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Wireless Communications Channels
Lecture 2: Propagation Mechanisms

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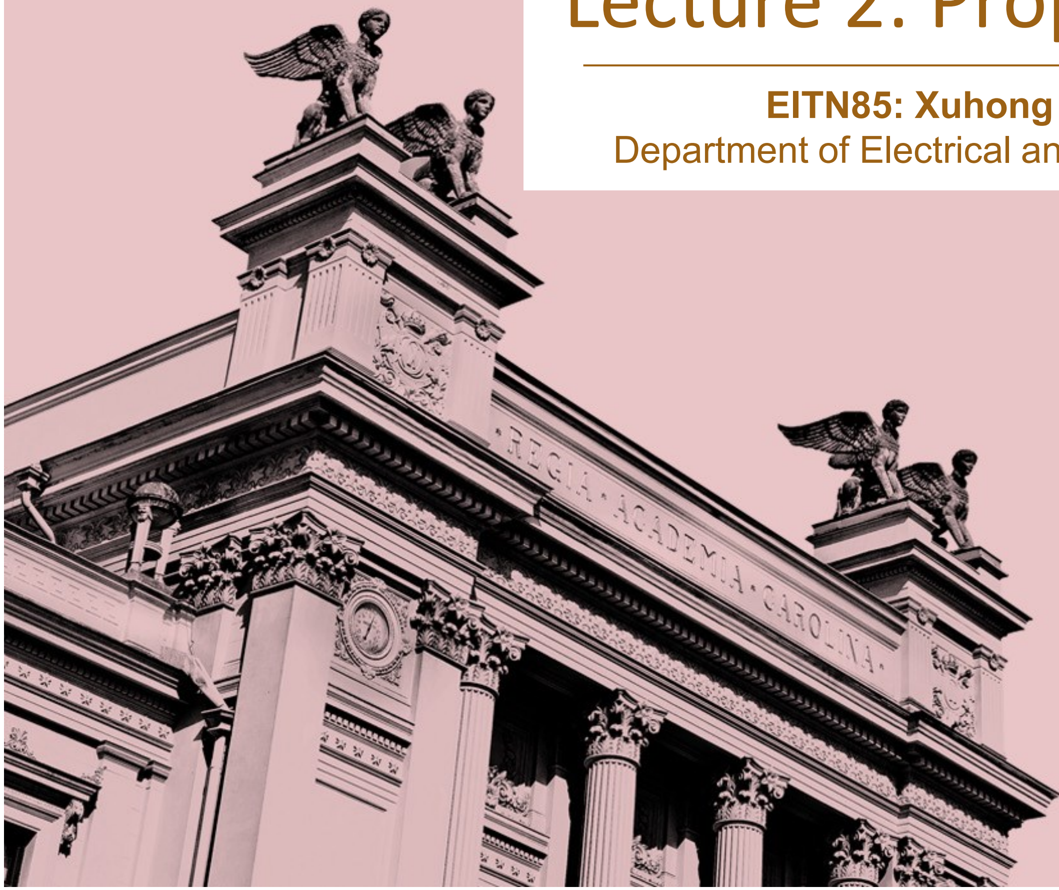

Recap: Last Lecture

Contents

Propagation mechanisms:

- ❑ Free space attenuation

- ❑ Reflection and transmission
- ❑ Diffraction
- ❑ Diffuse scattering
- ❑ Waveguiding

Examples from real world propagation scenarios

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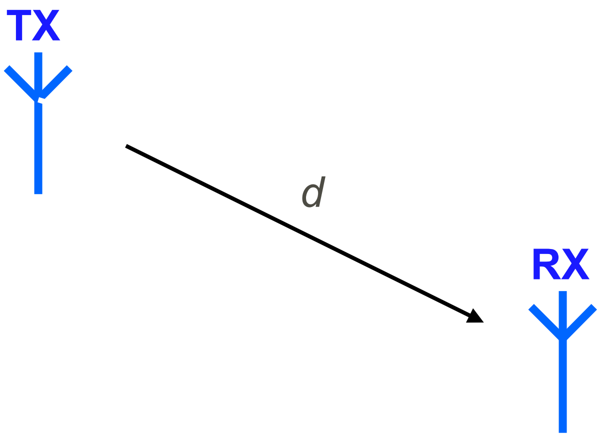
Free space attenuation

- Assume TX and RX antennas in **free space** and would like to derive the received power as a function of link distance and transmit power
  - Assume omnidirectional antennas for now



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Free space attenuation

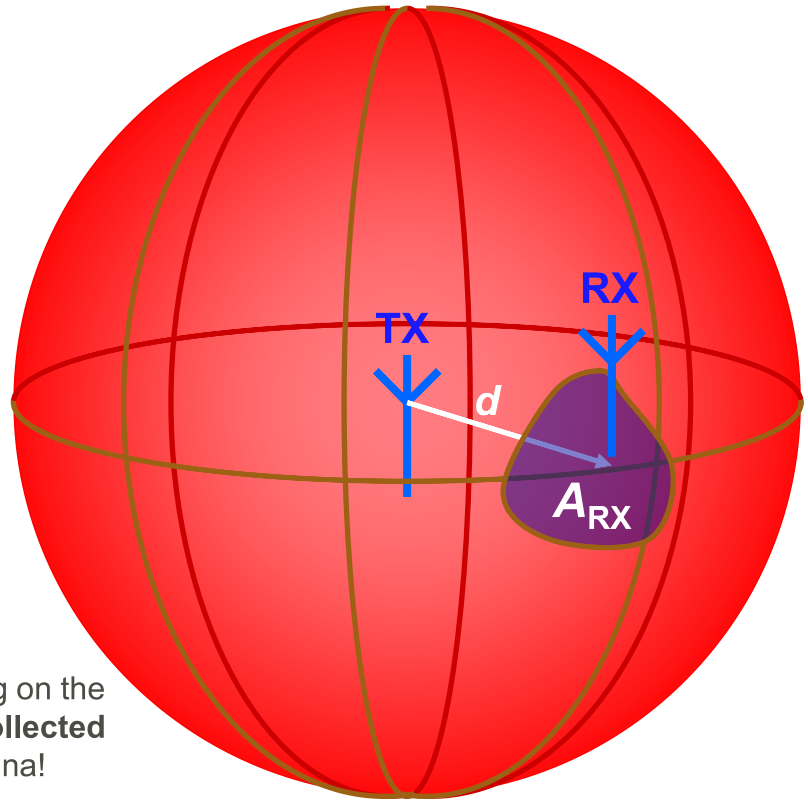
- Assume TX and RX antennas in **free space** and would like to derive the received power as a function of link distance and transmit power (omnidirectional antennas)

- Energy conservation: integral of power density over any **closed surface** = transmit power

- If TX antenna radiates isotropically, then power density on surface is $P_{\mathrm{TX}}/(4\pi d^2)$. Then,

$$P_{\mathrm{RX}}(d) = P_{\mathrm{TX}} \frac{1}{4\pi d^2} A_{\mathrm{RX}}$$

Power impinging on the area which is **collected** by the RX antenna!



Shpere of radius *d*

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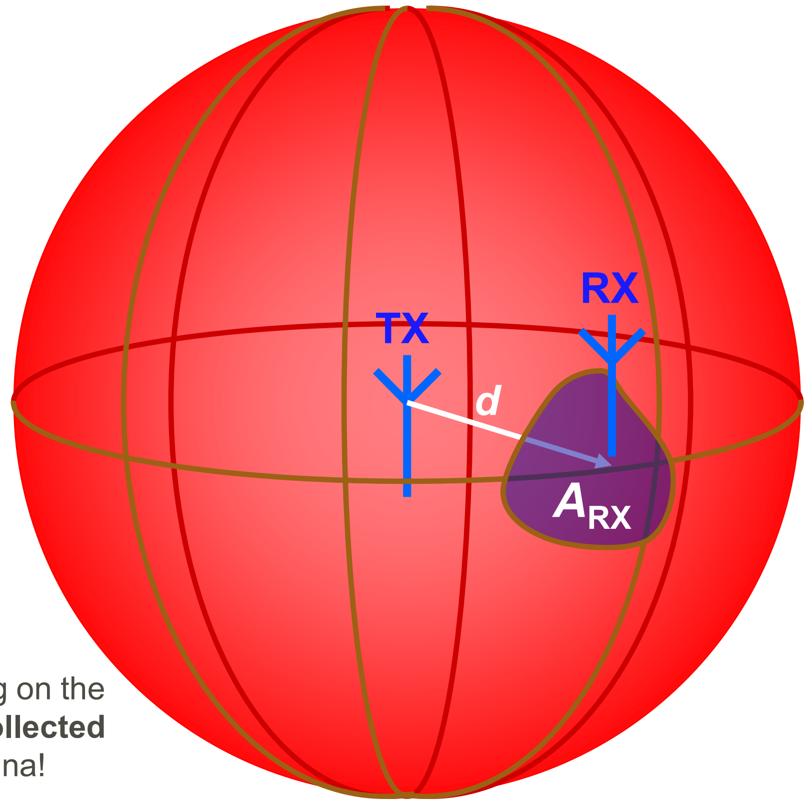


Shpere of radius *d*

- Product of TX power and gain is known as: effective isotropic radiated power (EIRP)

- Relationship between effective area and antenna gain: $G_{\mathrm{RX}} = \left(\frac{4\pi}{\lambda^2}\right) A_{\mathrm{RX}}$

Free space loss: Friis' law

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

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

Free space loss factor

RX power goes down as a function of frequency, for a fixed distance.

$$\Updownarrow$$

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

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

Question: What happens if *d* is 0 in * ?

Free space loss: Friis' law implications

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

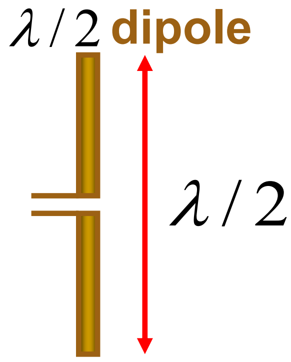
Free space loss:
What and where is the far field?

The free space loss calculations are only valid in the ”far field” of the antennas.

Far-field conditions are assumed far beyond the ”Rayleigh” distance:

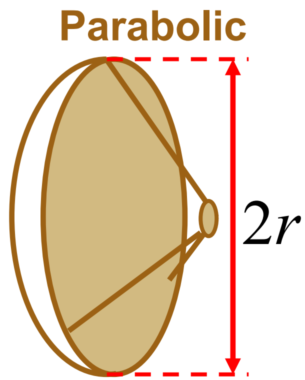
$$d_R = \frac{2L_a^{\,2}}{\lambda}$$

where L_a is the largest dimension of the antenna.



$$L_a = \lambda/2$$

$$d_R = \lambda/2$$



$$L_a = 2r$$

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

Another rule of thumb is: ”*At least* 10 wavelengths”

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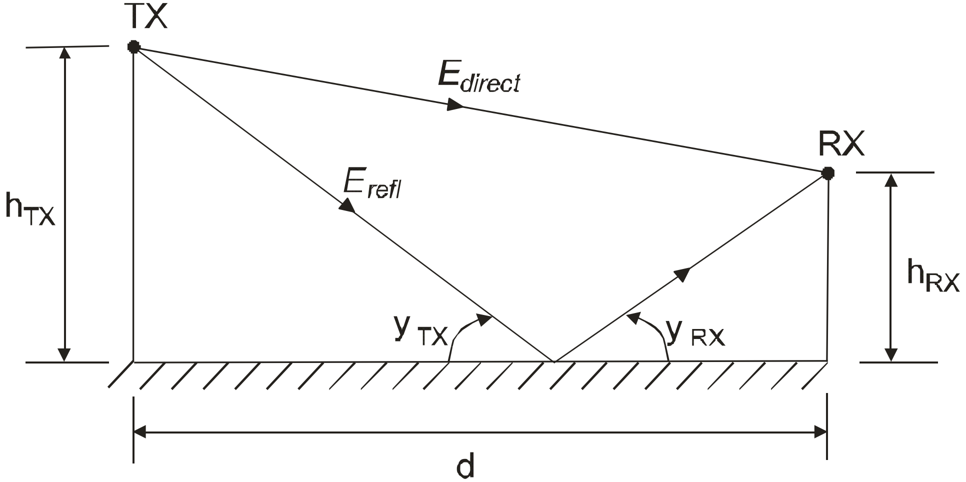
Quiz

Compute the Rayleigh distance of a square patch antenna receiving a signal with a gain of 10 dB.

The d^{-4} law – I

Instead of just considering a direct path, let's look at the following scenario



the power behaves as

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

for distances greater than

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

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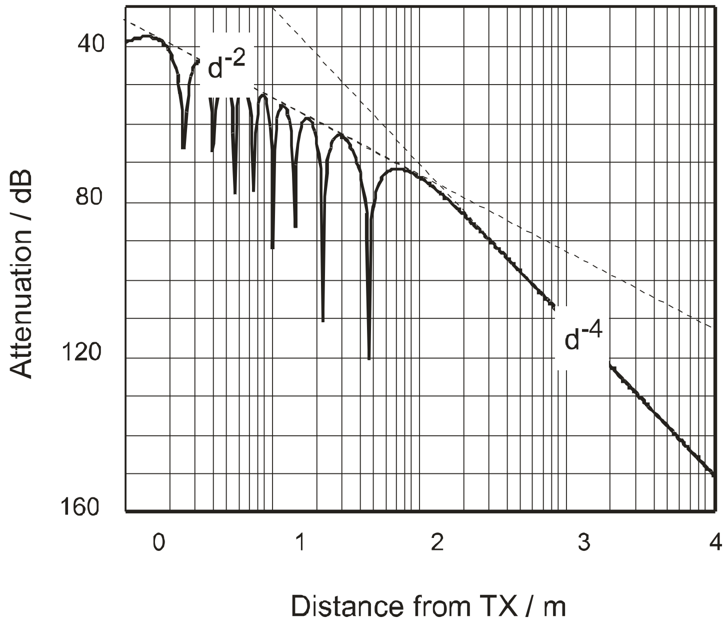
Continuation of Slide (10): How?

The d^{-4} law – II



- However …..
  - n=4 is not a universal decay exponent
  - Theoretical model is not fulfilled in practice
  - Breakpoint is rarely where theoretically predicted
  - Second breakpoint at the radio horizon

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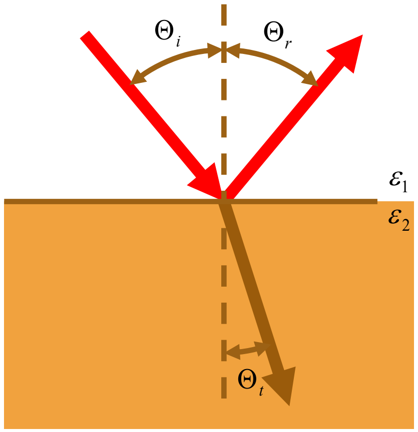
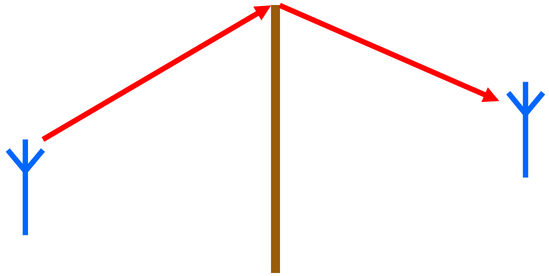
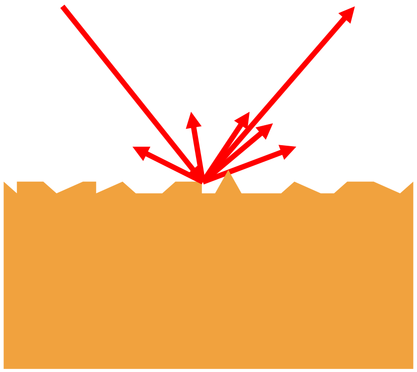
Fundamental propagation mechanisms



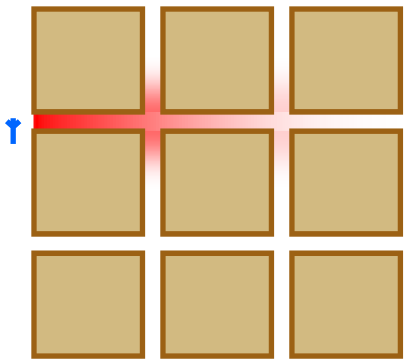
Reflection and transmission



Diffraction



Scattering



Waveguiding

Complex dielectric constant

Lets take a homogeneous planewave incident onto a dielectric half-space

conductivity

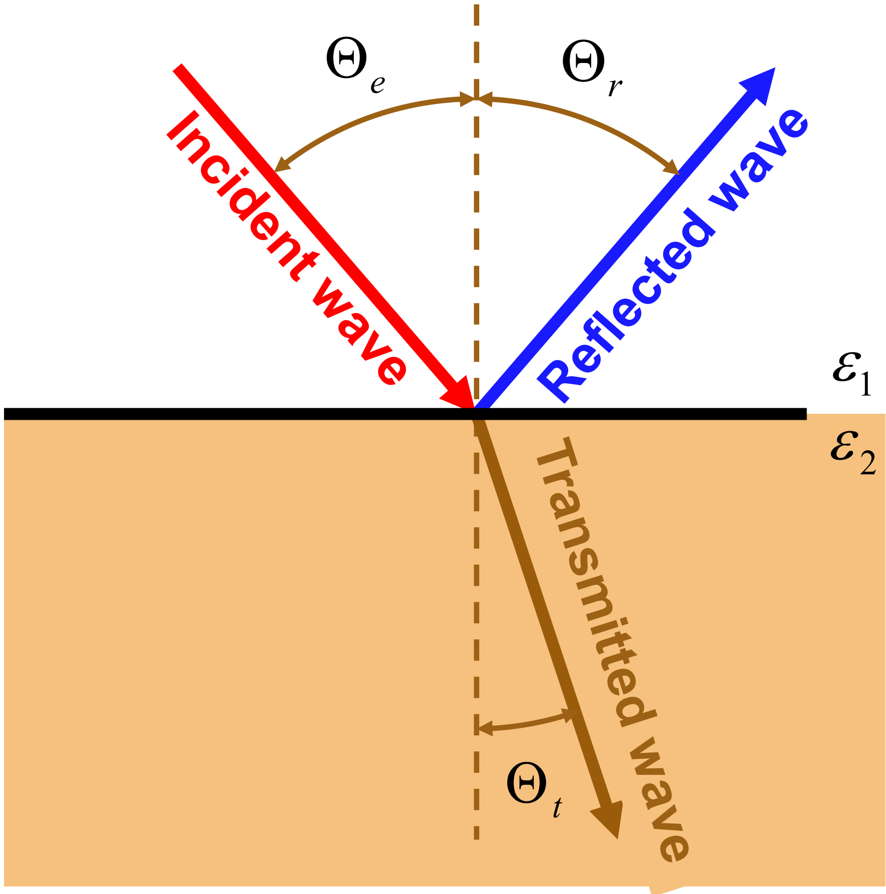
$$\delta_i = \varepsilon_i - j\frac{\sigma_{e,i}}{2\pi f_c}$$

dielectric constant, permittivity

Describes the dielectric material in one single parameter

Examples	Permittivity	conductivity
Concrete	6	10^{-2}
Gypsum	6.5	10^{-2}
Wood	23	10^{-11}
Glass	5	10^{-12}
Air	1	

Reflection and transmission



Reflected angle:

$$\Theta_e = \Theta_r.$$

Transmitted angle:

$$\frac{\sin\Theta_t}{\sin\Theta_e} = \frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}}$$

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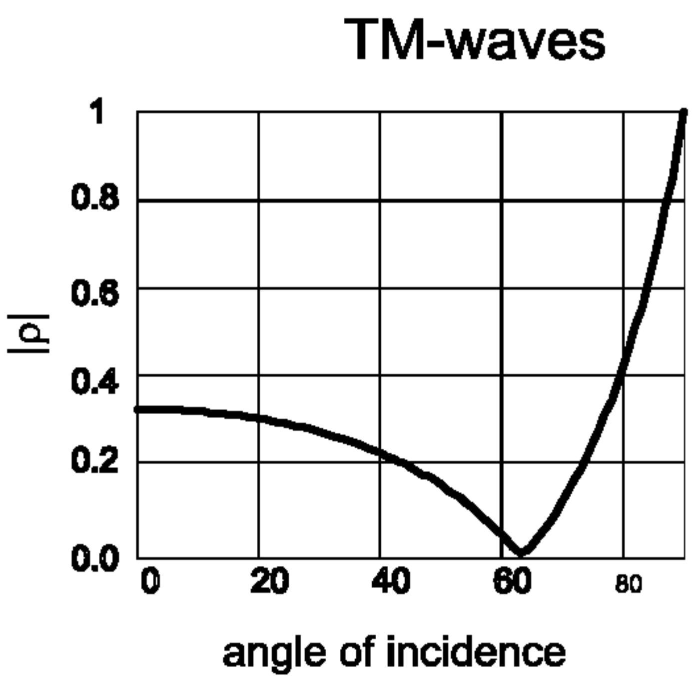
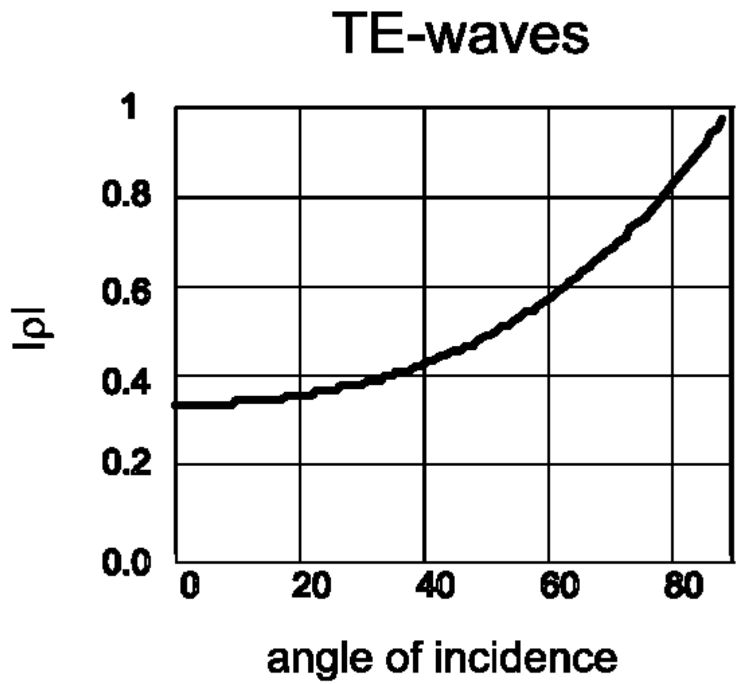
What is Reflection and Transmission Dependent on?

TM and TE Component Behaviors

Reflection coefficient

$$\rho_{TM} = -\frac{\sqrt{\delta_2}\cos\Theta_e - \sqrt{\delta_1}\cos(\Theta_t)}{\sqrt{\delta_2}\cos\Theta_e + \sqrt{\delta_1}\cos(\Theta_t)} \qquad \rho_{TE} = \frac{\sqrt{\delta_1}\cos(\Theta_e) - \sqrt{\delta_2}\cos(\Theta_t)}{\sqrt{\delta_1}\cos(\Theta_e) + \sqrt{\delta_2}\cos(\Theta_t)}$$





Transmission coefficient

$$T = \sqrt{1 - \rho^2}$$

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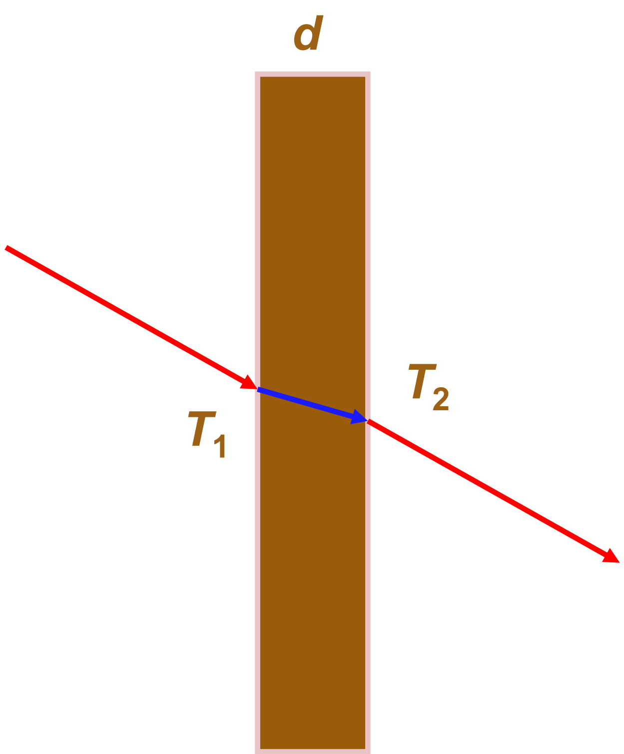
Transmission through layered structures



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

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

Wall with thickness *d* and two dielectrics

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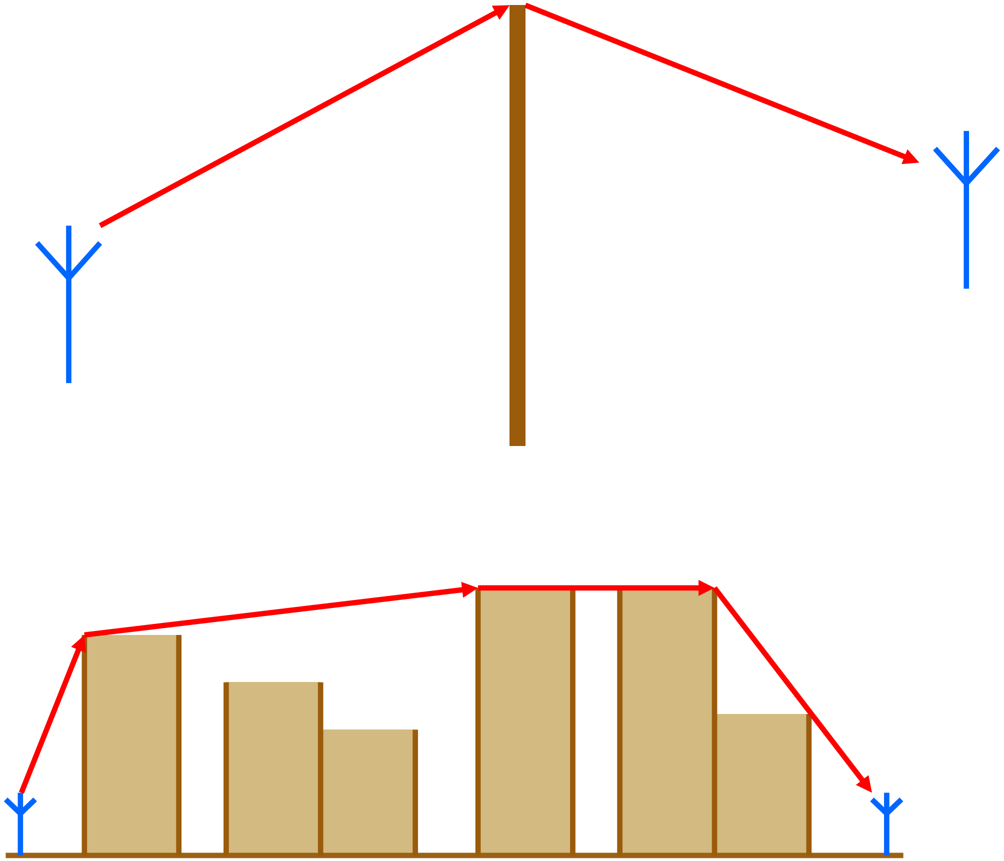
Diffraction: The principle



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

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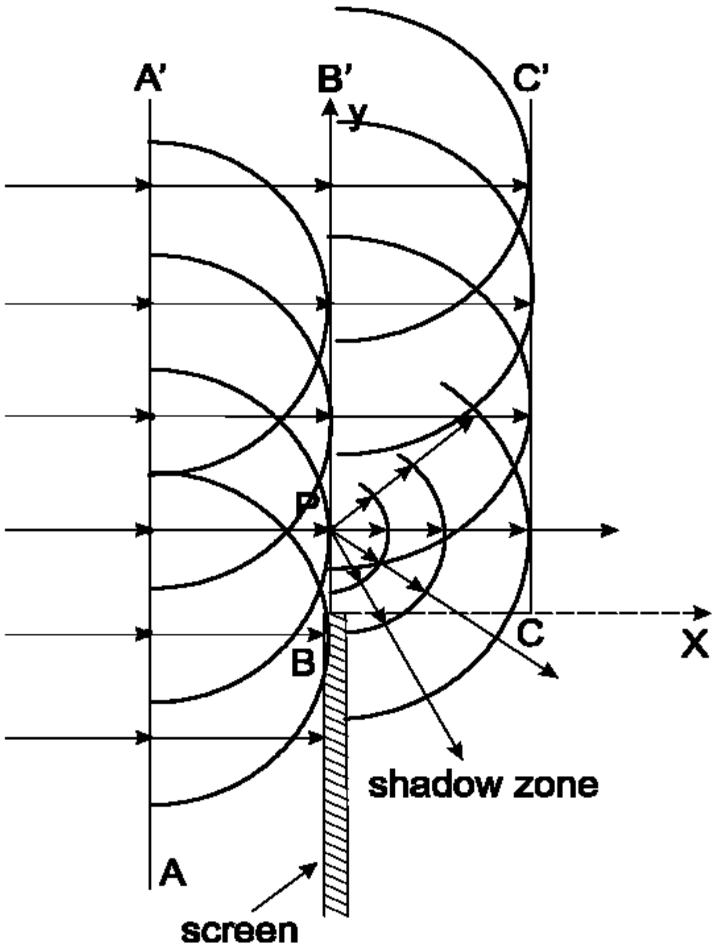
Diffraction: Huygen's principle



Each point of a wavefront can be considered as a source of a spherical wave

➡ **Bending around corners and edges**

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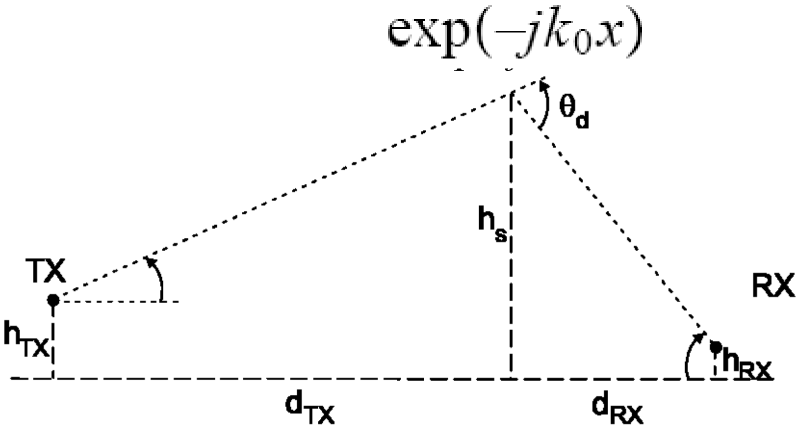
Diffraction coefficient



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

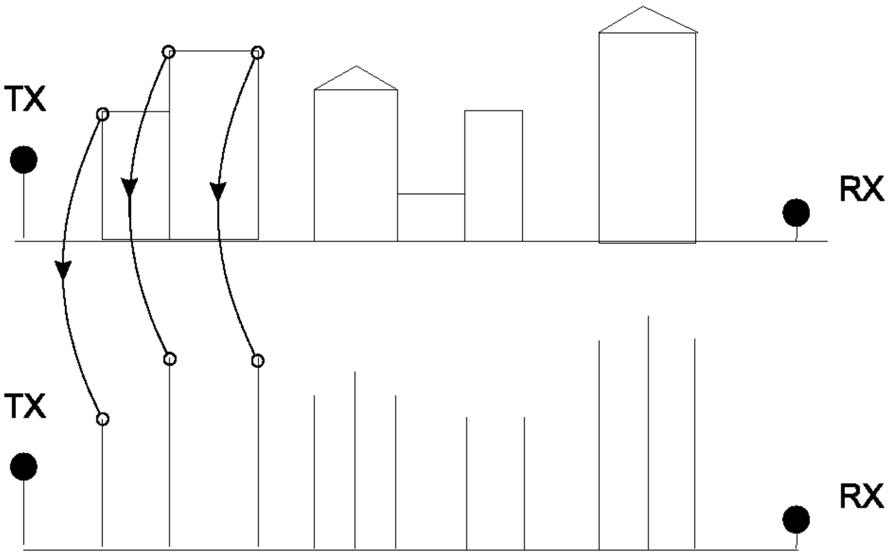
$$\nu_F = \alpha_k \sqrt{\frac{2d_1d_2}{\lambda(d_1+d_2)}}$$

Total field

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

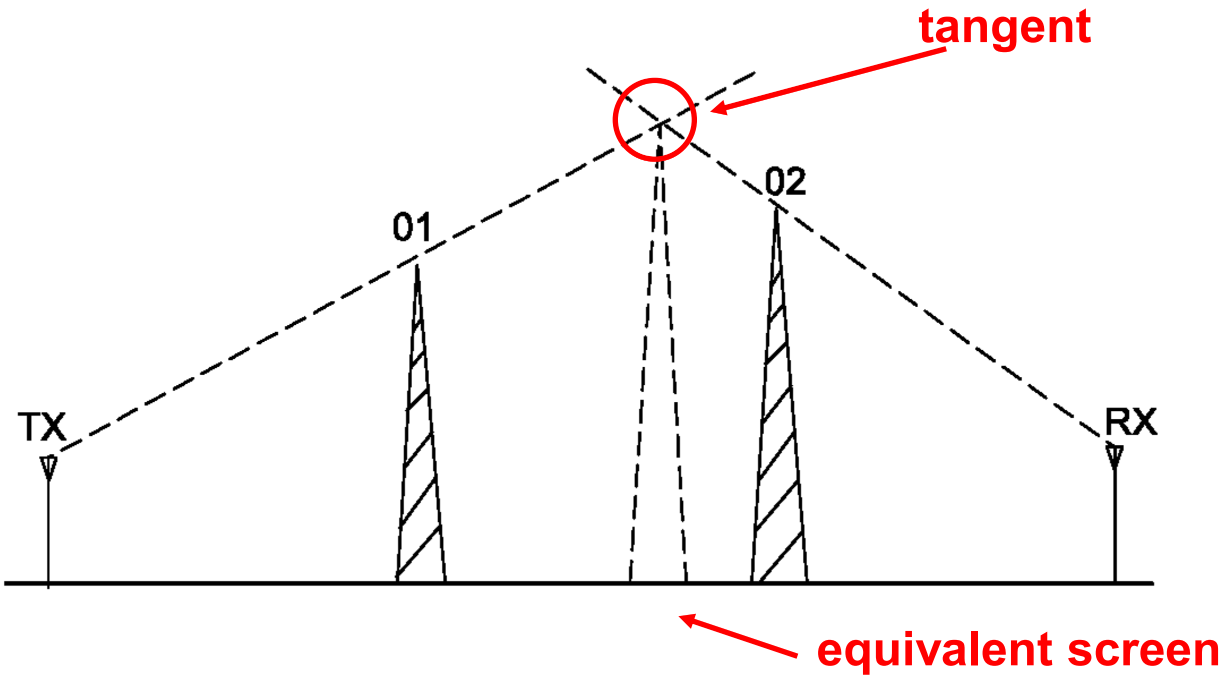
Fresnel integral

Diffraction in real environments



For real environments we can represent buildings and objects as multiple screens

Diffraction: Bullington's method



Replace all screens with one equivalent screen

Height determined by the steepest angle

Simple but a bit optimistic

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

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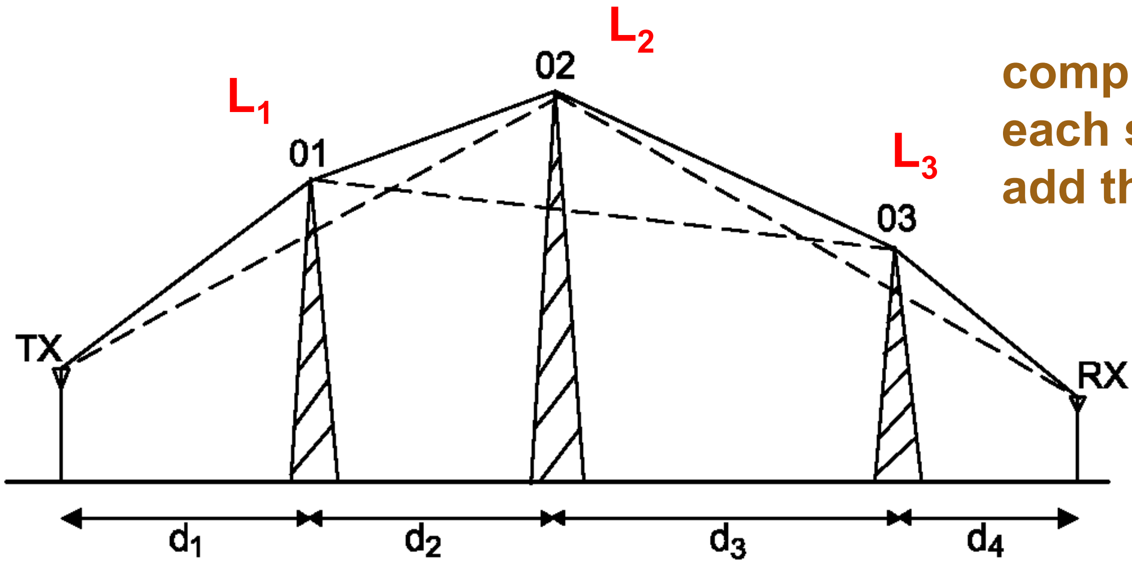
Diffraction – Epstein-Petersen Method



compute diffraction loss for each screen separately and add the losses

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

The same approach is used also for the ITU model, but with an empirical correction factor

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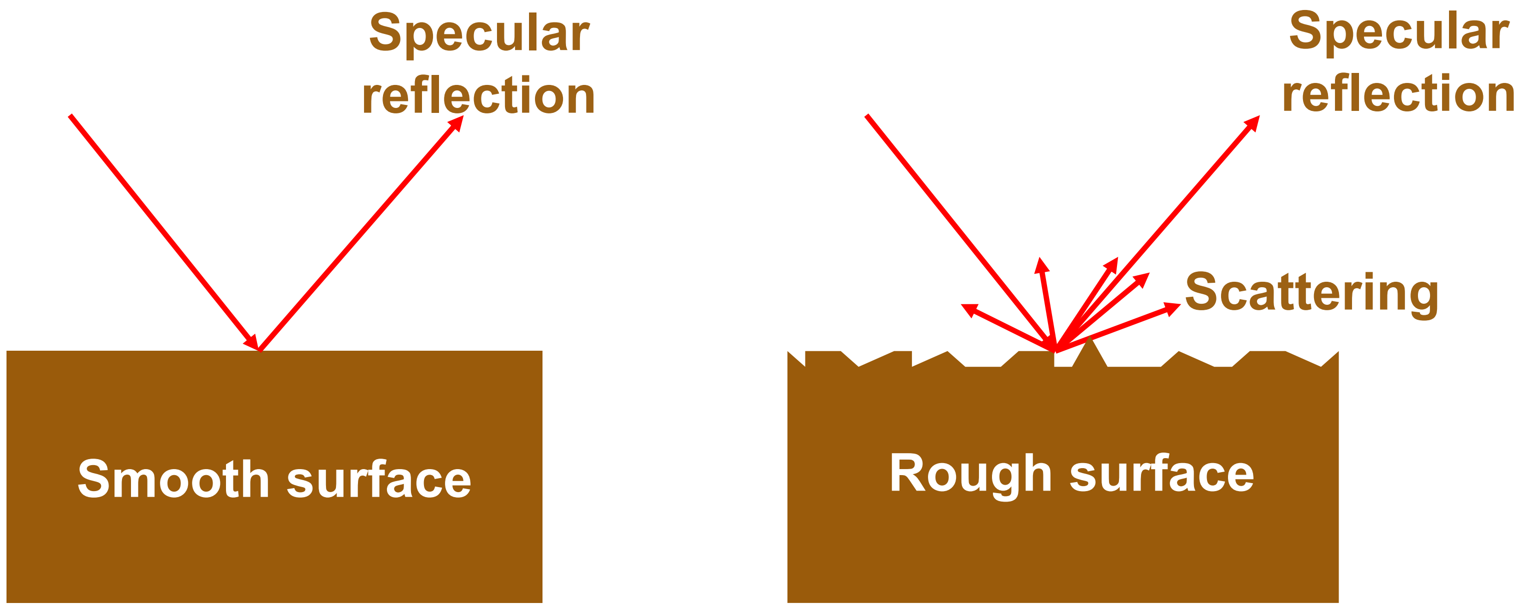
Diffuse Scattering



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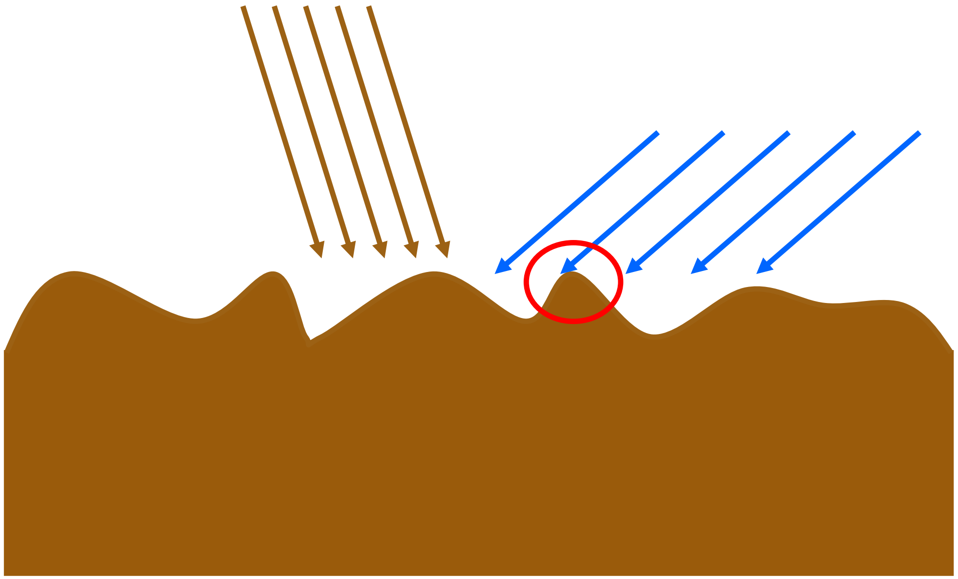
Kirchhoff theory – scattering by rough surfaces



calculate distribution of the surface amplitude

assume no "shadowing" from surface

calculate a new reflection coefficient

for Gaussian surface distribution

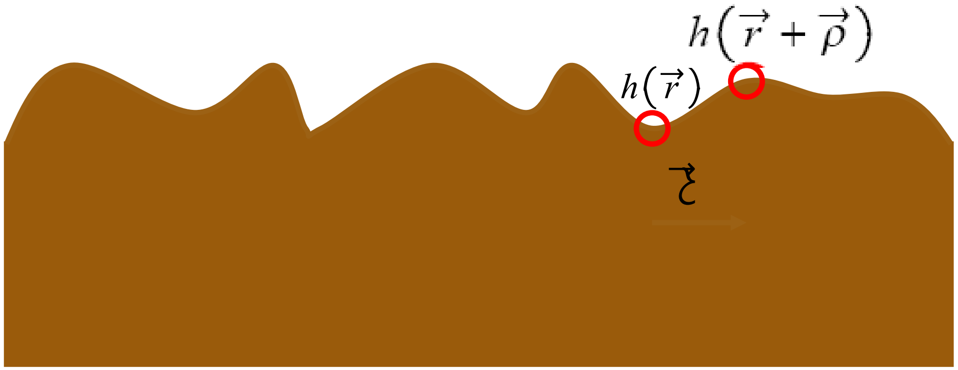
angle of incidence

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

standard deviation of height

Pertubation theory – scattering by rough surfaces

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



Include shadowing effects by the surface

includes spatial correlation of surface – how fast are the changes in height

based on calculation of an “effective” dielectric constant

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

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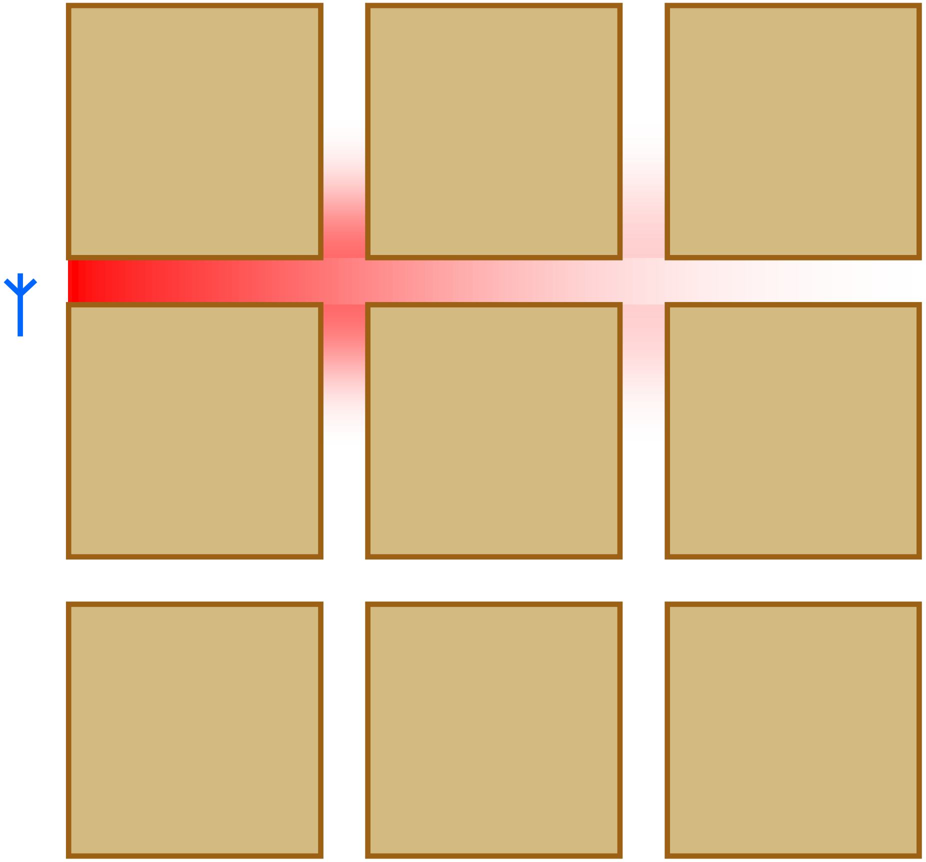
Waveguiding

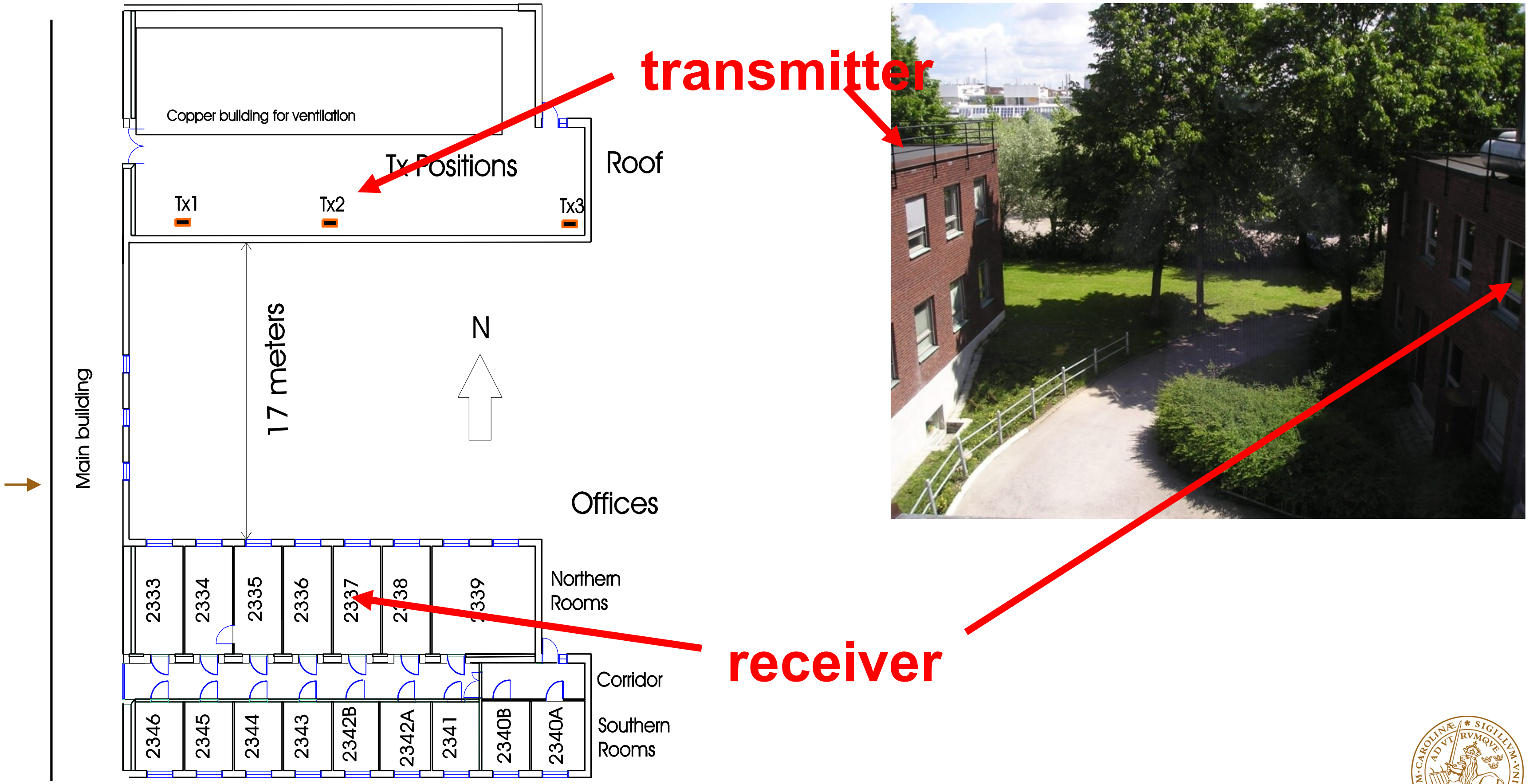


Waveguiding effects often result in lower propagation exponents

***n* =1.5-5**

This means lower path loss along certain street corridors

How does the signal reach the receiver
Outdoor-to-indoor



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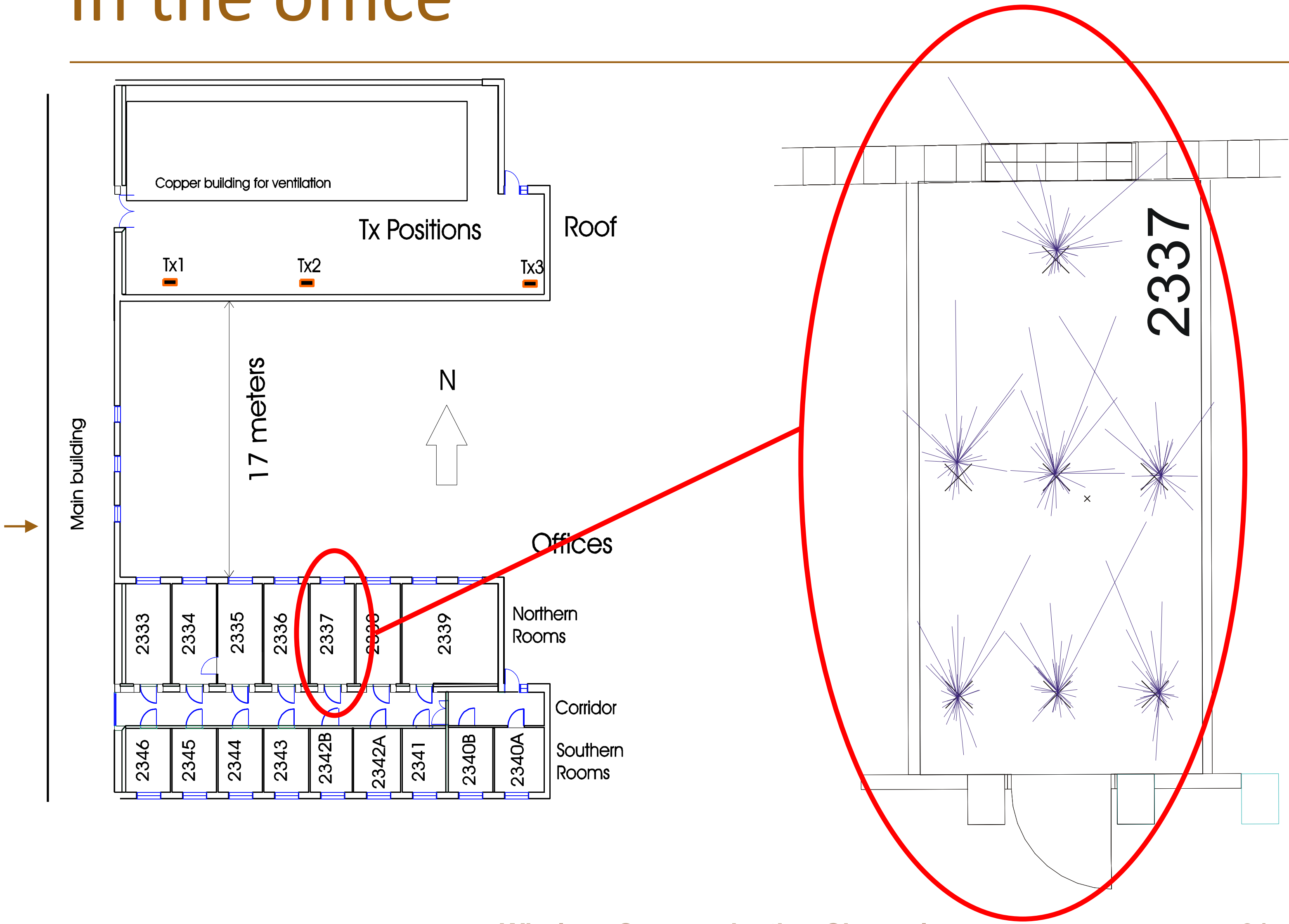
How does the signal reach the receiver
In the office



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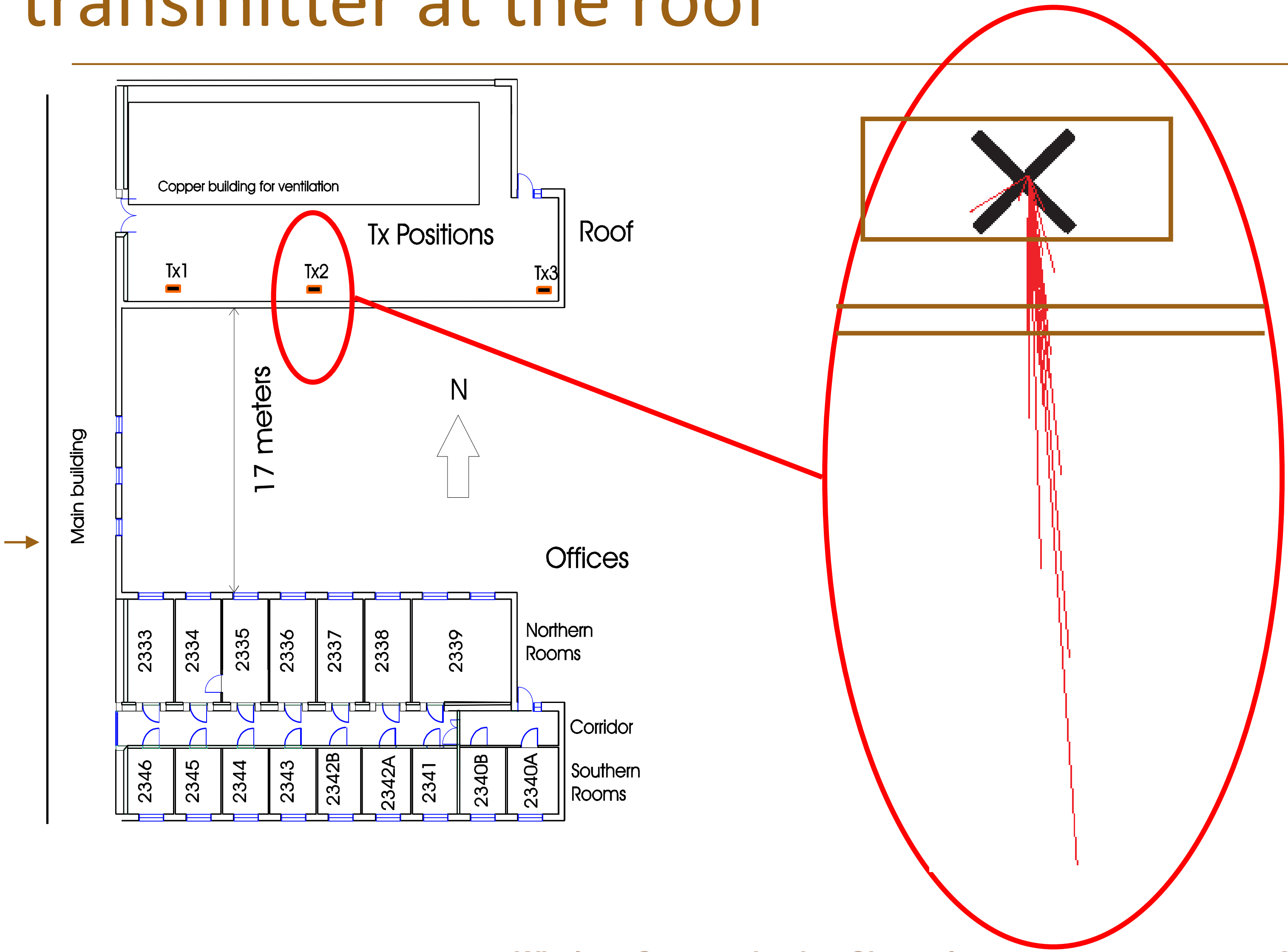
How does the signal leave the transmitter at the roof



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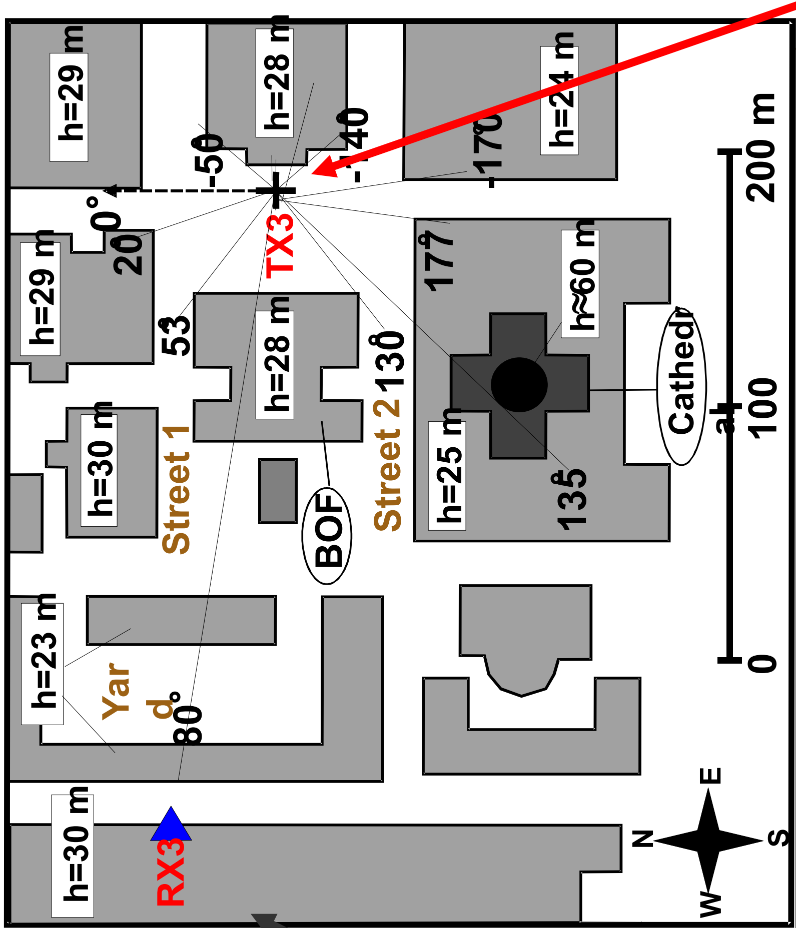
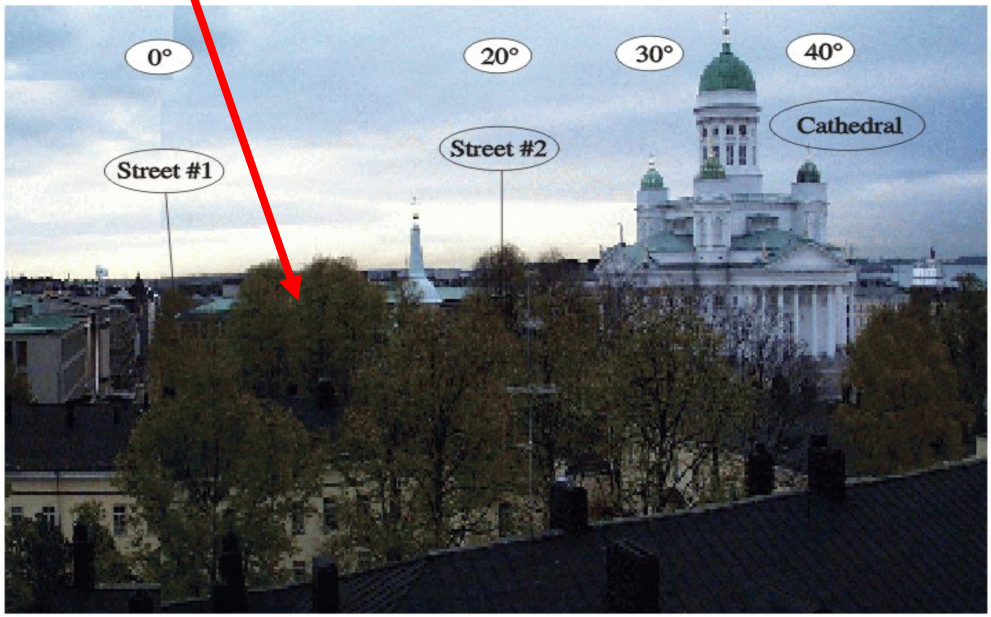
How does the signal reach the receiver outdoor urban

Transmitter





Receiver

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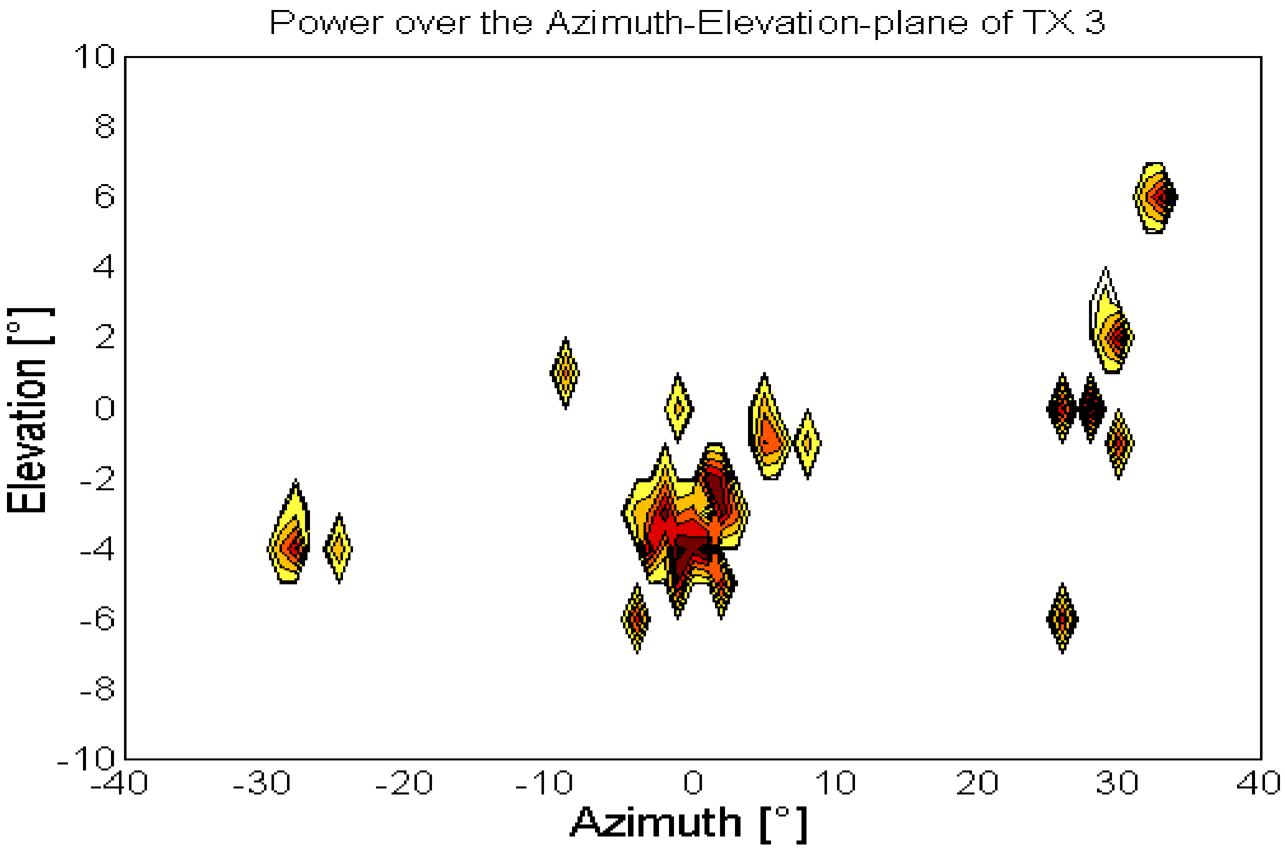
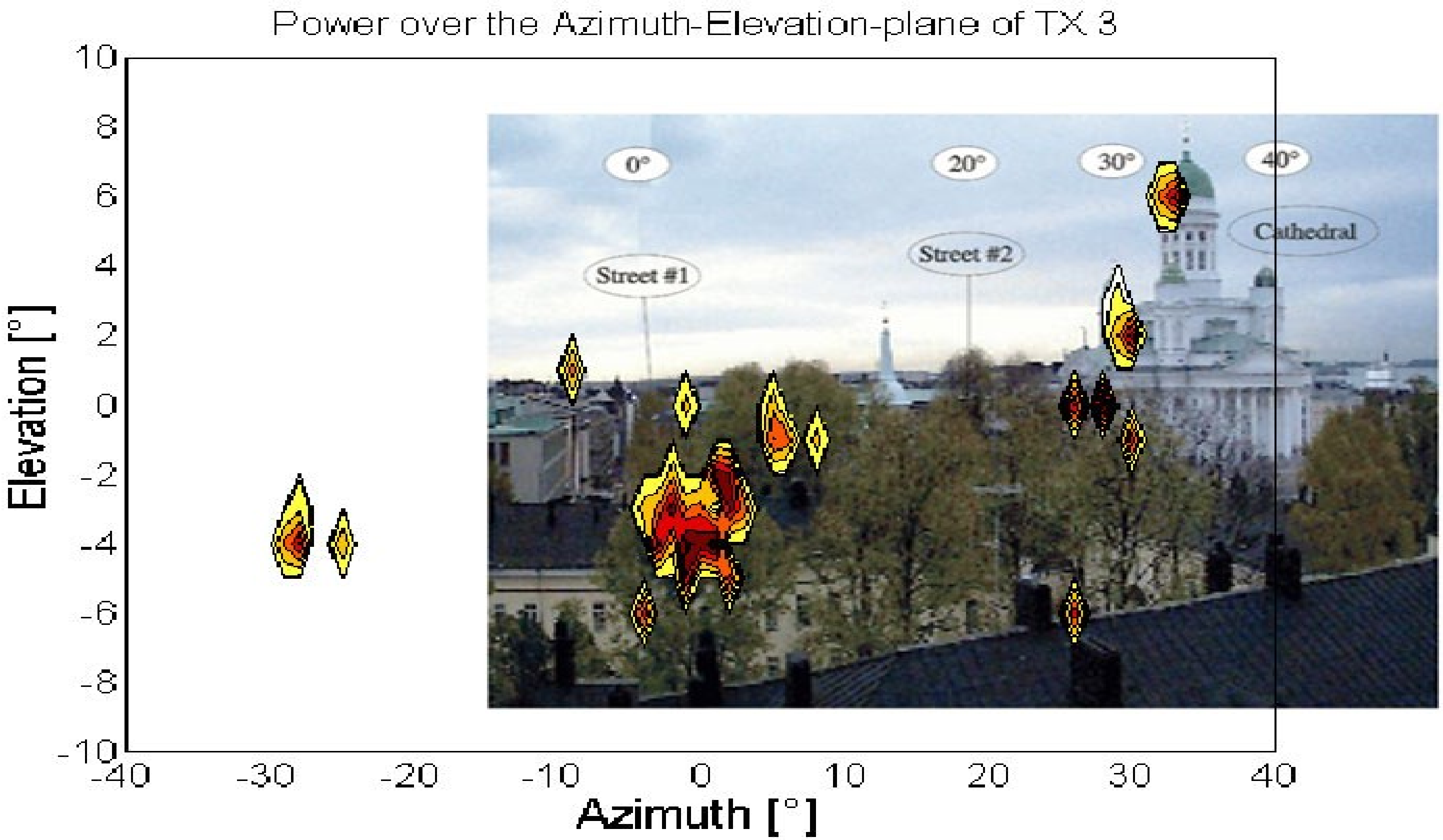
Signal arrives from some specific areas



Diffraction, reflection, scattering, transmission



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