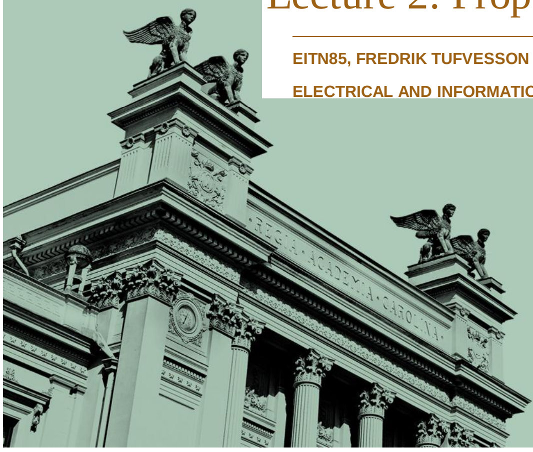
Wireless Communication Channels
Lecture 2: Propagation mechanisms

EITN85, FREDRIK TUFVESSON

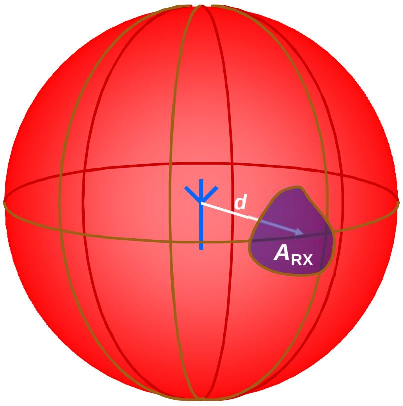
ELECTRICAL AND INFORMATION TECHNOLOGY



Contents

- Free space loss
- Propagation mechanisms
  - Transmission
  - Reflection
  - Diffraction
  - Scattering
  - Waveguiding
- Examples from propagation scenarios

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):

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

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Free-space loss
Friis' law

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

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

⇔ **Valid in the far field only!**

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

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

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Free-space loss
What is far field?

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

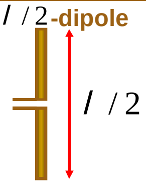
Far-field conditions are assumed ”far beyond” the Rayleigh distance:

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

where L_a is the largest dimesion of the antenna.

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

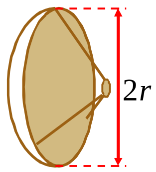
$\lambda/2$-dipole



$L_a = \lambda/2$

$d_R = \lambda/2$

Parabolic



$L_a = 2r$

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

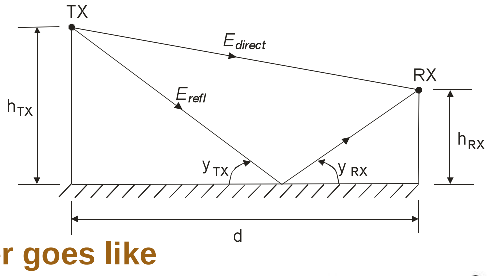
Example

- Cellular phone, height 10 cm, f_c=900 MHz
  Rayleigh distance d_R=2*0.1²/0.333=6 cm
  For this device the limit is the 10-lambda rule of thumb.

- Microwave link, antenna diameter 1.2 m, f_c=26 GHz
  Rayleigh distance d_R=2*1.2²/0.011=250 m
  For this device the limit is the Rayleigh distance

The d^{-4} law (1)

For the following scenario



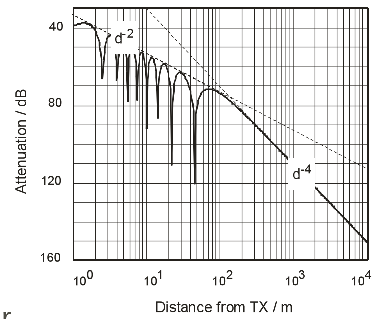
the power goes like

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

for distances greater than

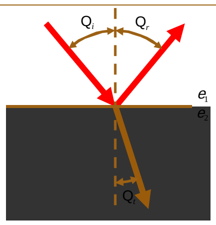
$$d_{\text{break}} \gtrsim 4 h_{TX} h_{RX} / \lambda$$

The d^{-4} law (2)

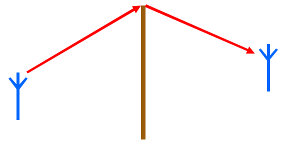


- However …..
  - n=4 is not a universal decay exponent
  - Theoretical model is not fulfilled in practice
  - Breakpoint is rarely where theoretically predicted
  - Second breakpoint at the radio horizon

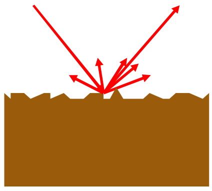
Propagation mechanisms



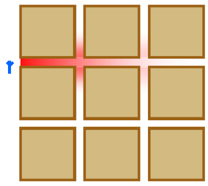
Reflection and transmission



Diffraction



Scattering



Waveguiding

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Complex dielectric constant

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

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

dielectric constant, permittivity (ε_i)

Describes the dielectric material in one single parameter

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

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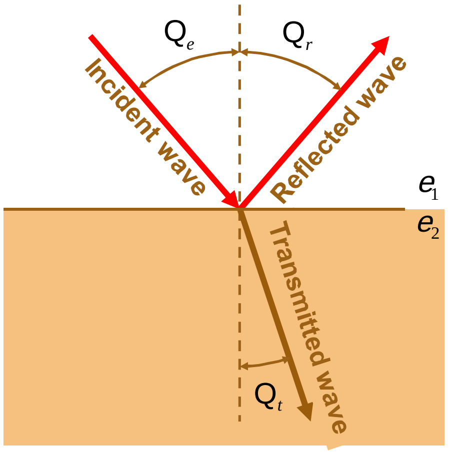
Reflection and transmission



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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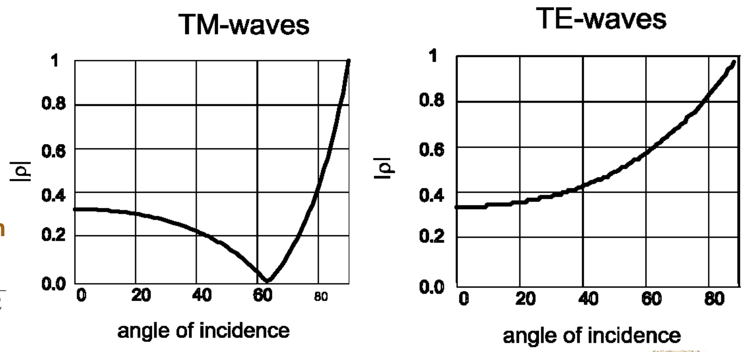
TM and TE waves behave differently

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

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

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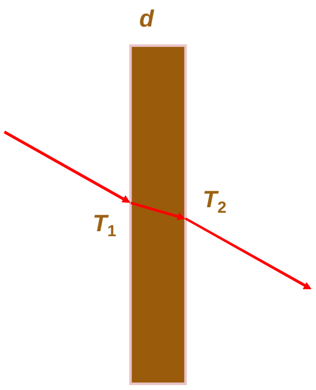
Transmission through walls – layered structures



Total transmission coefficient

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

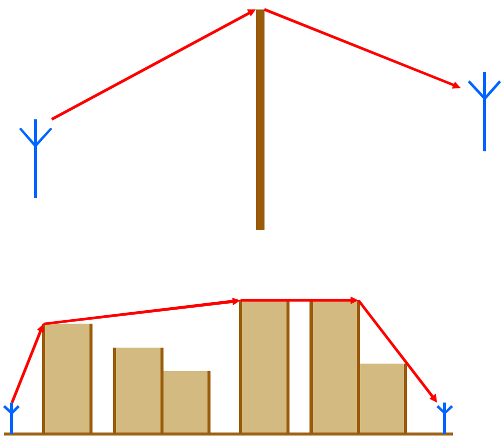
total reflection coefficient

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

with the electrical length in the wall

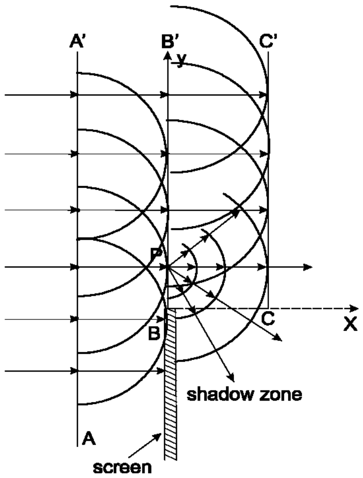
$$\alpha = \frac{2\pi}{\lambda} \sqrt{\varepsilon_1}\, d_{\text{layer}} \cos(\Theta_t)$$

Diffraction



- 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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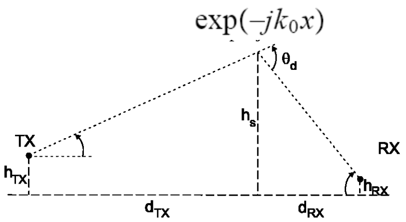
Diffraction coefficient



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

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

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

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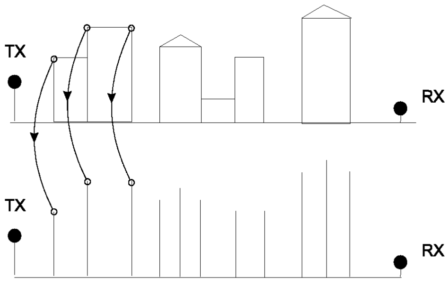
Diffraction in real environments



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

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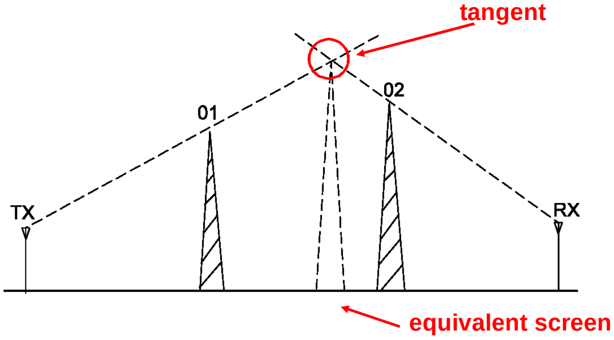
Diffraction – Bullington's method



Replace all screens with one equivalent screen

Height determined by the steepest angle

Simple but a bit optimistic

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

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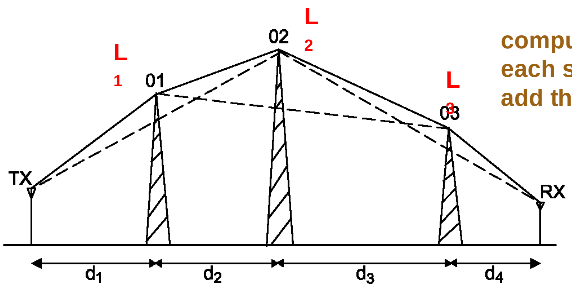
Diffraction – Epstein-Petersen Method

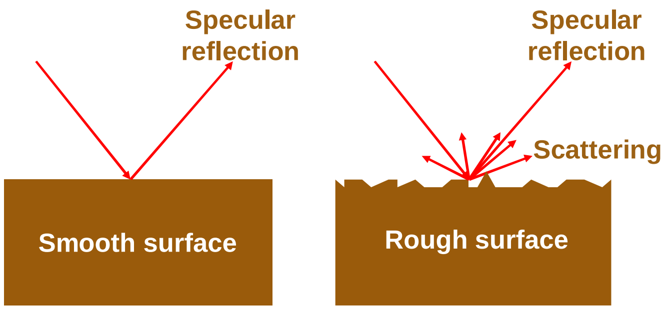


compute diffraction loss for each screen separately and add the losses

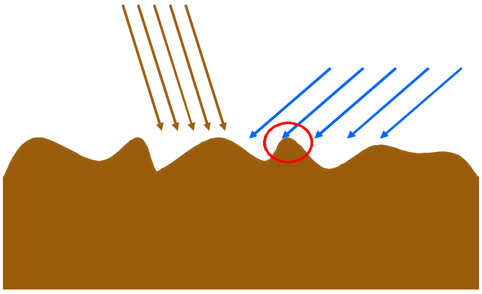
$L_{tot}=L_1+L_2+L_3$

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

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

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

angle of incidence

standard deviation of height

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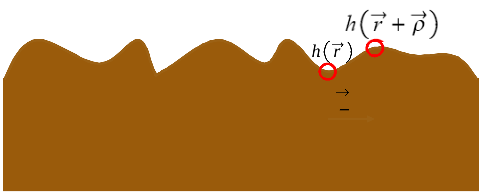
Pertubation theory – scattering by rough surfaces

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



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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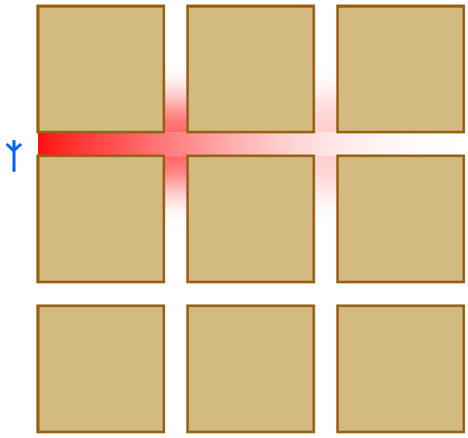
Waveguiding



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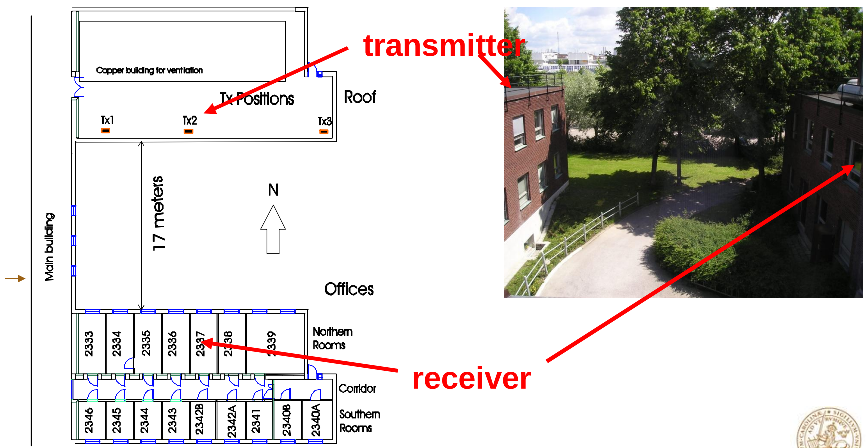
How does the signal reach the receiver Outdoor-to-indoor



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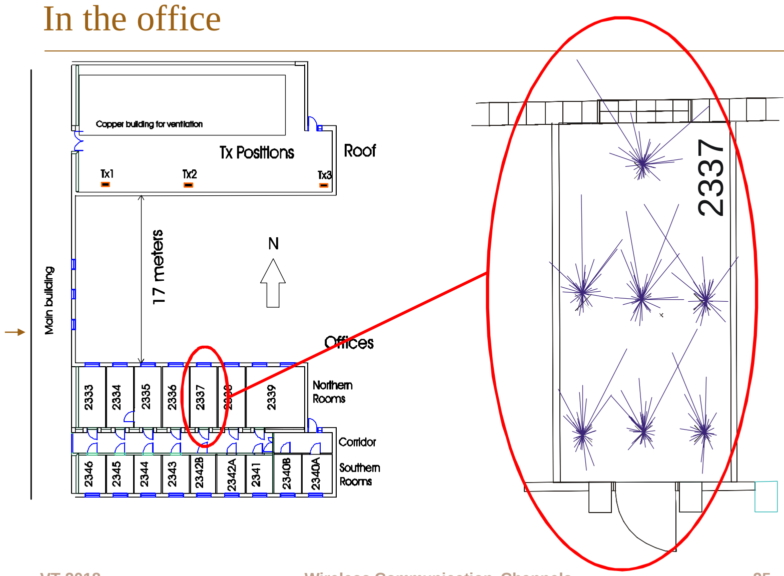
How does the signal reach the receiver In the office



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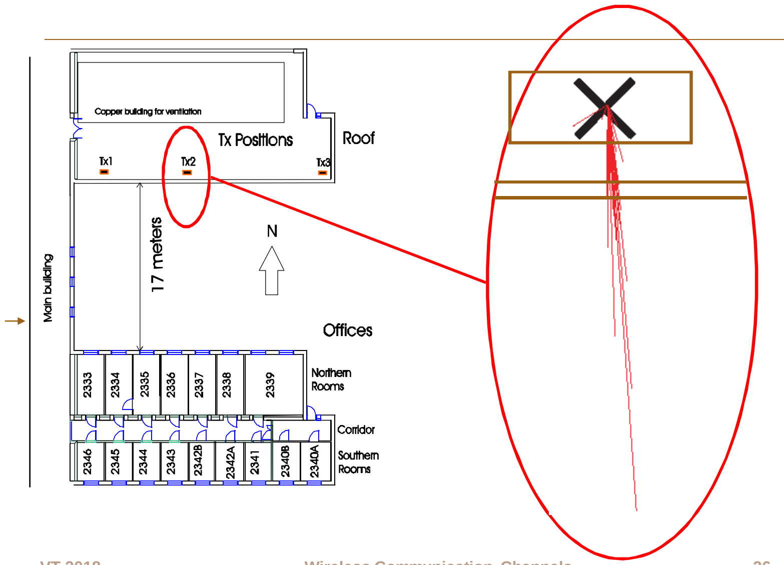
How does the signal leave the transmitter at the roof



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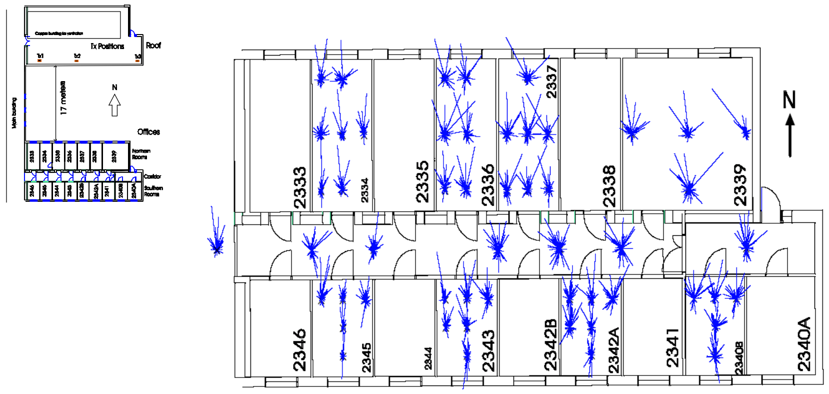
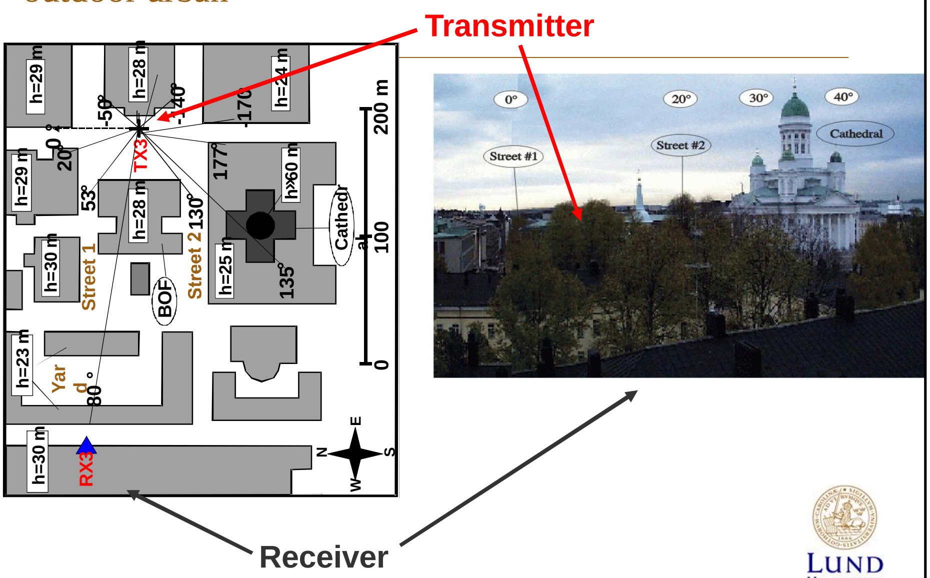
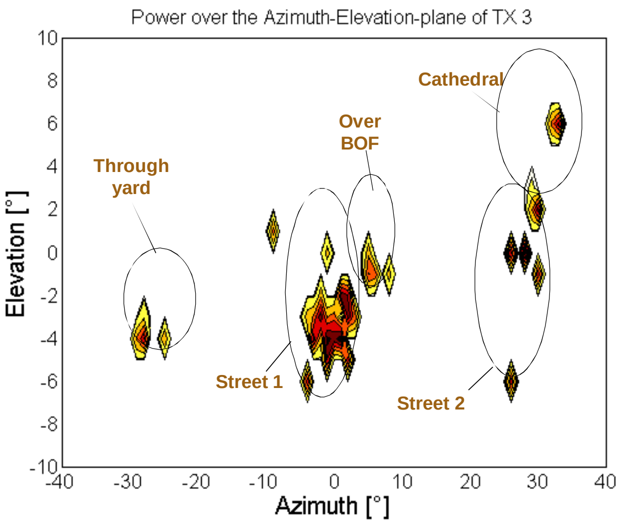
In all offices



How does the signal reach the receiver outdoor urban



Signal arrives from some specific areas



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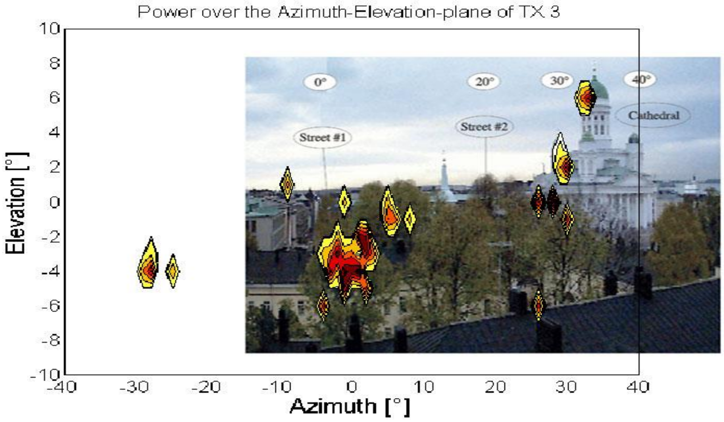
Diffraction, reflection, scattering, transmission



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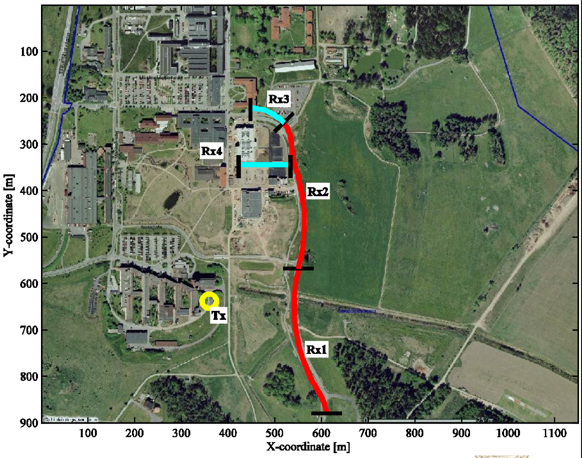
Outdoor 300 MHz peer-to-peer scenario

- Center frequency:
  - 285 MHz, 20MHz bandwidth
- Peer-to-peer measurement:
  - TX, 1.8m (BS)
  - RX, 2.1m (MS)
- Four routes:
  - 322, 320, 80, 110 m
  - semi-rural scenario
  - sub-urban scenario



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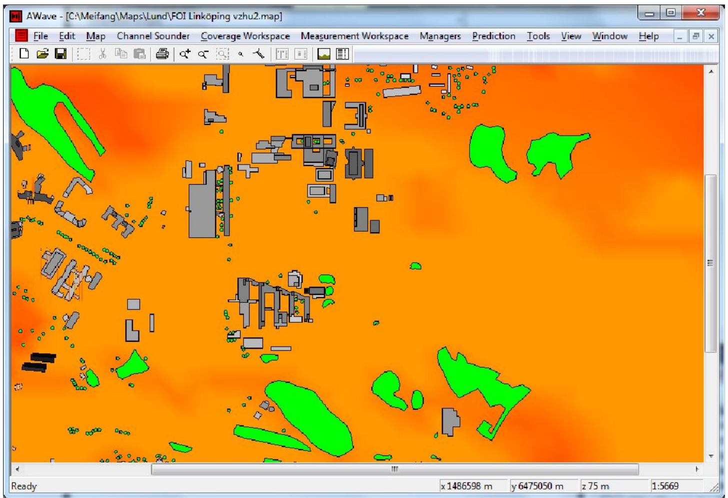
Digital 3D map of the environment



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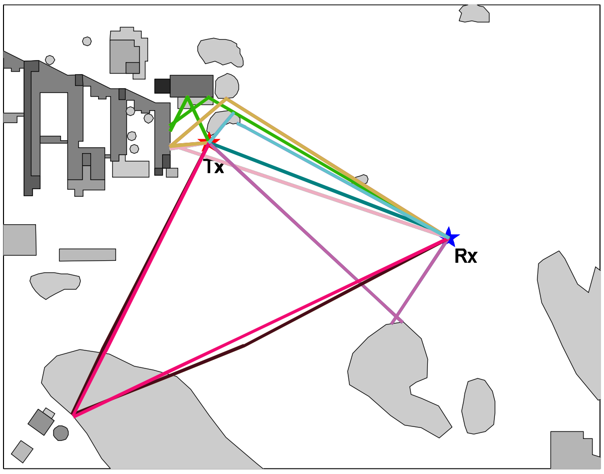
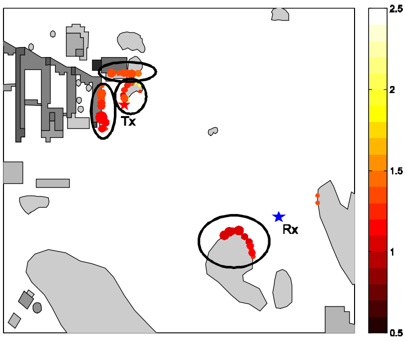
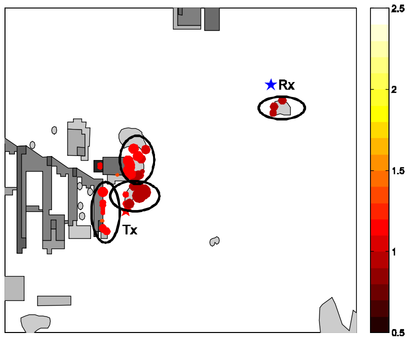
Visualized paths for a particular Tx/Rx position



Interaction points, 20 strongest MPCs



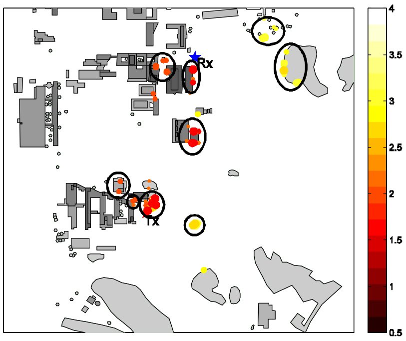
LOS



NLOS

Radius of circles reflects power, color reflects delay

Interaction points, 20 strongest MPCs

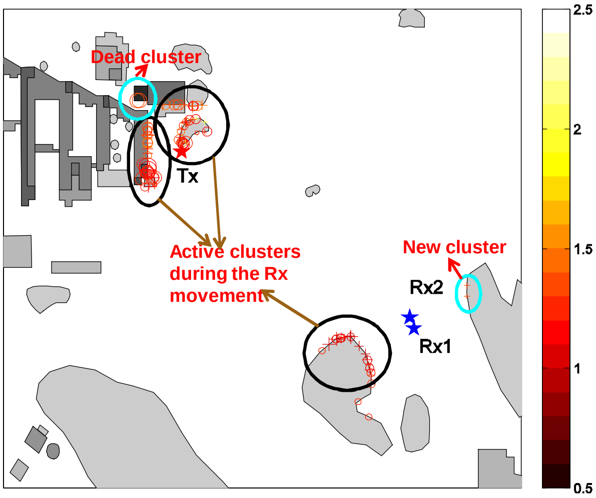


NLOS

NLOS

Radius of circles reflects power, color reflects delay

Multipath components tend to appear in clusters, moving Rx



As Rx is moving (10 wavelengths, approximately 10 meters), clusters disappear and new clusters appear.

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