
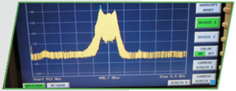


Radio Engineering

Lecture 2: Antennas and Propagation

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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 $G_{\mathrm{TX}} = 10$ dB and $G_{\mathrm{RX}} = 0$ dB,
- Cable losses at TX $L_{\mathrm{TX}} = 5$ 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

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

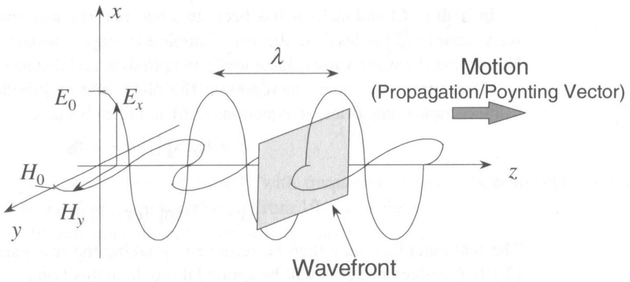


Figure 2.1: A plane wave

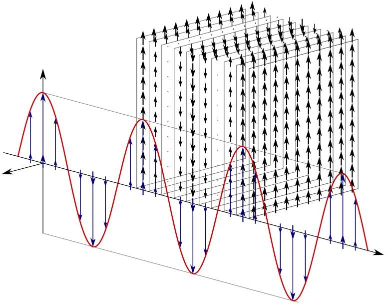
Linear and circular polarized plane waves (1)

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

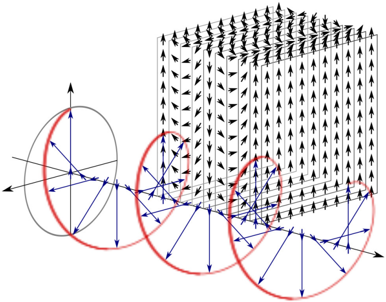
$$\mathbf{E} = E_x\mathbf{x} + E_y\mathbf{y}$$

- *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

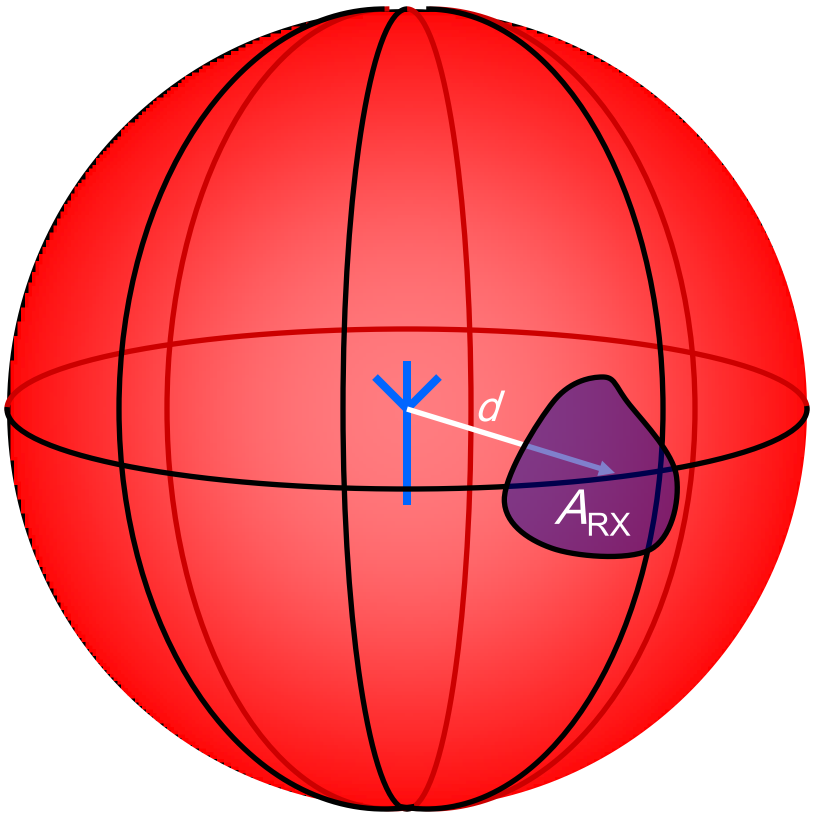
Without reliable channel models, it is hard to design radio systems that work well in *real* environments.

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



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):

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

Free-space loss
Friis' law

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

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

$$\Longleftrightarrow$$

Valid in the far field only

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

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

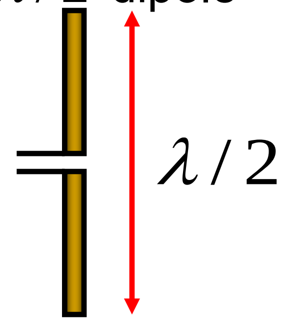
Free-space loss
What is far field?

Rayleigh distance:

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

where L_a is the largest dimesion of the antenna.

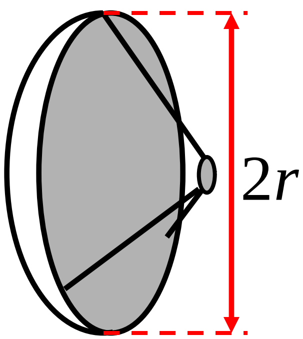
$\lambda/2$-dipole



$L_a = \lambda/2$

$d_R = \lambda/2$

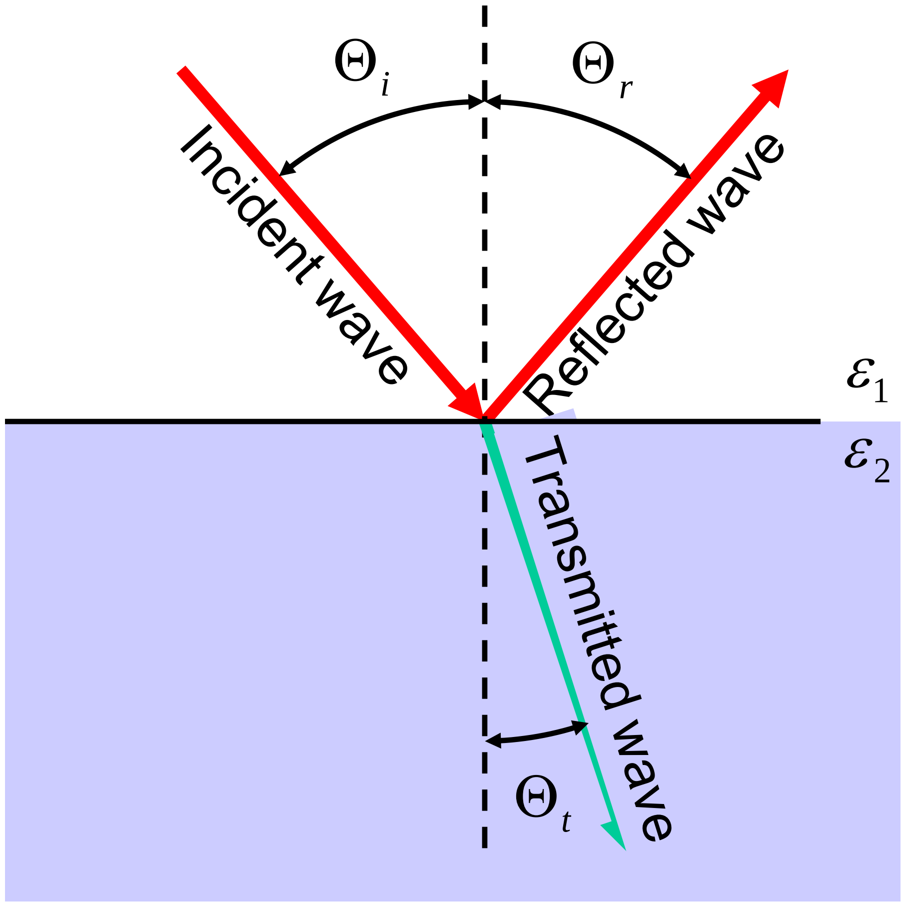
Parabolic



$L_a = 2r$

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

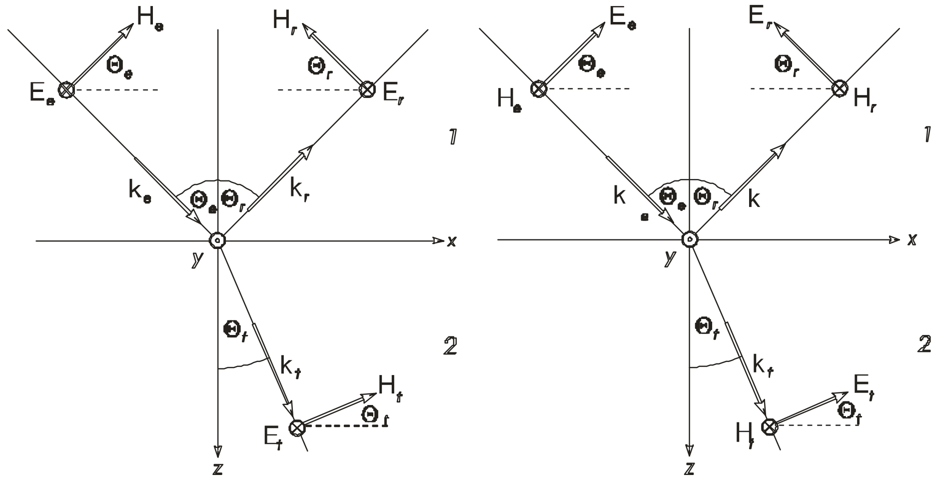
Reflection and transmission (1)



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

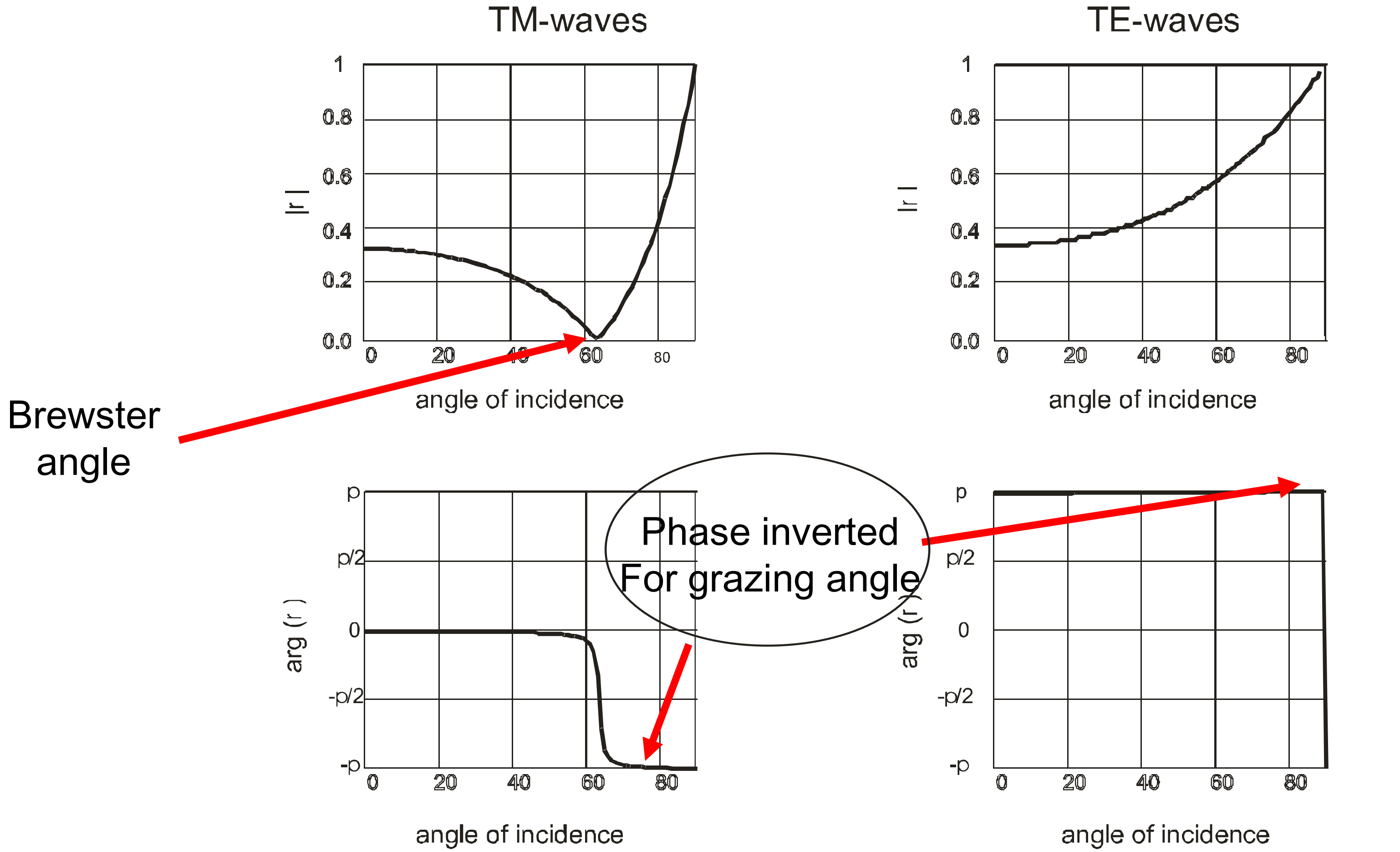
TE TM



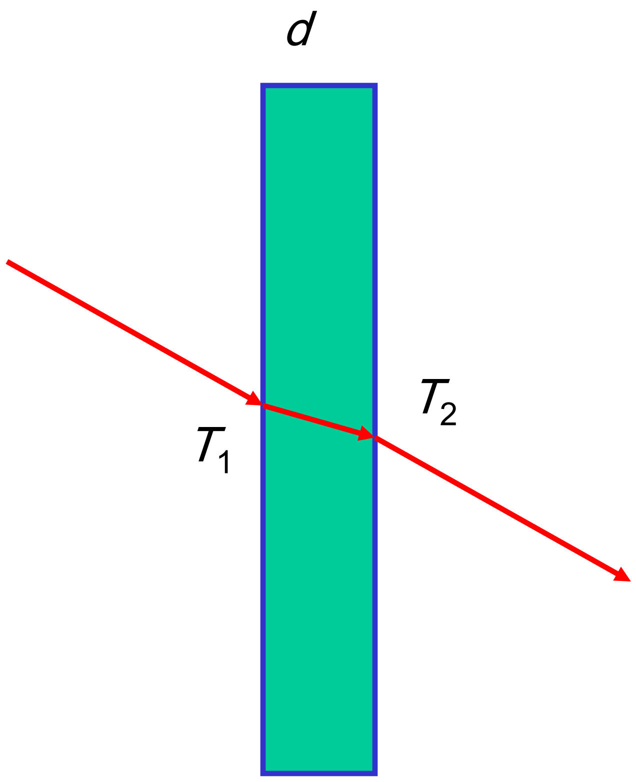
Reflection and transmission (3)

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

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



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

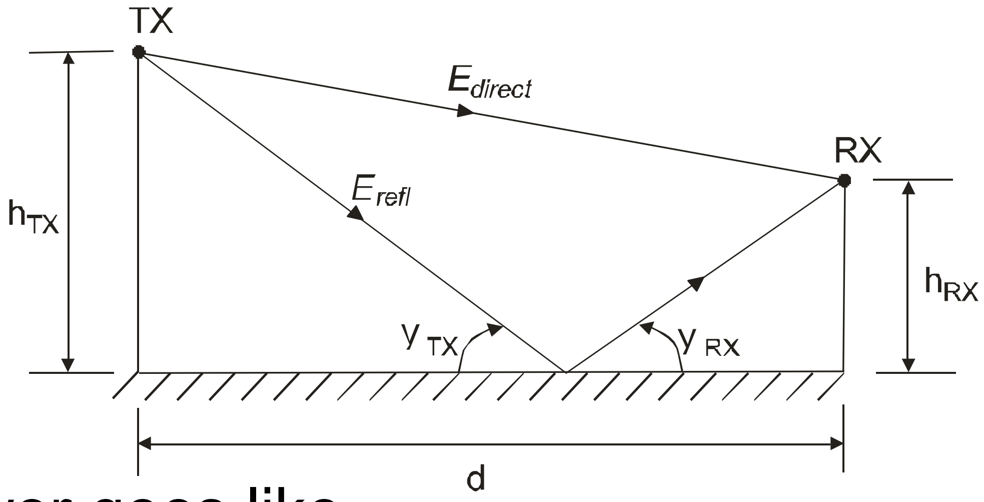
$$\rho = \frac{\rho_1 + \rho_2 e^{-j2\alpha}}{1 + \rho_1 \rho_2 e^{-2j\alpha}}$$

with the electrical length in the wall

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

The d^{-4} law (1)

- For the following scenario



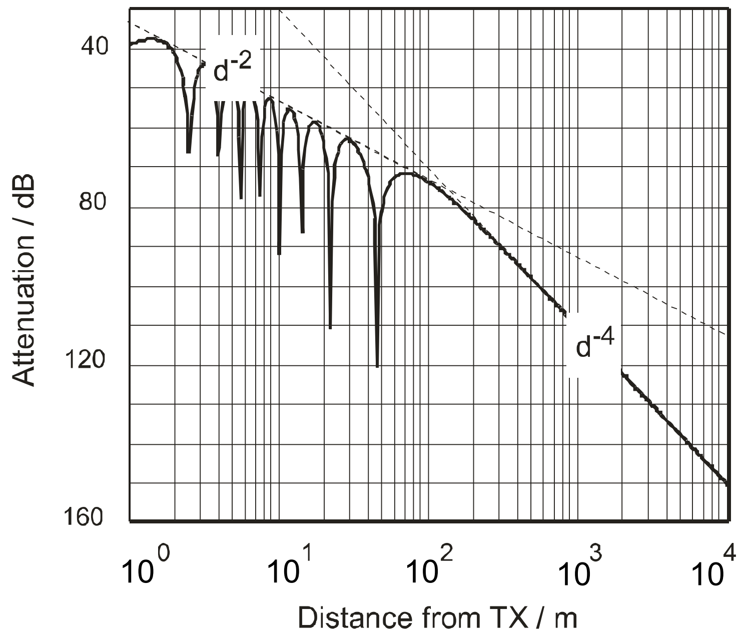
- the power goes like

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

- for distances greater than

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

The d^{-4} law (2)

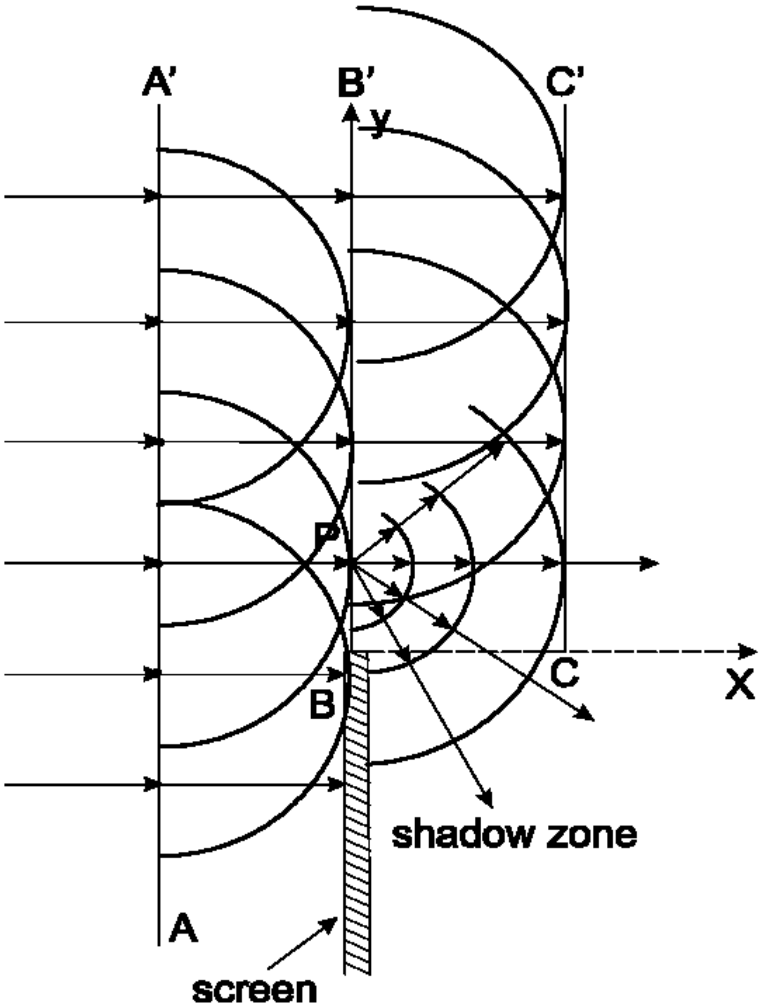


htx = 5m

hrx = 1.5m

fc = 900MHz

Diffraction, Huygen’s principle



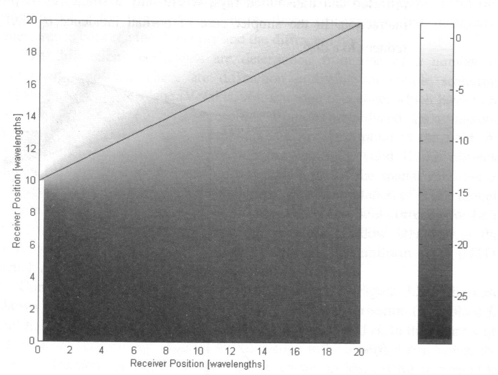
* Semi-infinite screen
* Each point of the wavefront can be considered as a source of a spherical wave
* Screen eliminates parts of the waves
* Constructive and destructive interference

Fresnel integral

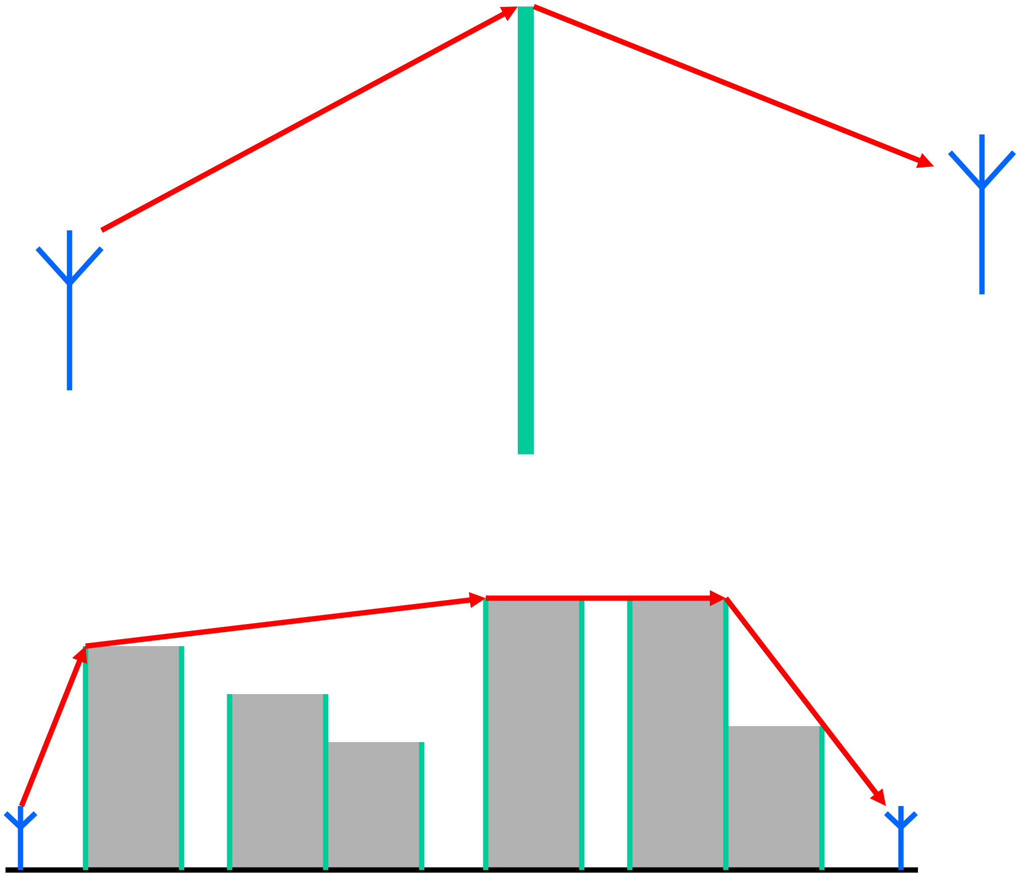
- The electric field (for $x \geq 0$) can be expressed as

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

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

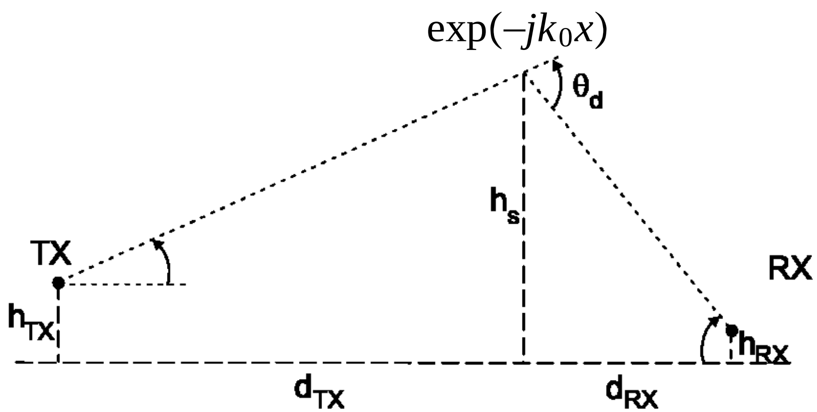


Diffraction



- 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

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

with the Fresnel parameter

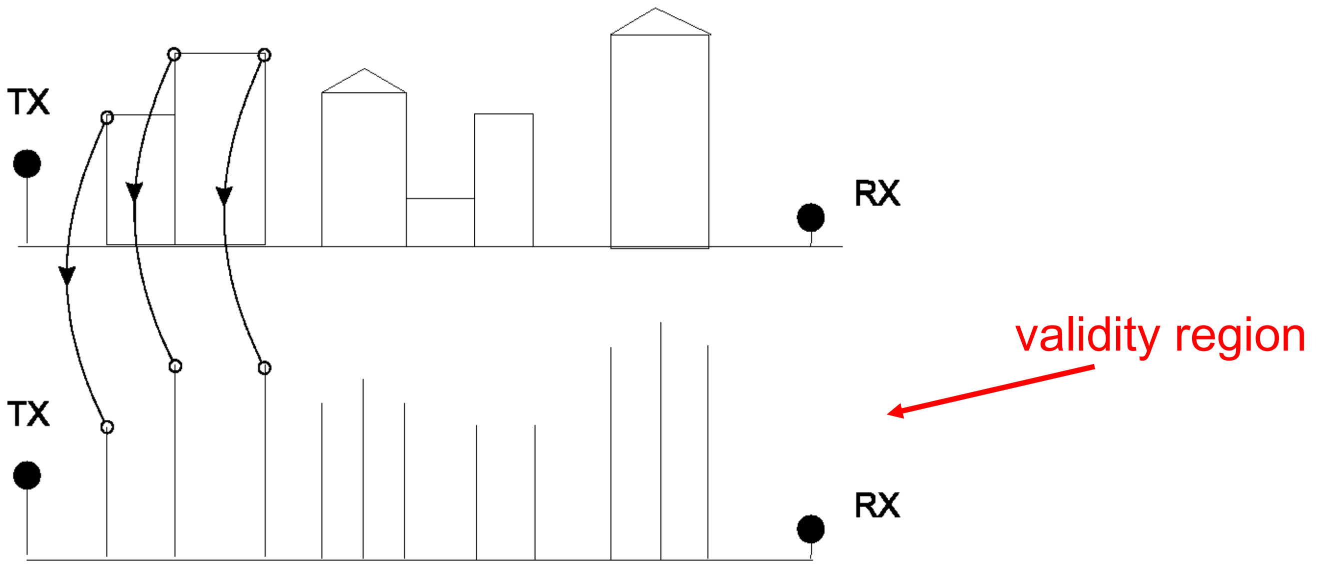
$$\nu_F = \alpha_k \sqrt{\frac{2d_1d_2}{\lambda(d_1+d_2)}}$$

Total field

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

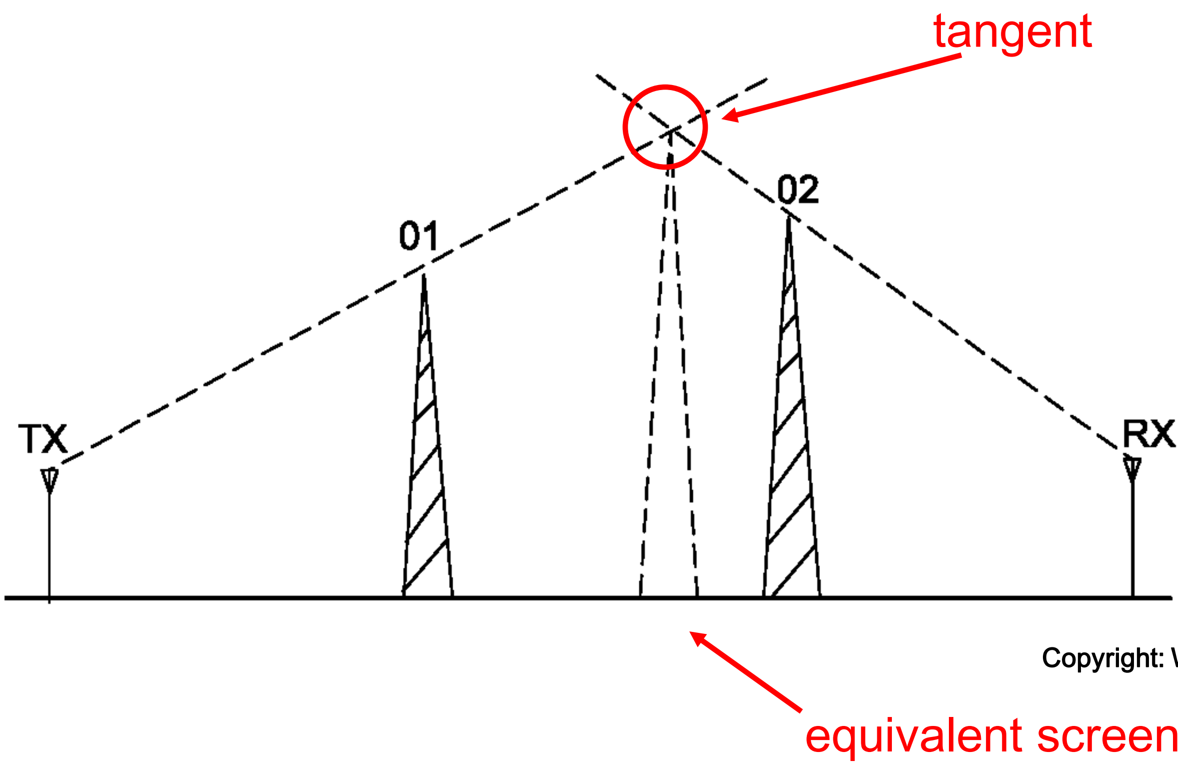
Fresnel integral

Diffraction in real environments



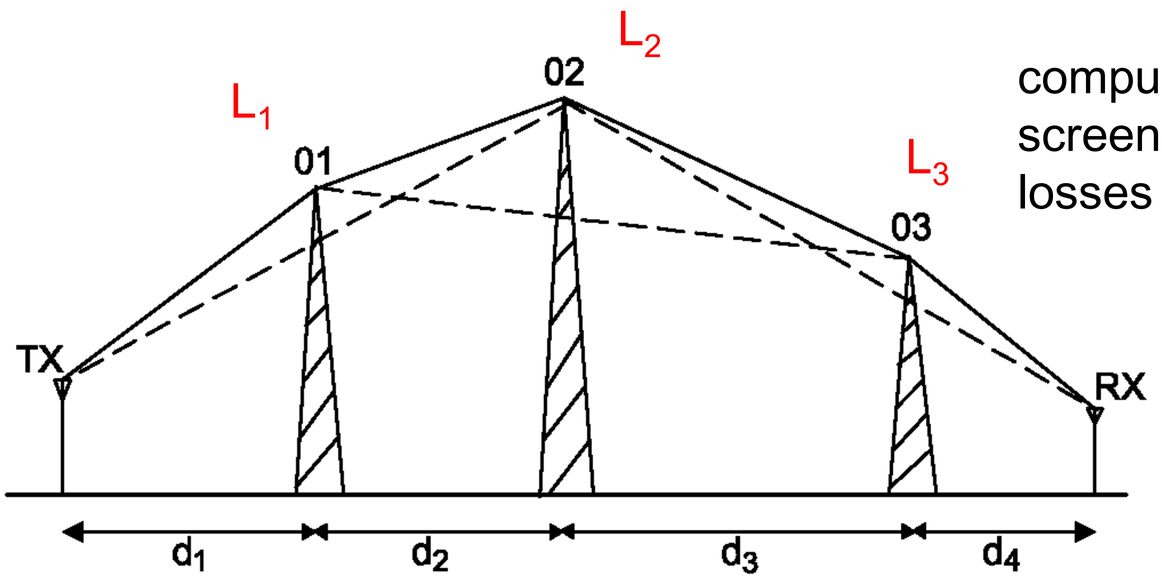
Approximation of multiple buildings by a series of screens

Diffraction – Bullington's method



$$E_{\text{total}} = \exp(-jk_0 x)\left(\frac{1}{2} - \frac{\exp(-j\pi/4)}{\sqrt{2}} F\left(\nu_{\mathrm{F}}\right)\right) \qquad \nu_{\mathrm{F}} = \alpha_k \sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$$

Diffraction – Epstein-Petersen Method



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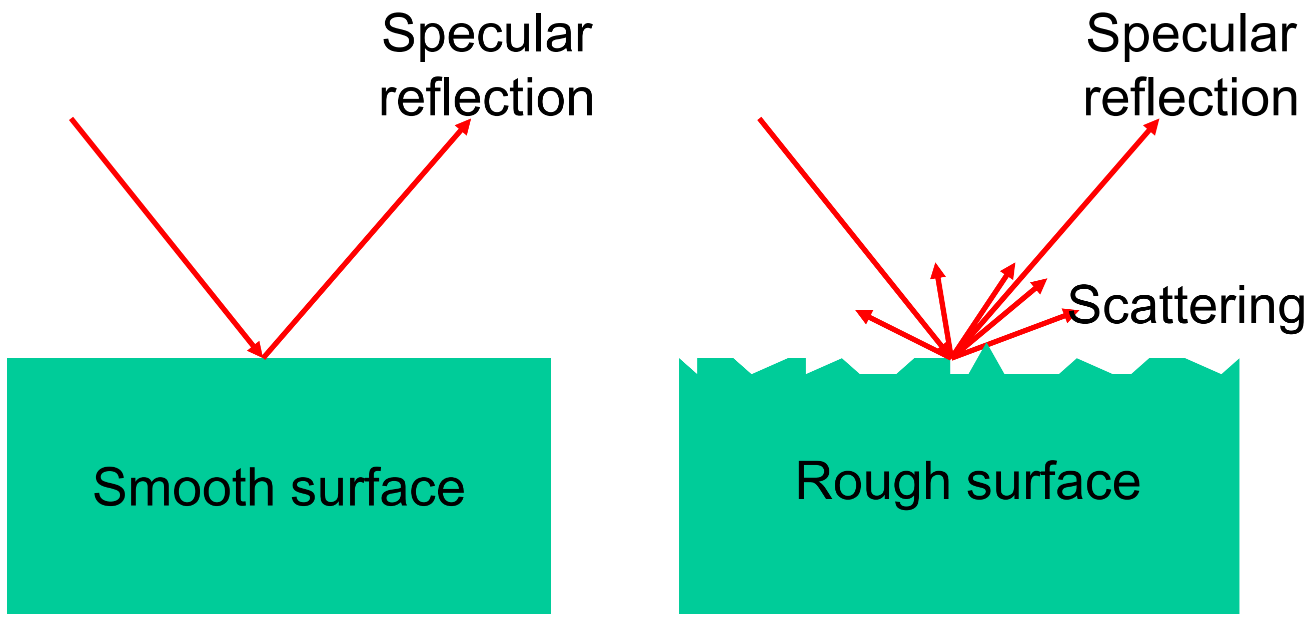
compute diffraction loss for each screen separately and add the losses

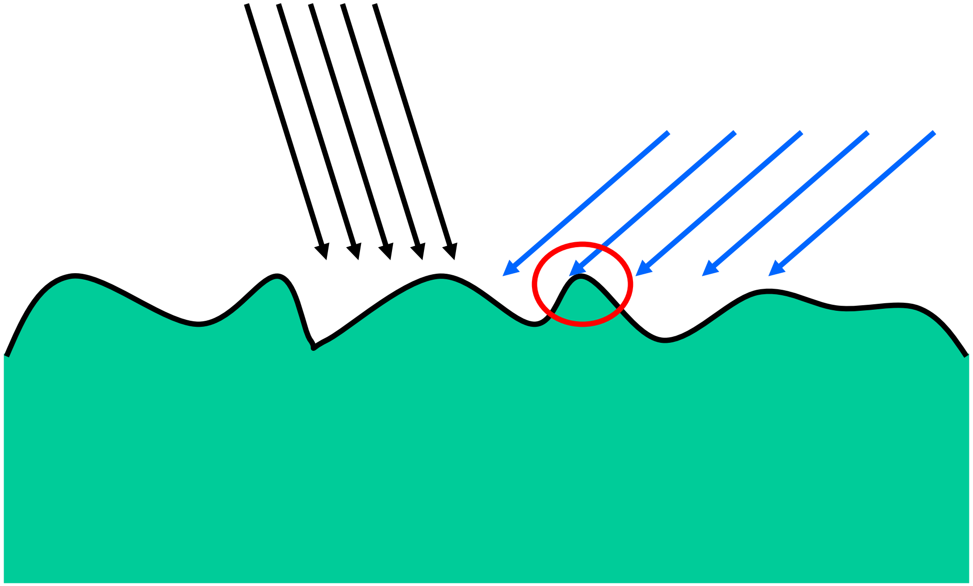
$$L_{tot}=L_1+L_2+L_3$$

Scattering



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

Kirchhoff theory – scattering by rough surfaces



for Gaussian surface distribution

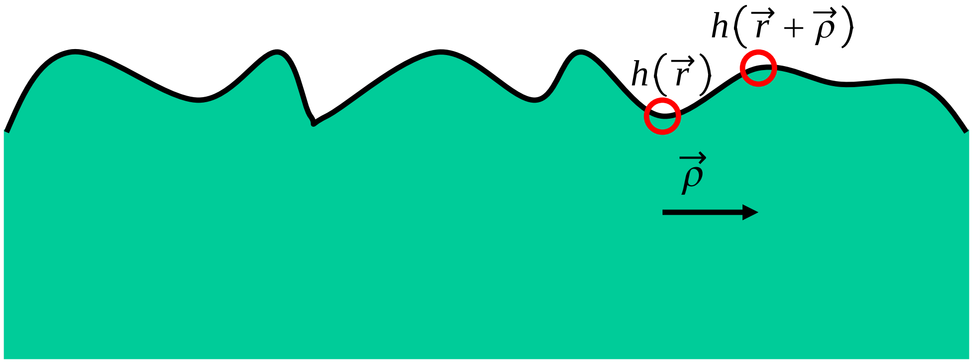
$$\rho_{\mathrm{rough}} = \rho_{\mathrm{smooth}} \exp\left[-2\left(k_0 \sigma_{\mathrm{h}} \sin\psi\right)^2\right]$$

angle of incidence

standard deviation of height

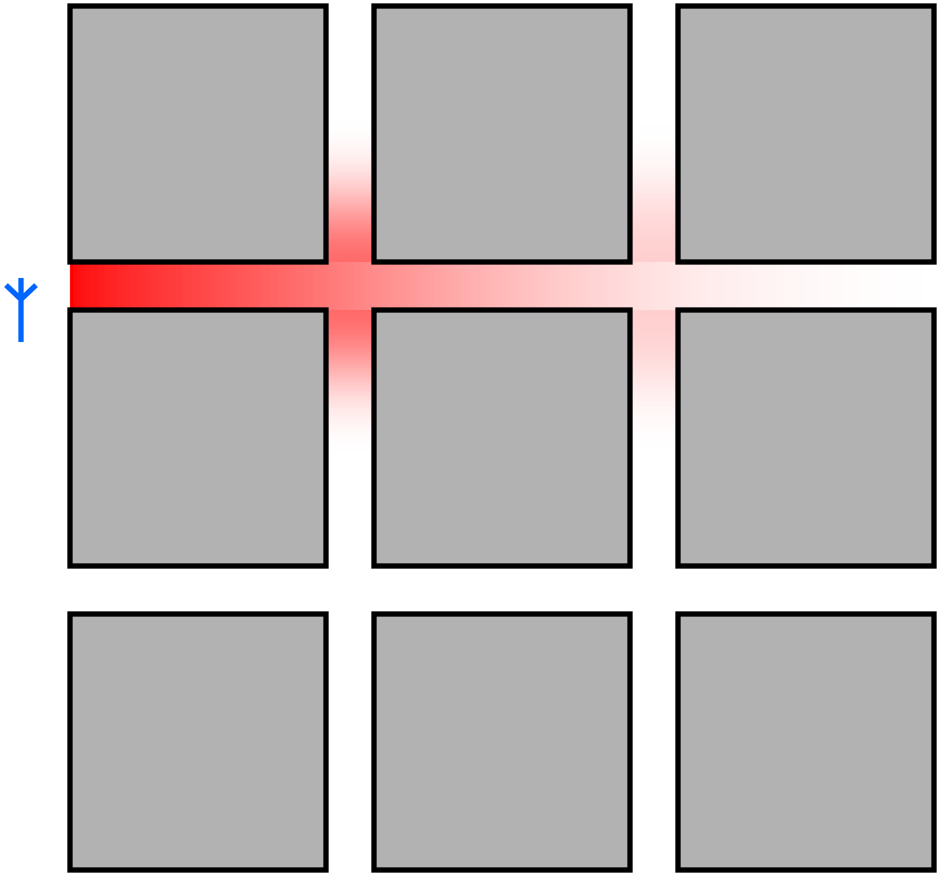
Pertubation theory – scattering by rough surfaces

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



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

Waveguiding



Waveguiding effects often result in lower propagation exponents

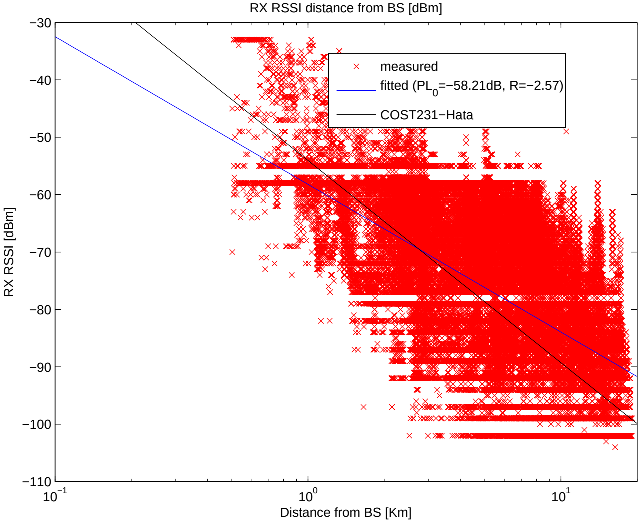
n=1.5-5

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)