu_F = -2y/\sqrt{\lambda x}$ and $F(\nu_F)$ is the Fresnel integral

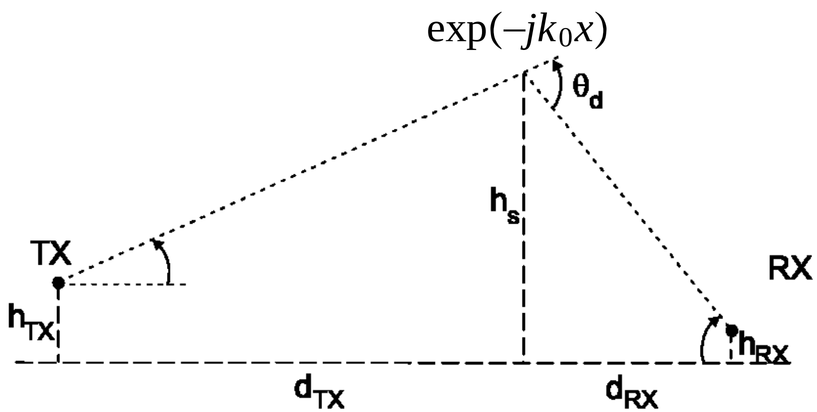


Diffraction



- Single or multiple edges
- makes it possible to go behind corners
- less pronounced when the wavelength is small compared to objects

Diffraction coefficient



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

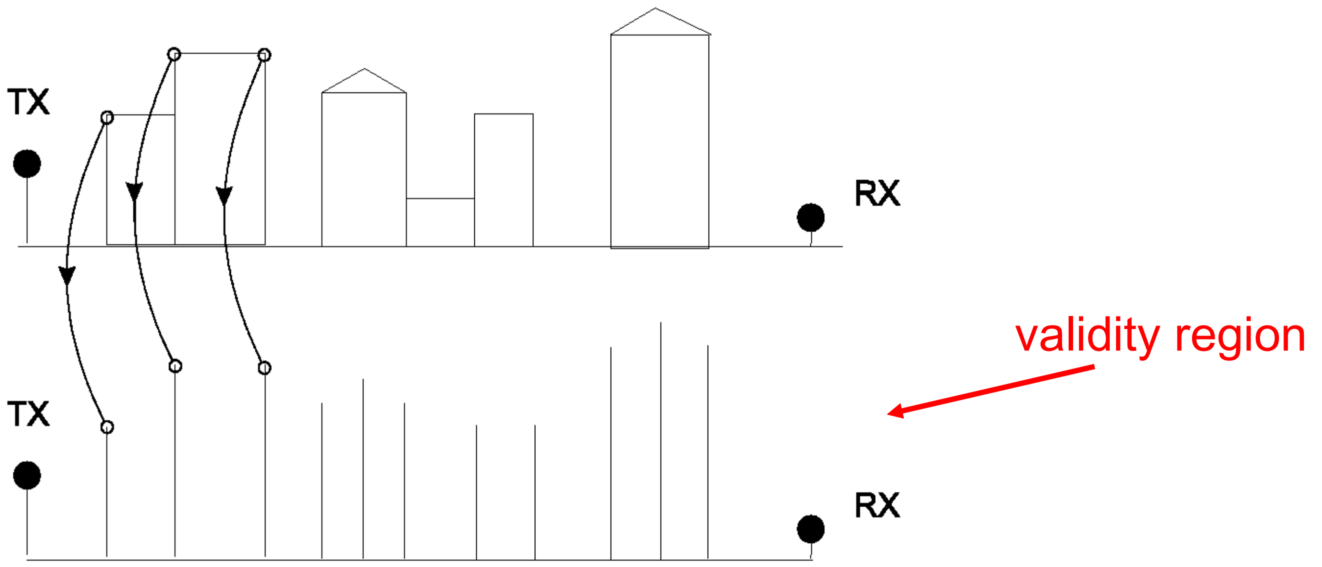
$$\nu_F = \alpha_k \sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$$

Total field

$$E_{\text{total}} = \exp(-jk_0 x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}} F\left(\nu_F\right)\right)$$

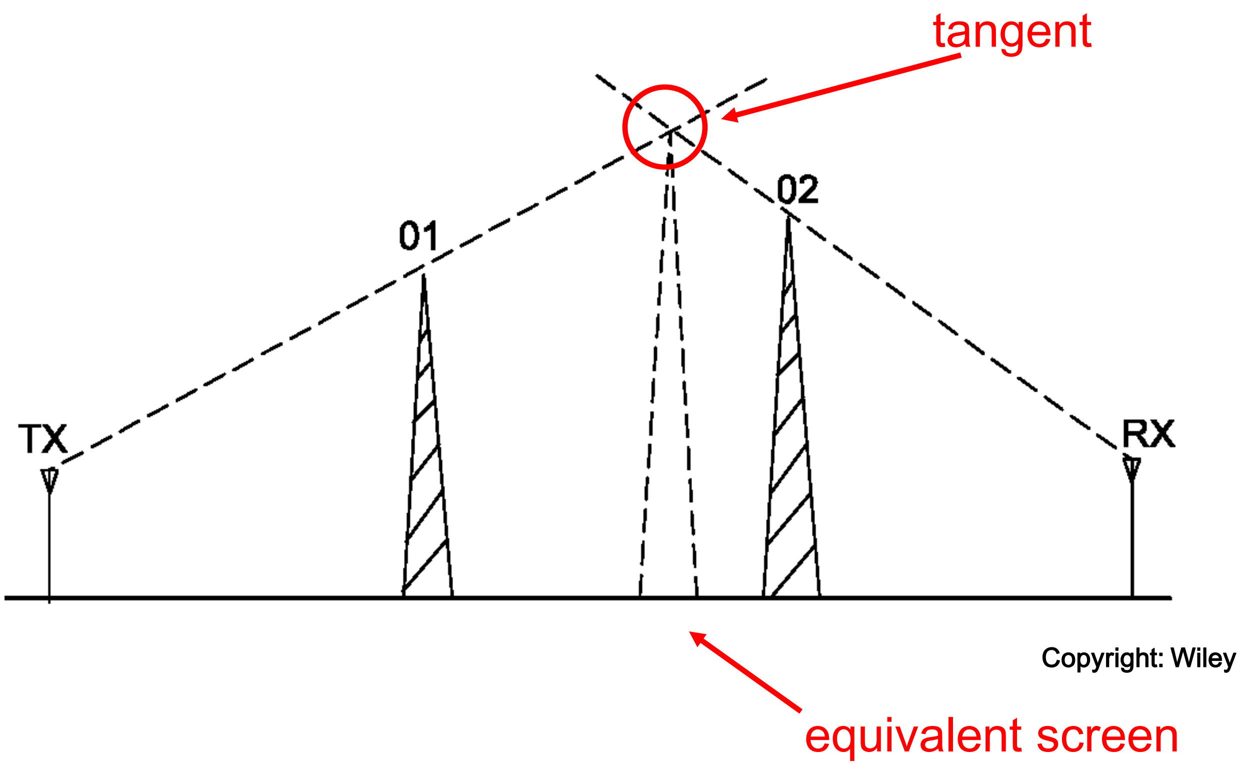
Fresnel integral

Diffraction in real environments



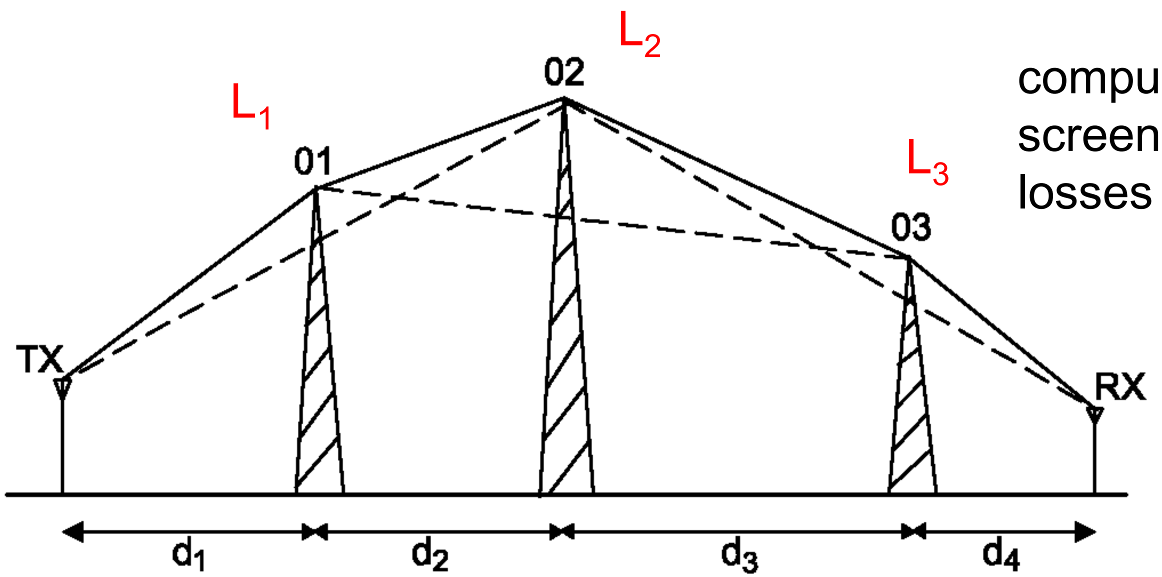
Approximation of multiple buildings by a series of screens

Diffraction – Bullington's method



$$E_{\text{total}} = \exp(-jk_0x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}}F\left(\nu_{\text{F}}\right)\right) \qquad \nu_{\text{F}} = \alpha_k\sqrt{\frac{2d_1d_2}{\lambda(d_1+d_2)}}$$

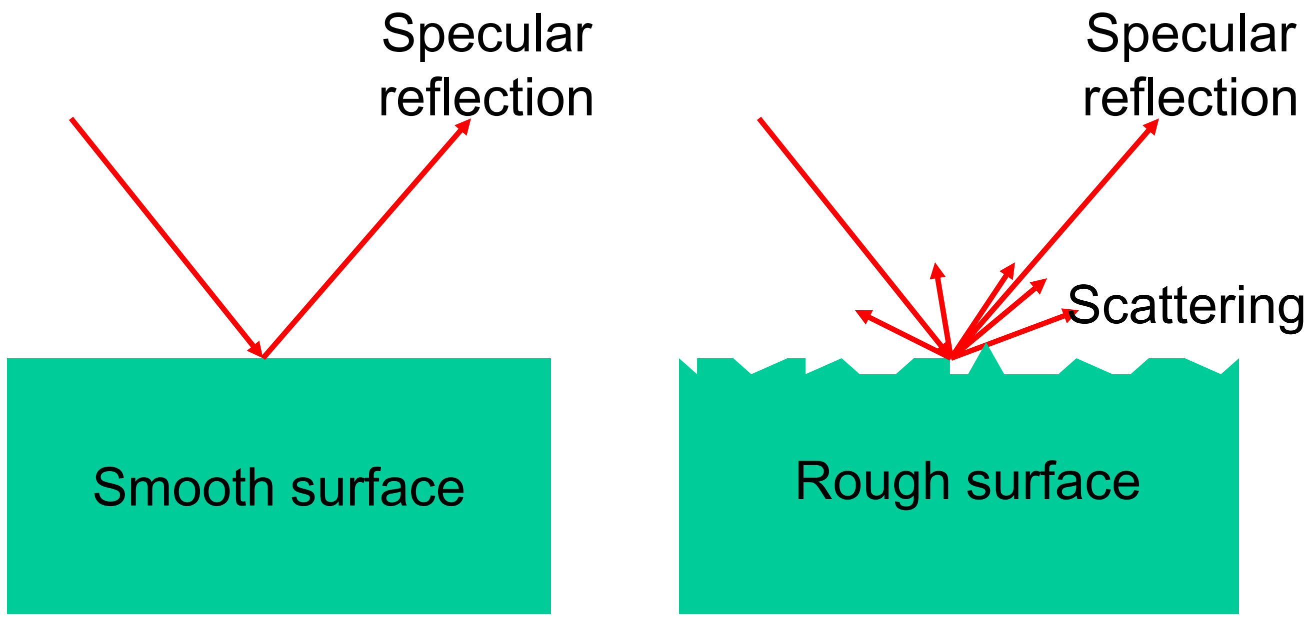
Diffraction – Epstein-Petersen Method



compute diffraction loss for each screen separately and add the losses

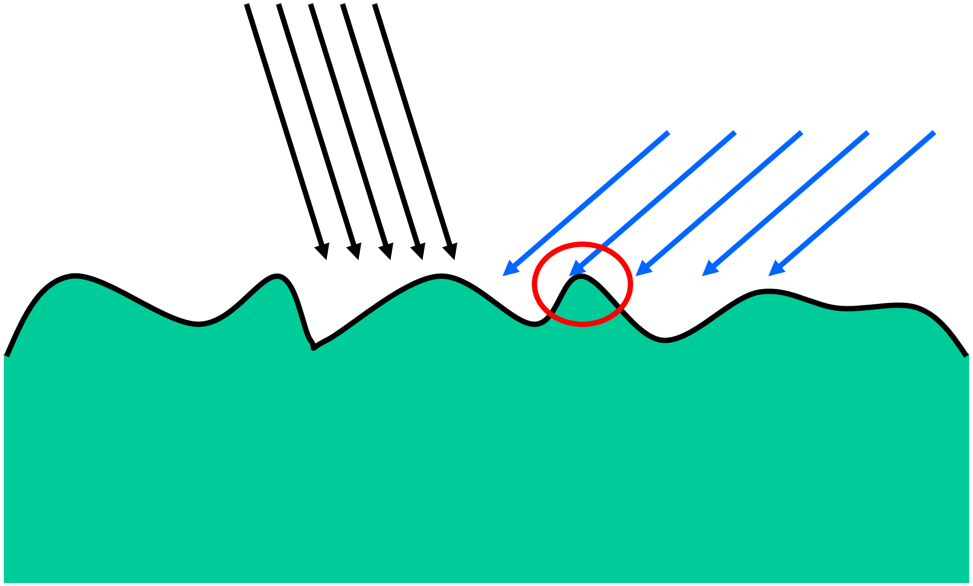
$$L_{tot}=L_1+L_2+L_3$$

Scattering



A surface is smooth, when the average height is smaller than the wavelength

Kirchhoff theory – scattering by rough surfaces



for Gaussian surface distribution

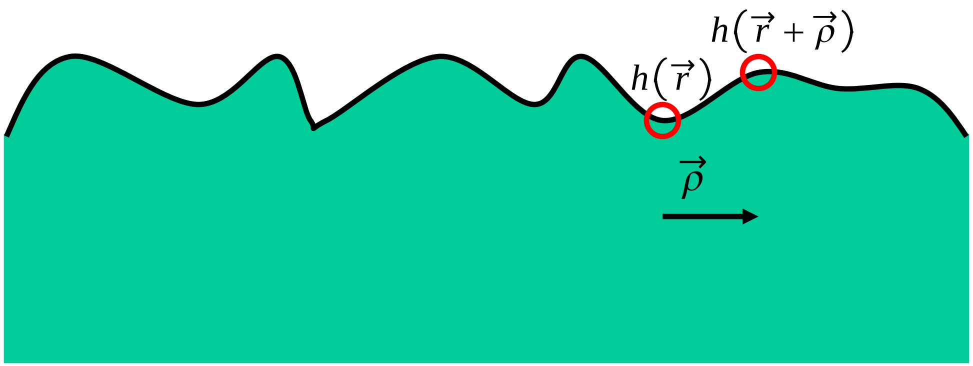
angle of incidence

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

standard deviation of height

Pertubation theory – scattering by rough surfaces

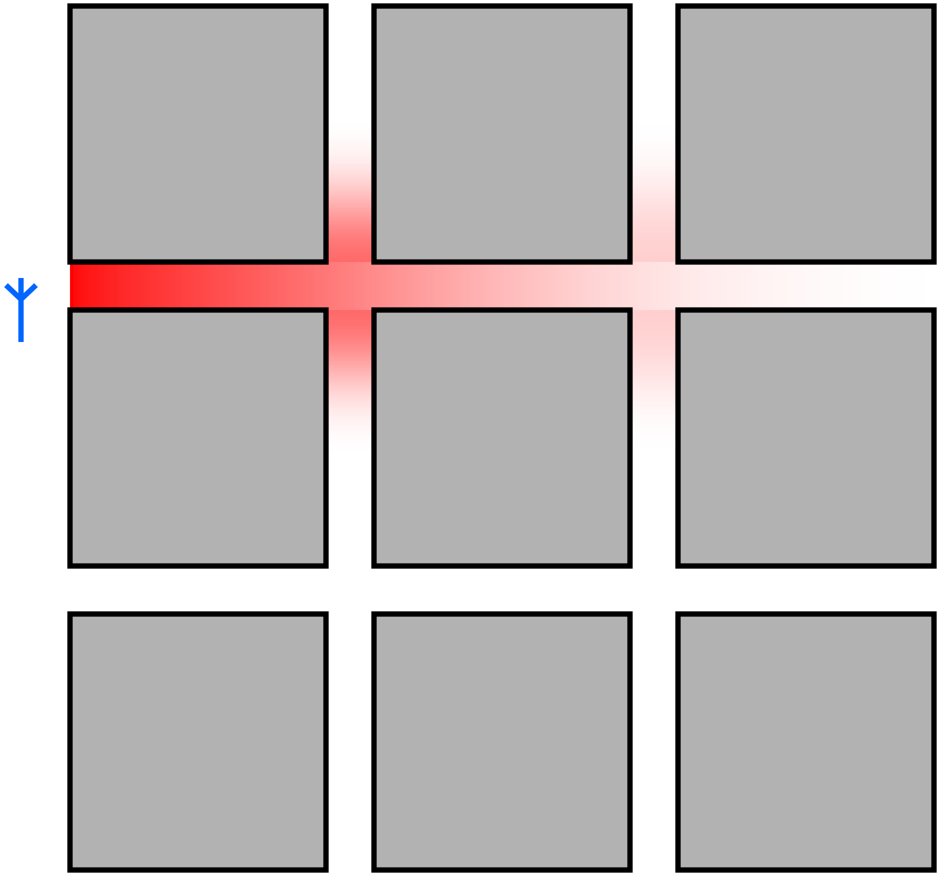
$$\sigma_{\mathrm{h}}^2 W(\vec{\rho}) = E_{\vec{r}}\{h(\vec{r})h(\vec{r}+\vec{\rho})\}$$



derive effective dielectric constant based on roughness and then use Snells law

More accurate than Krichhoff theory, especially for large angles of incidence and “rougher” surfaces

Waveguiding



Waveguiding effects often result in lower propagation exponents

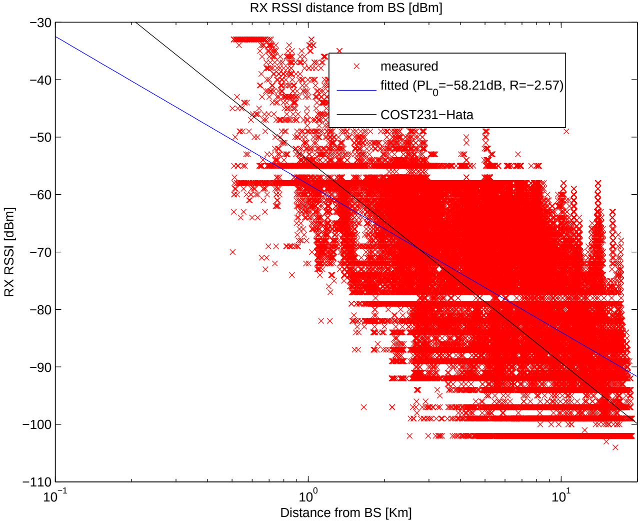
n=1.5-5

This means lower path loss along certain street corridors

Empirical path loss models

- Analytical path loss models: free space, d^{-4} law
- They require exact knowledge of environment, and are not always exact
- Alternative: empirical models based on measurements

Empirical path loss models: Example



Empirical path loss models: Method

- Plot received signal level P vs. distance d on a log-log scale
- Use linear regression to fit a linear function (use $P_0 = PL(d_{ref})$ as reference point)

$$r_i = P_0|_{\text{dB}} + n * \log(d_i/d_{ref}), \quad i = 0, \ldots, N-1$$

- “Standardized” empirical models
  - Okumura-Hata
  - Walfish-Ikegami
  - Motley-Keenan (indoor)