# Wireless Communications Channels
# Lecture 2: Propagation Mechanisms

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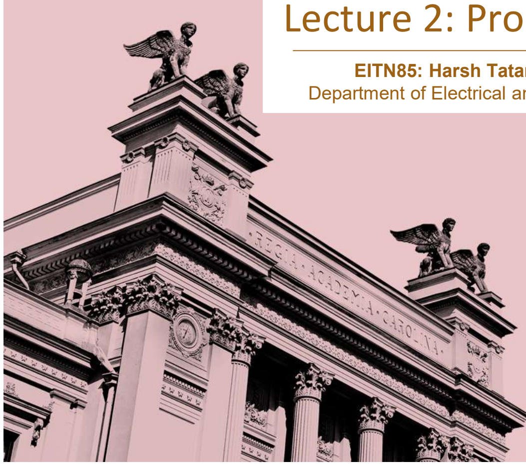

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## Contents

**Propagation mechanisms:**

- ❑ Free space attenuation
- ❑ Reflection and transmission
- ❑ Diffraction
- ❑ Diffuse scattering
- ❑ Waveguiding

**Examples from real world propagation scenarios**



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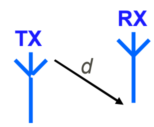
# Free space attenuation

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



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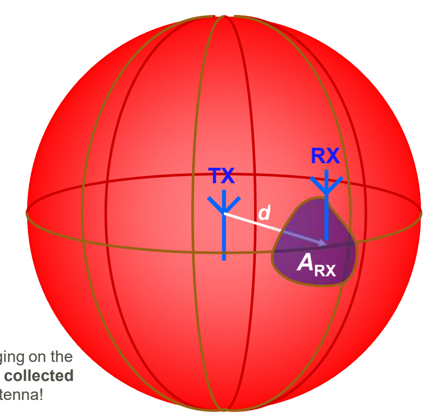
# Free space attenuation

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

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

**Question!**

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




Shpere of radius *d*



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# Free space attenuation

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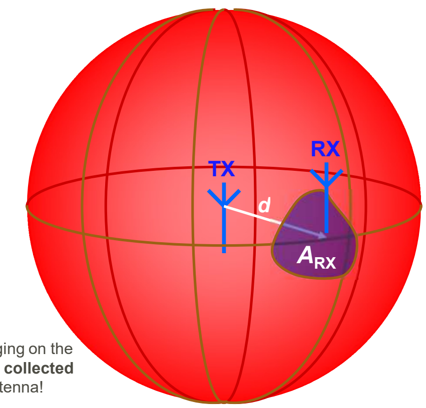
**Question!**

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

- Product of TX power and gain is known as: effective isotropic radiated power (EIRP)
- Relationship between effective area and antenna gain: $G_{\mathrm{RX}} = \left(\frac{4\pi}{\lambda^2}\right) A_{\mathrm{RX}}$




Shpere of radius *d*

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# 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.

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

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

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

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

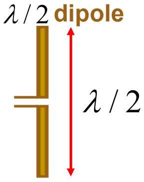
The free space loss calculations are only valid in the "far field" of the antennas.

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.

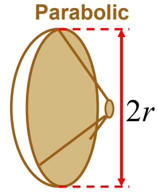
$\lambda/2$ **dipole**




$L_a = \lambda/2$

$d_R = \lambda/2$

**Parabolic**




$L_a = 2r$

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

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

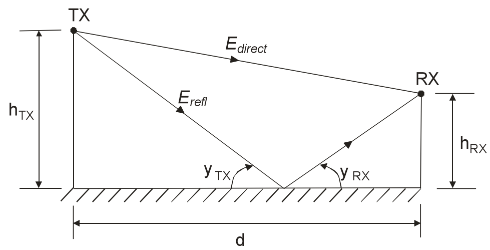


# Quiz

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**

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

**for distances greater than**

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



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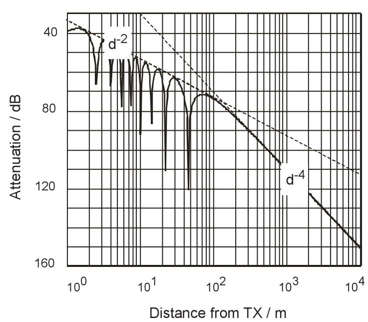
# The d$^{-4}$ law – II




- 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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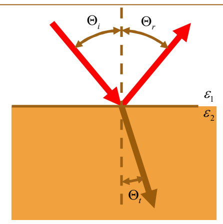
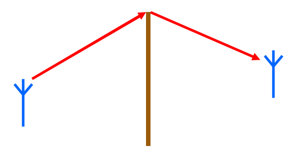
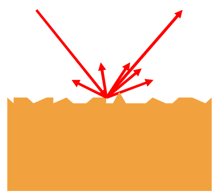
# Fundamental propagation mechanisms



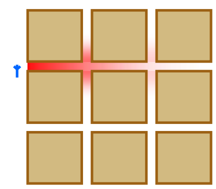
Reflection and transmission



Diffraction



Scattering



Waveguiding





# Complex dielectric constant

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

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

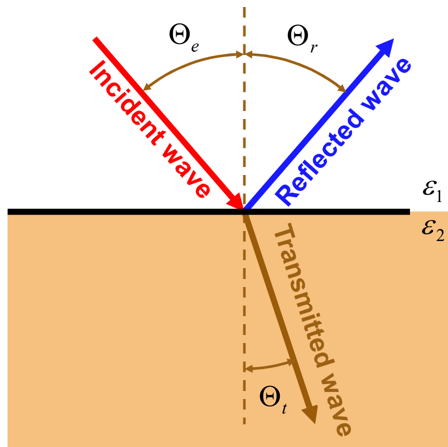
conductivity ($\sigma_{e,i}$)

dielectric constant, permittivity ($\varepsilon_i$)

**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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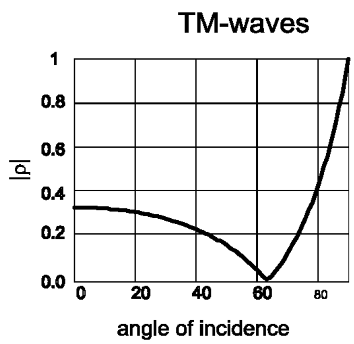
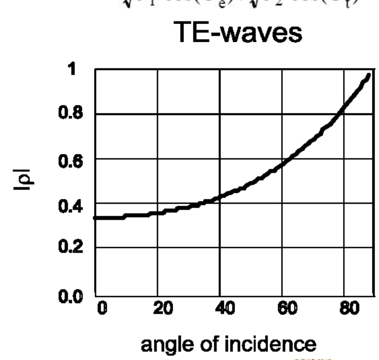
## TM and TE Component Behaviors

**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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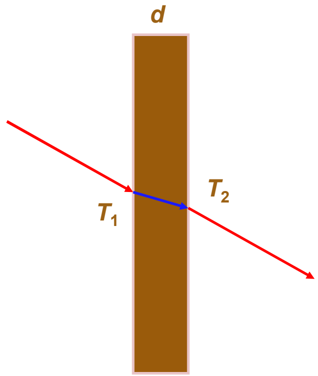
# Transmission through layered structures




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

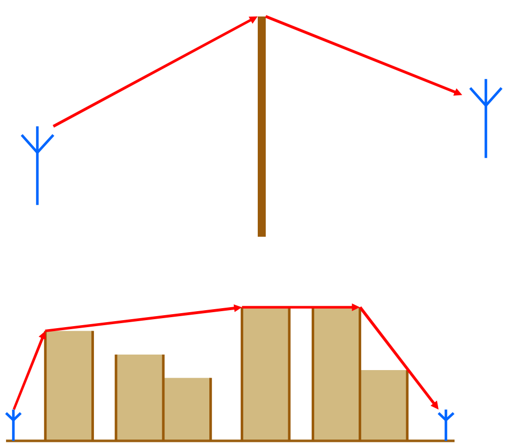
$$\alpha = \frac{2\pi}{\lambda}\sqrt{\varepsilon_1}\, d_{\text{layer}} \cos(\Theta_t)$$

Wall with thickness *d* and two dielectrics



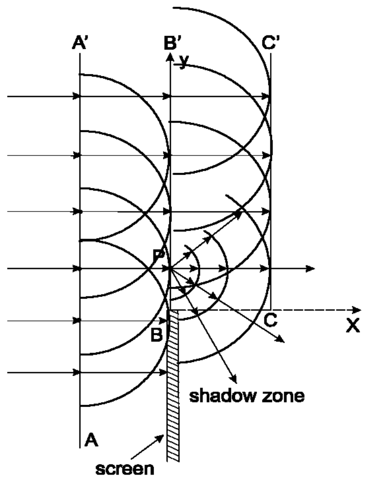


# Diffraction: The principle



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

# 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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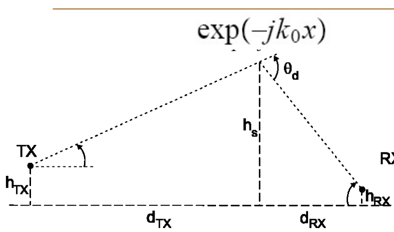
# Diffraction coefficient




**The Fresnel integral is defined**

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

**Total field**

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

**Fresnel integral**

**with the Fresnel parameter**

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



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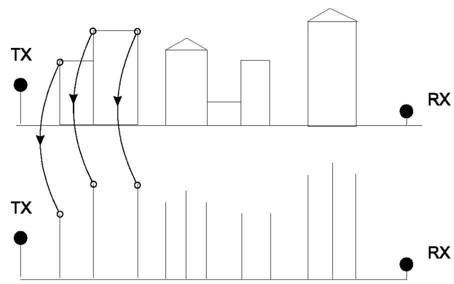
# Diffraction in real environments




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



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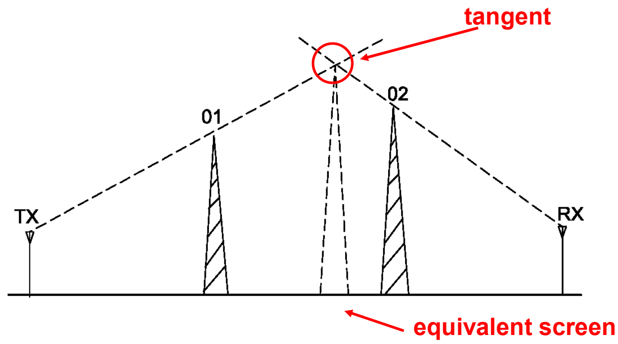
# Diffraction: Bullington's method




**Replace all screens with one equivalent screen**

**Height determined by the steepest angle**

**Simple but a bit optimistic**

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

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



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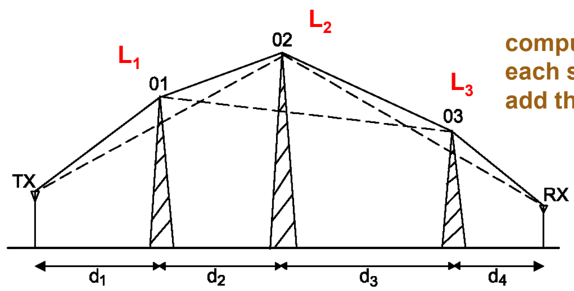
# Diffraction – Epstein-Petersen Method



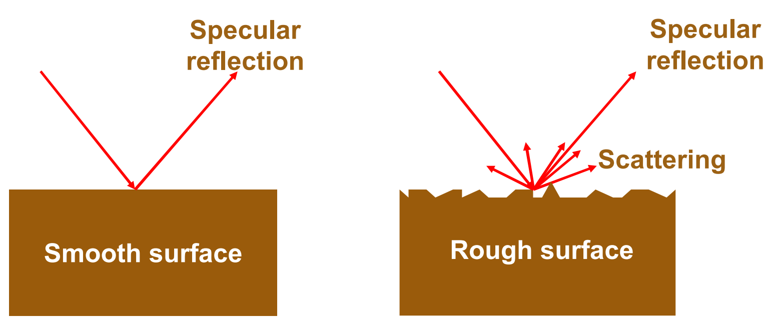

compute diffraction loss for each screen separately and add the losses

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

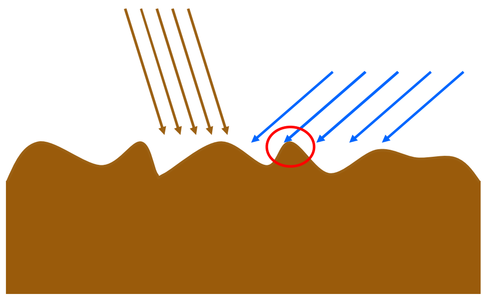
The same approach is used also for the ITU model, but with an empirical correction factor



# Diffuse Scattering



## 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**

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

**standard deviation of height**



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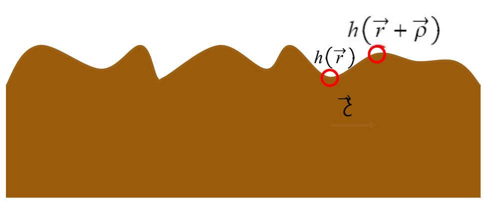
## Pertubation theory – scattering by rough surfaces

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




**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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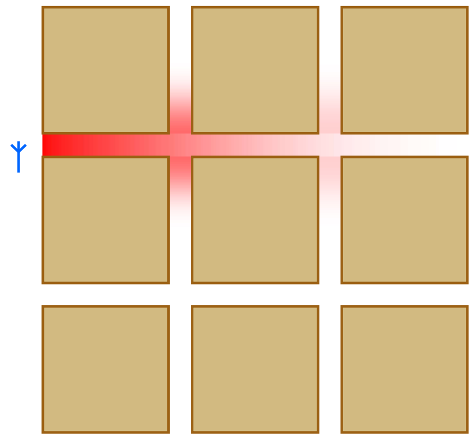
# Waveguiding



**Waveguiding effects often result in lower propagation exponents**

***n*** **=1.5-5**

**This means lower path loss along certain street corridors**



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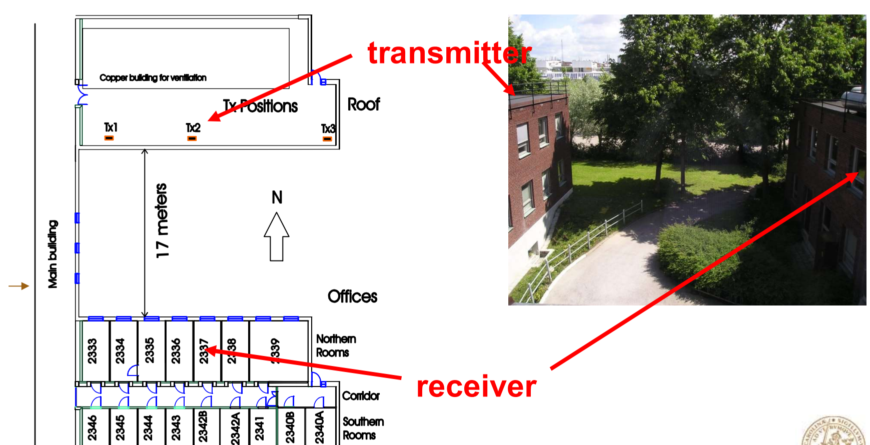
# How does the signal reach the receiver Outdoor-to-indoor



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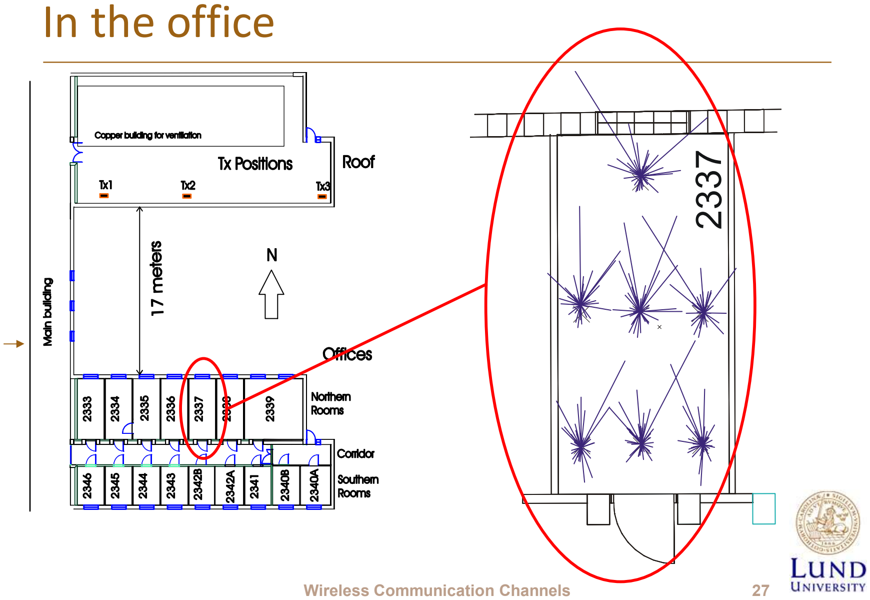
# How does the signal reach the receiver In the office



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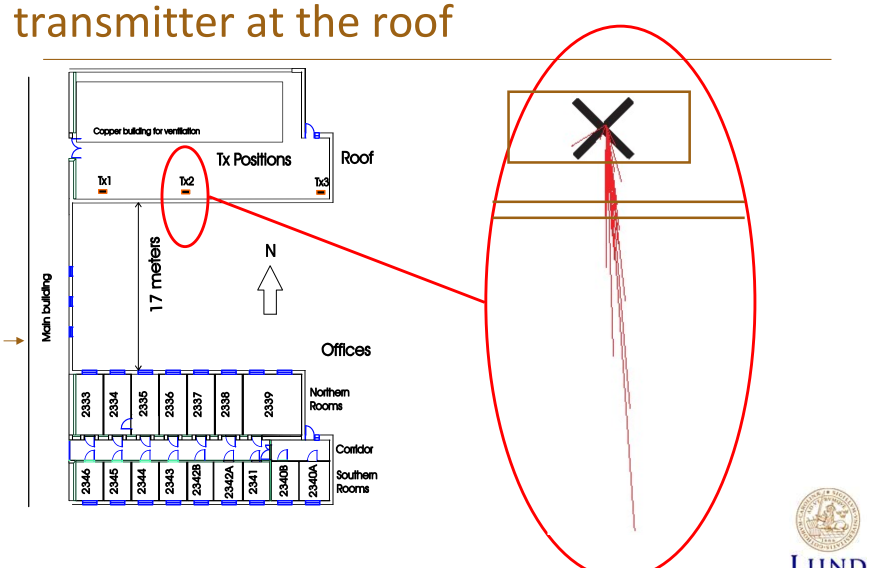
# How does the signal leave the transmitter at the roof



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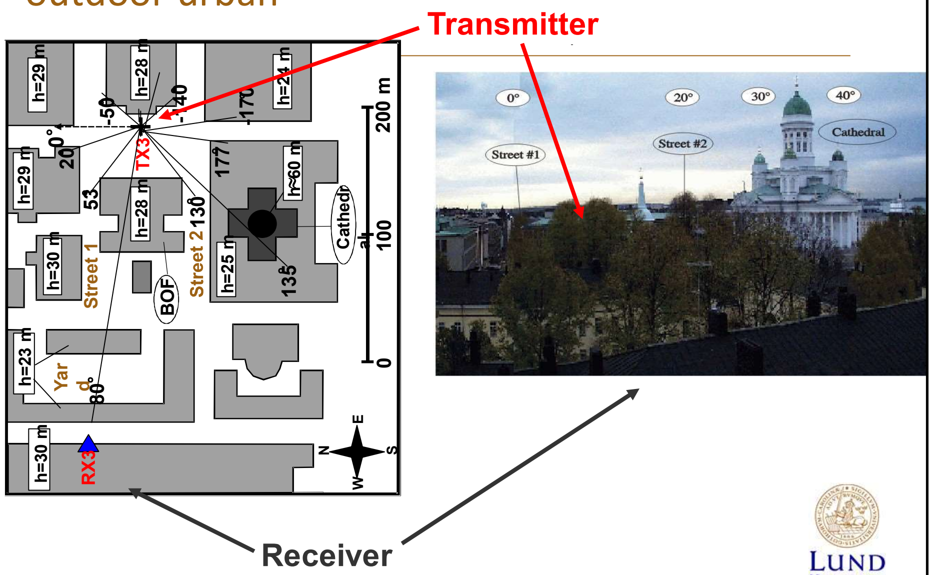
# How does the signal reach the receiver outdoor urban



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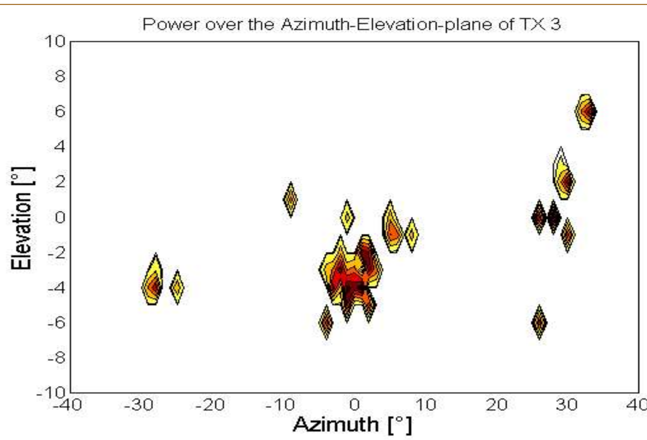
# Signal arrives from some specific areas



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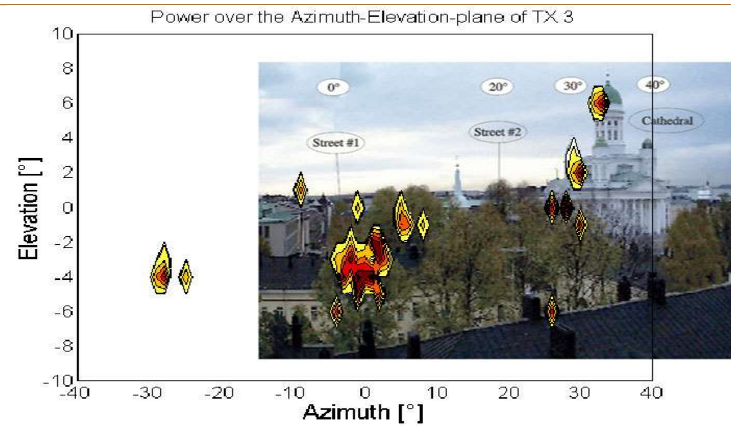
## Diffraction, reflection, scattering, transmission

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