Radio Propagation Basics

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- Beware of misprints!!! These materials are preliminary notes intended for my lectures only and may contain misprints. Feedback is welcome: if you have noticed serious faults, or have improvement suggestions, please describe it exactly and let me know.

Objective:

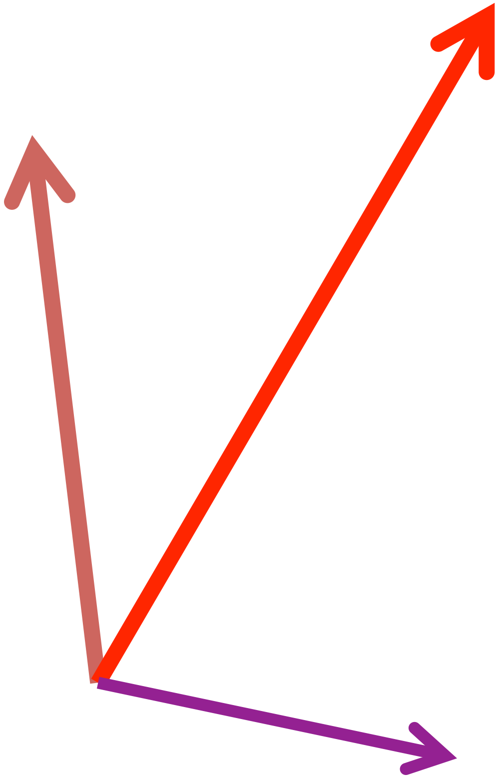
- to refresh basic radio physics needed to better understand the operation of wireless networks

Classical physics

- ~100 years from Coulomb (1736–1806) to Maxwell (1831-1879)
  - Electricity and magnetism were considered as separate (and mysterious) phenomena until Maxwell unification and Hertz (1857 – 1894) experiments
  - EM wave is associated with accelerating/ decelerating electric charges
- ~100 years from Maxwell to IEEE 802.11

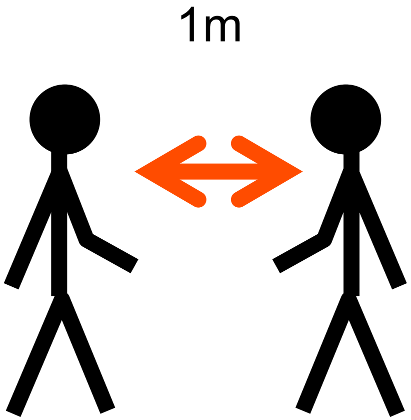
http://www.amanogawa.com/archive/wavespdf.html

What is EM field?



- A spatial distribution of stress - forces acting on an electric charge
  - A pair of coupled vectors E + H
    - (Magnitude, Direction, Orientation)
  - Varying in time and space
    - Six numbers at every point:
      - $E_x(x,y,z,t)$, $E_y(x,y,z,t)$, $E_z(x,y,z,t)$
      - $H_X(x,y,z,t)$, $H_Y(x,y,z,t)$, $H_Z(x,y,z,t)$

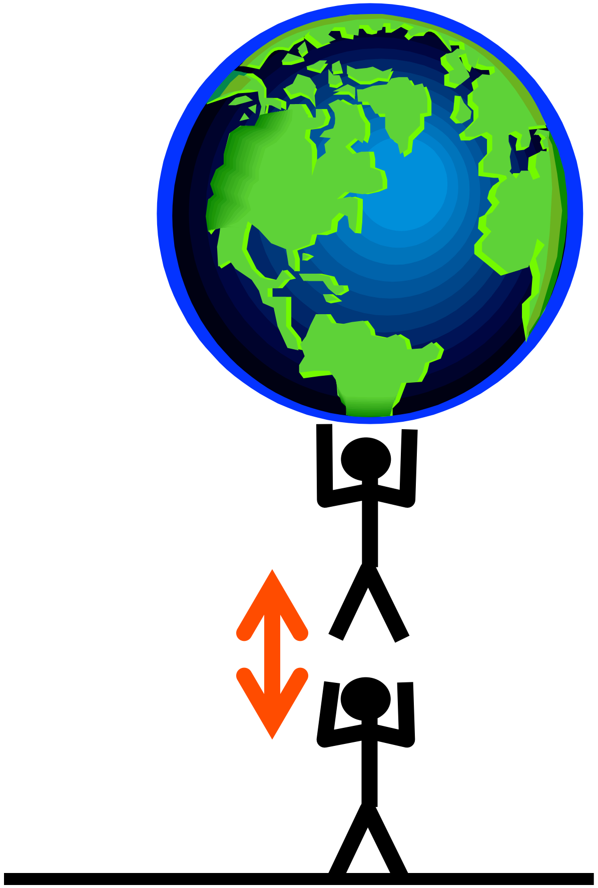
How strong is the EM force?



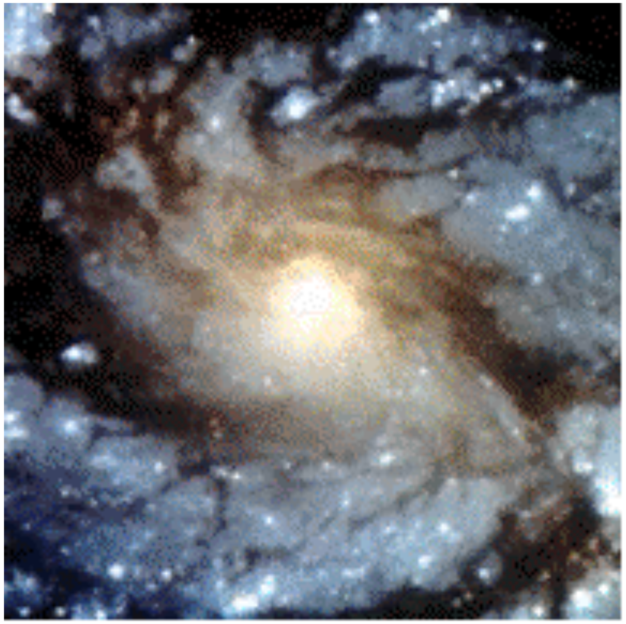
- Feynmann’s quiz: imagine 2 persons at 1 m distance; their bodies consist of balanced set of electrons & protons - they are neutral
  - Imagine we decrease the number of electrons in each by 1%
  - Now they would have more protons than electrons and repulse each other
  - How strong would be the repulsive force?
    - Could it be strong enough to move a hair? Or stronger?

Richard Feynman
1918 –1988)

Feynman calculated that…



- the E force would be strong enough to lift the whole Earth!
  - Richard Feynman (1918 – 1988);
  - Nobel Prize in Physics (1965)



Click image to enlarge

- Classic electromagnetic theory: the EM wave once radiated travels with no limits in time and distance, with the speed of light
  - In an unlimited, uniform, lossless medium
  - During the travel, the EM energy can transforms into another form

Distance: EM forces generated in distant stars and galaxies can move electrons in our eyes - we can see them!

Consequences

- The EM field in any point around us is a vector combination of uncountable components generated at distant in the past
  - Natural & man-made
- At any moment in a chosen reference point in space, there is actually a single electric vector E (H) - the result of superposition of the component vectors E (H) produced by all radiation sources

EM waves develop science

- Arno Penzias & Robert Wilson (Bell Telephone Labs) observed in 1965 a weak EM radiation - cosmic noise
  - They showed that the noise has been generated in a specific moment billions years ago! (they got the 1978 Nobel Prize)
  - This was an experimental support of the Big-Bang theory of the Origin of the Universe

- EM theory still develops on sub-atom scale
  - Abdus Salam 1979
    http://nobelprize.org/nobel_prizes/physics/laureates/1979/salam-bio.html;
    http://en.wikipedia.org/wiki/Abdus_Salam
- New theories (e.g. String Theory)

Abdus Salam (1926 –1996)

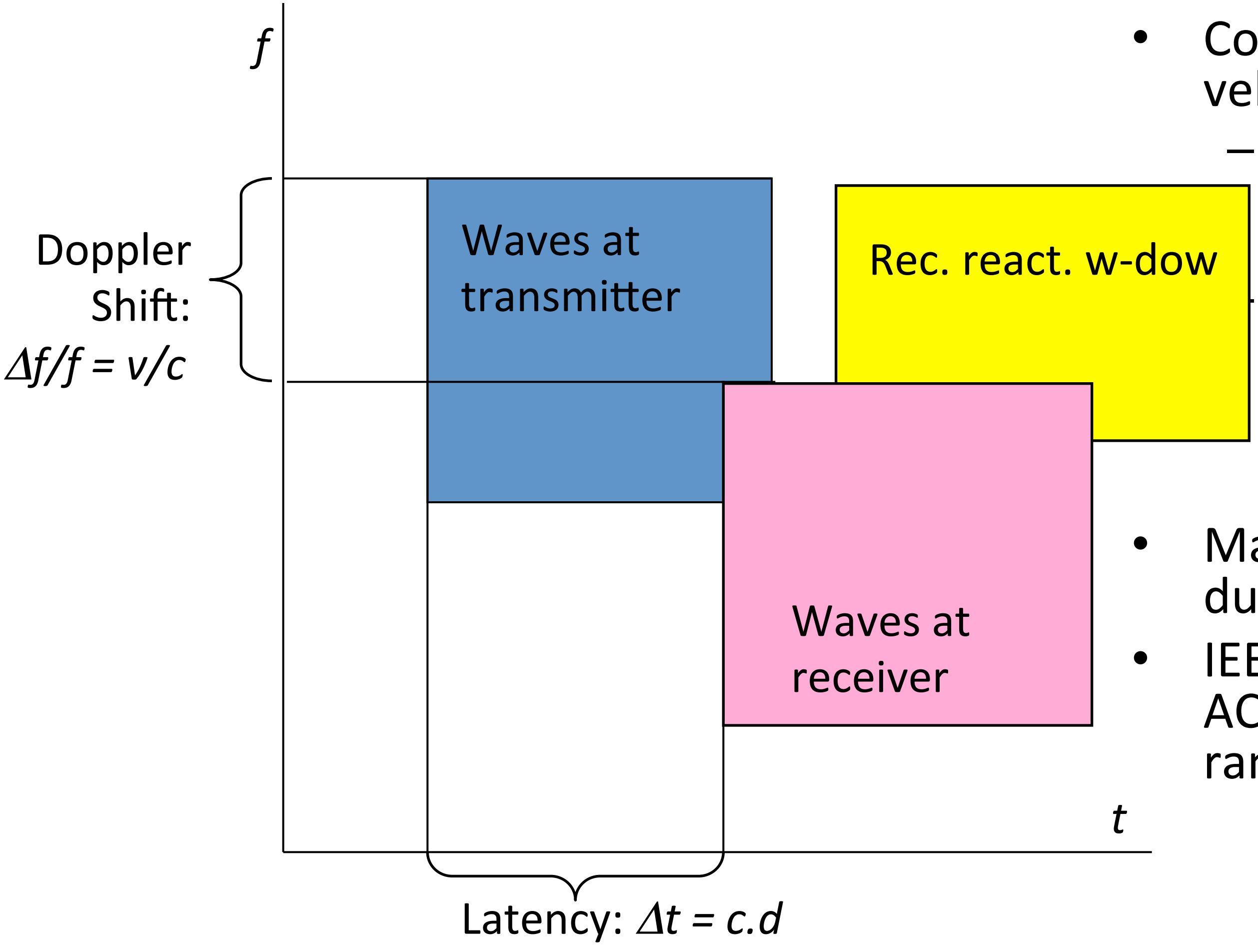
Nobel prize: 1979
ICTP Founder: 1964

Sandro Radicella

Why consider propagation?

1. Could my system operate correctly (wanted signal)?
   - Required quality of service (signal strength) over the required distance/ area/ volume, given the geographic/ climatic region and time period
2. Could my system coexist with other systems (unwanted signals “in” and “out”)?
   - Will my system suffer unacceptable interference?
     - » Degradation of service quality and/ or service range/ area due to potential radio interference
   - Will it produce such interference to other systems?

Latency & frequency shift



f

Doppler Shift: $\Delta f/f = v/c$

Waves at transmitter

Rec. react. w-dow

Waves at receiver

t

Latency: $\Delta t = c.d$

- Consequences of limited velocity of radio wave:
  - Received wave is delayed due to the travel time
  - Received wave-frequency is shifted due to Doppler effect (if transmitter and receiver move)
- Mars exploration crash due to Doppler
- IEEE 802.11 protocol ACK time slot limits the range

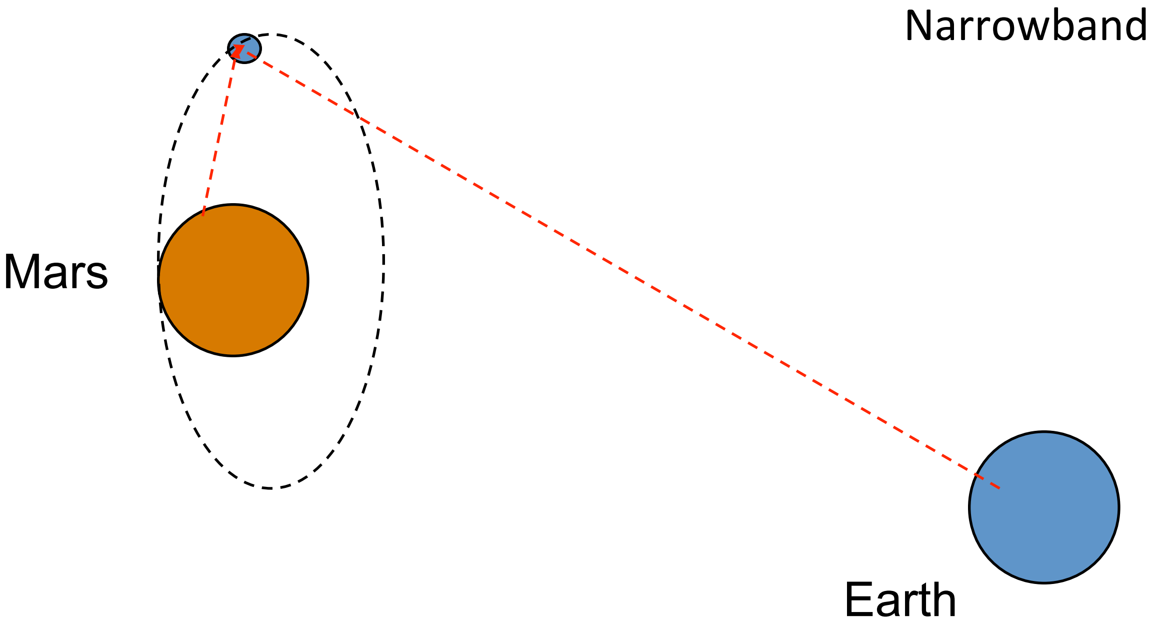
Doppler effect

= the apparent change in frequency of a wave that is perceived by an observer moving relative to the source of the wave

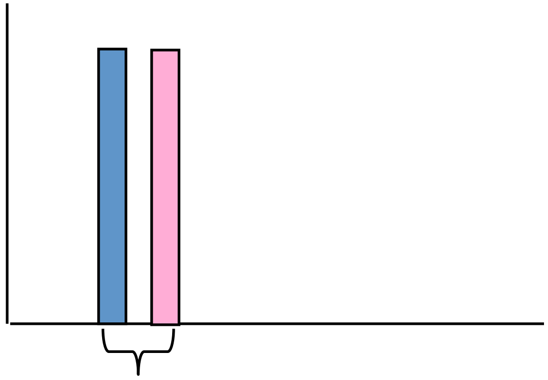
- » Simulation: http://www.falstad.com/ripple/ex-doppler.html

Johann Christian Andreas Doppler (1803 – 1853; Austrian mathematician and physicist)
http://en.wikipedia.org/wiki/Christian_Doppler

Example: Mars exploration



Narrowband telemetry system



http://marsrover.nasa.gov/classroom/Communication via the Mars Orbiter

Principal propagation effects

- Basic energy spreading
- Effects of obstructions and ground (indoor, outdoor)
- Tropospheric effects (outdoor)
  - clear air; non-clear air
- Ionospheric effects (outdoor)

Energy spreading

- Often we ignore vectorial character of EM waves, considering power-flux density PDF
  - PDF unit: W/m$^{2)}$
- Spreading
  - Spherical (3-D):
    - » PDF decreases with distance squared (in vacuum)
  - Planar (2-D):
    - » PDF decreases with distance (vacuum)
- No spreading (1-D, or planar wave):
    - » PDF does not depend on distance (vacuum)

Vectorial power-flow treatment: http://www.amanogawa.com/archive/docs/EM8.pdf

What is propagation model?

- Relation between the signal radiated and signal received as a function of distance and other variables
- Different models
  - Various dominating propagation mechanisms
    - different environments (indoor-outdoor; land-sea-space; …)
    - different applications (point-to-point, point-to-area, …)
    - different frequency ranges
    - …
- Many models include random variability

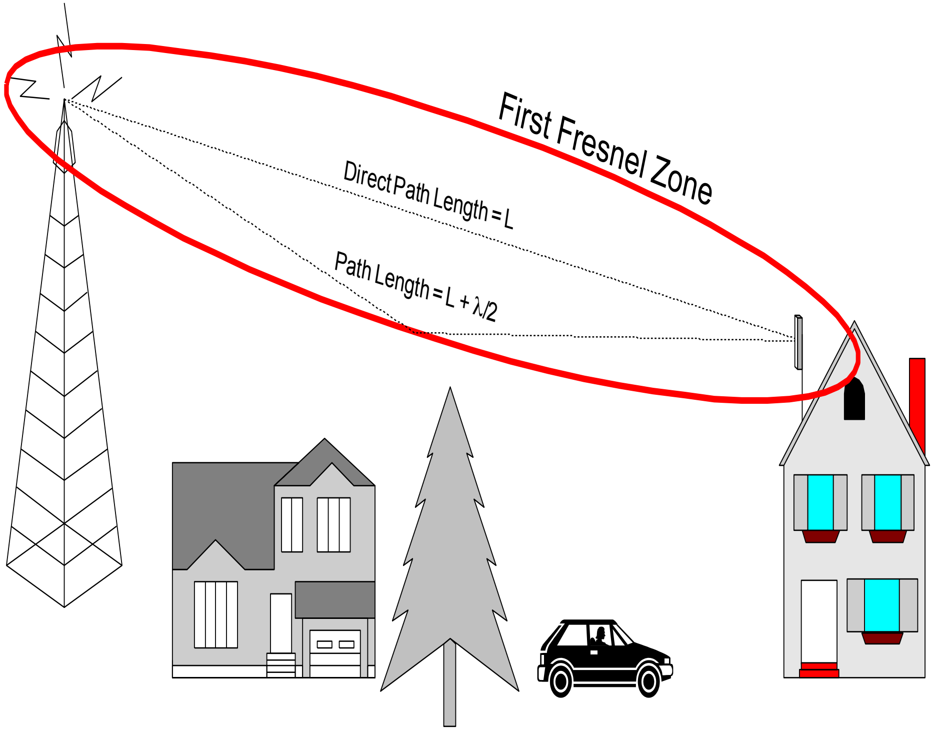
Free-space model

- The simplest model: energy 3D spreading -- propagation loss is proportional to square distance:

  FreeSpacePropagLoss = $(4\pi d/\lambda)^2$ [W/W]

- Too abstract for most practical applications
  - Suitable only for very preliminary analyses
  - Corrections for the polarization, environment, weather, climate, season, time, etc.
  - Random effects

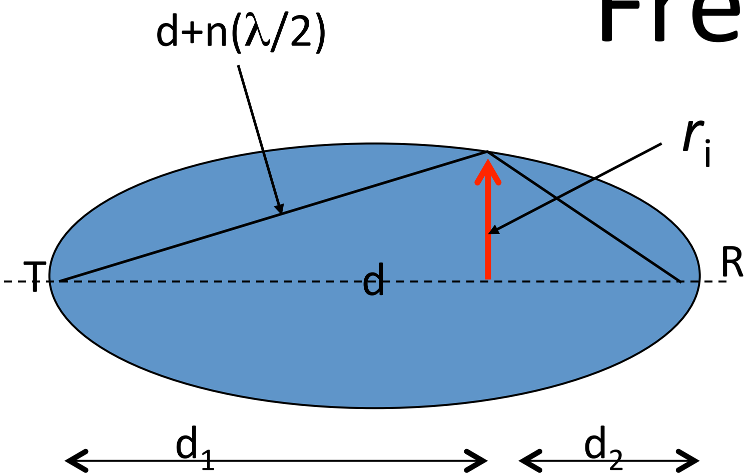
LOS model



Avaya

- Power flow from T to R concentrates in the 1st Fresnel zone
- LOS model ≅ Free-space model if:
  - Distance < Radio Horizon
  - No reflections, absorption & other propagation effects
    - 1st Fresnel zone unobstructed

Fresnel Zone



$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d}} \le \frac{1}{2}\sqrt{\lambda d}$$

r_1 : radius of the 1st Fresnel zone, m

$d = d_1 + d_2$: distance T-R, m

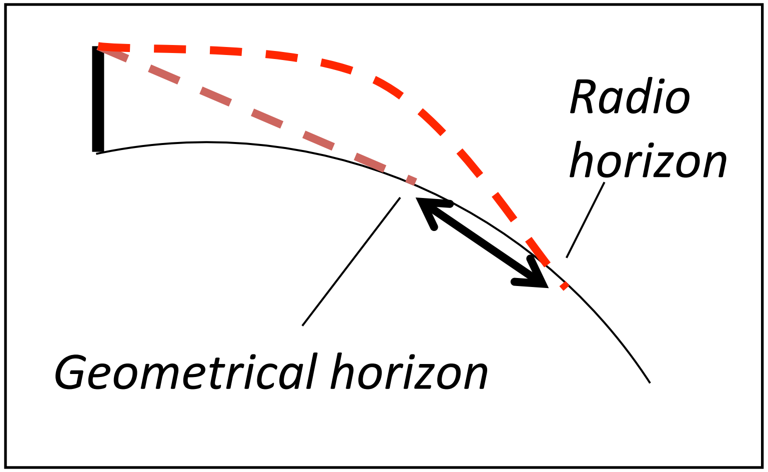
λ : wavelength, m

d_1, d_2 : distance to R and to T, m

Example: max. radius of the 1st Fresnel zone at 3 GHz (λ= 0.1m) with T – R distance of 4 km:
= (1/2)sqrt(0.1*4000) = 10m

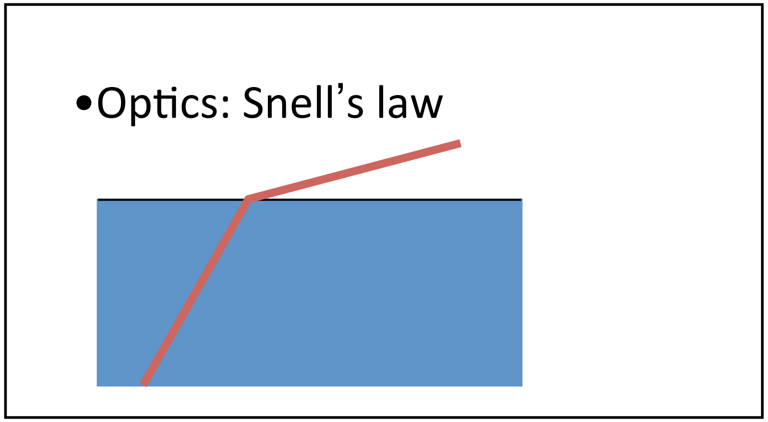
- Fresnel zones are loci of points of constant path-length difference of λ/2 (180^0 phase difference)
    - The n-th zone is the region enclosed between the 2 ellipsoids giving path-length differences n(λ/2) and (n-1)(λ/2)
- The 1st Fresnel zone corresponds to n = 1

LOS – Radio Horizon

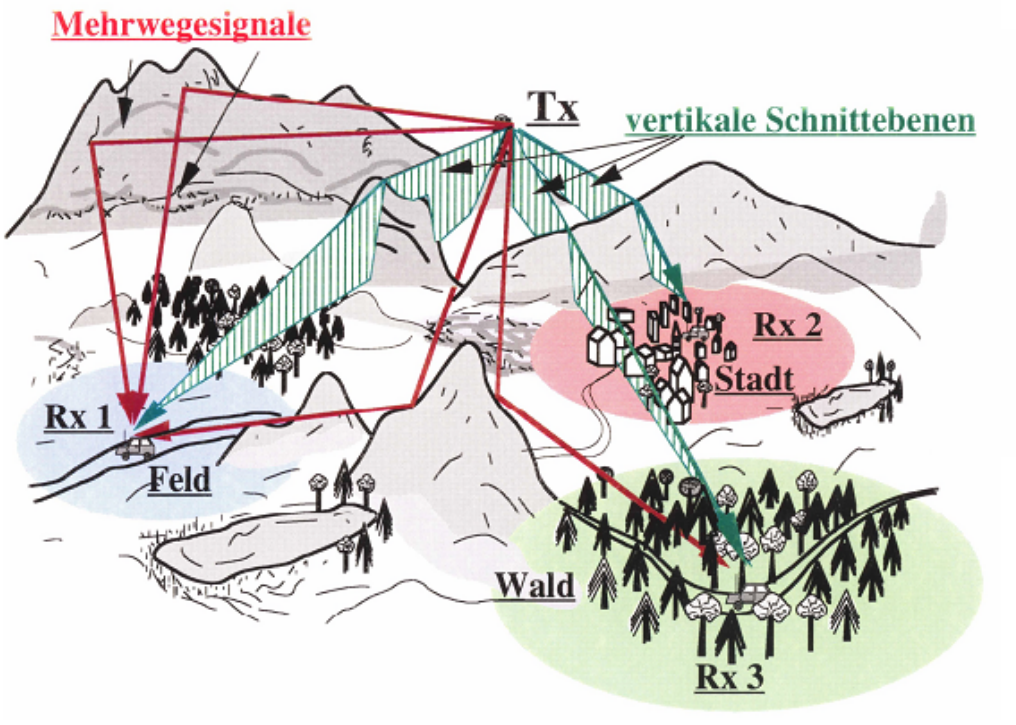


- *Earth curvature*
- *Radio waves go behind the geometrical horizon due to refraction: the air refractivity changes with height, water vapor contents, etc.*
- *In standard conditions the radio wave travels approximately along an arc bent slightly downward.*
- *K-factor is a scaling factor of the ray path curvature. K=1 means a straight line. For the standard atmosphere K=4/3. An equivalent Earth radius KR_{earth} 'makes' the path straight*
- *Departure from the standard conditions may led to subrefraction, superrefraction or duct phenomena.*
- *Strong dependence on meteorological phenomena.*
- *Should be taken into account when planning for a clear Fresnel zone! (see MLINK software)*

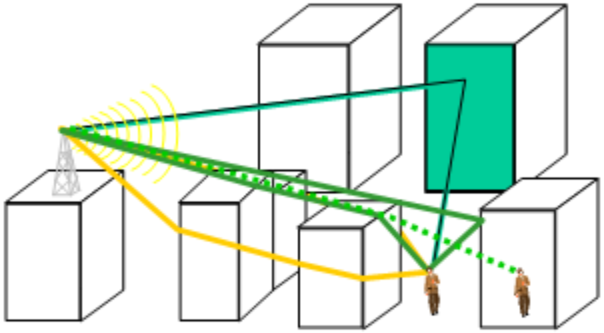
•Optics: Snell's law



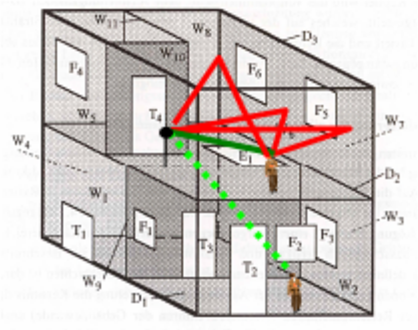
Typical propagation environments



macro cell



small macro cell / micro cell

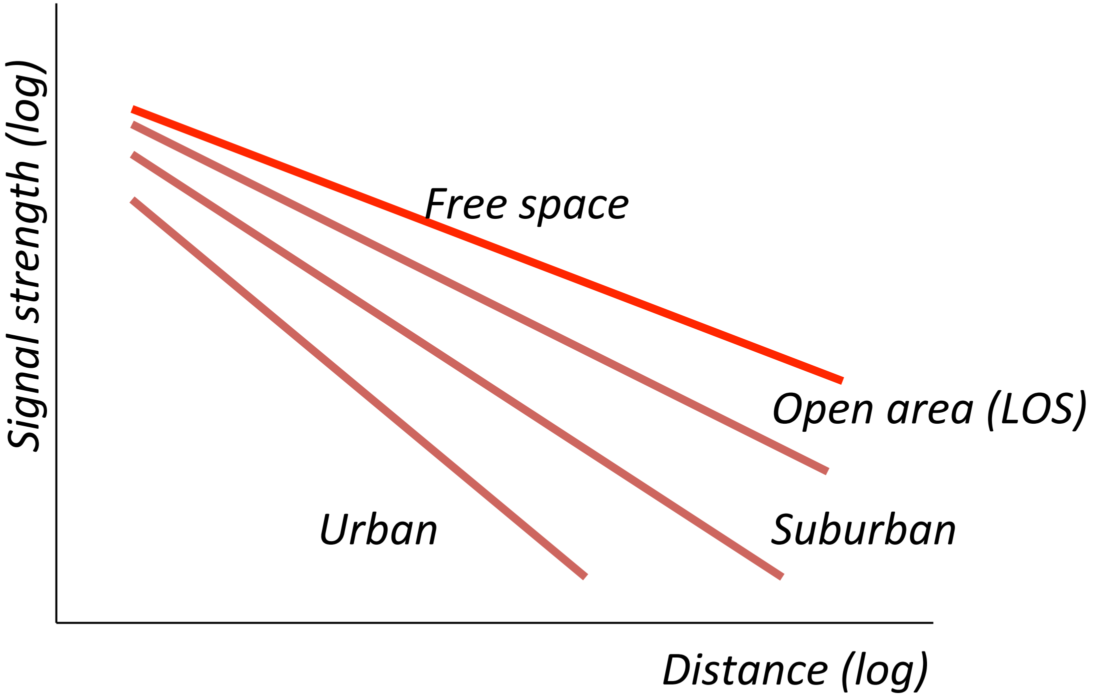


pico cell

Source: Kurner T; 1st COST2100 Training School, Wroclaw, Feb 2008

Okumura-Hata model

Long-term average



Microwave transmission gain up to the radio horizon:

$G_{avrg} = Kd^{-n}$

K, n – constants

Typically: $3 \leq n \leq 5$

n = 2: free space

n = 4: two-ray model

The best results – when the constants are determined experimentally for a given environment

Outdoor propagation

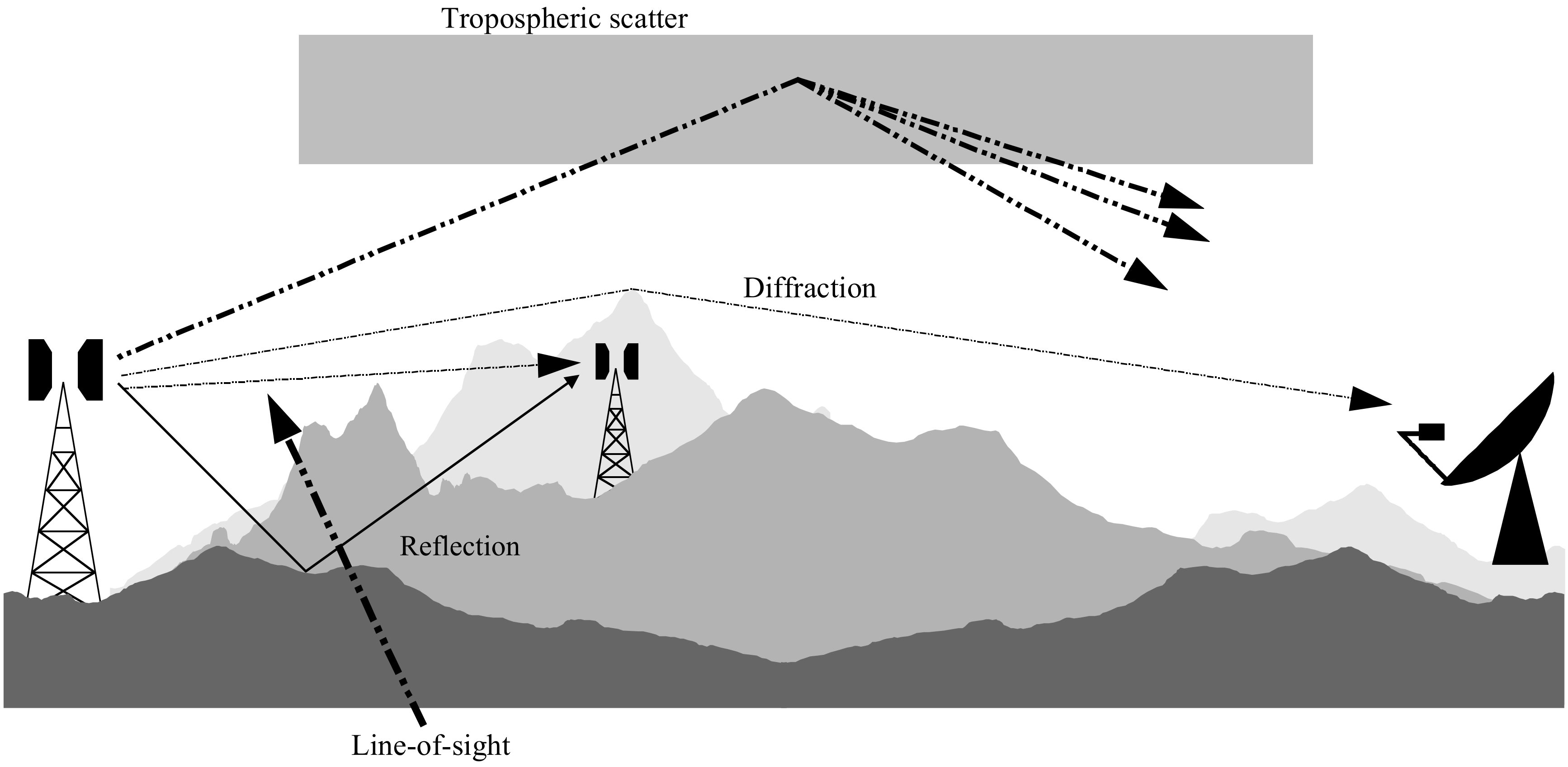
Dependence on

- Wavelength (frequency)
- Polarization
- Environment
  - Climate
  - Weather
- Sun activity
  - Time (ionosphere)

Outdoor propagation: long-term modes

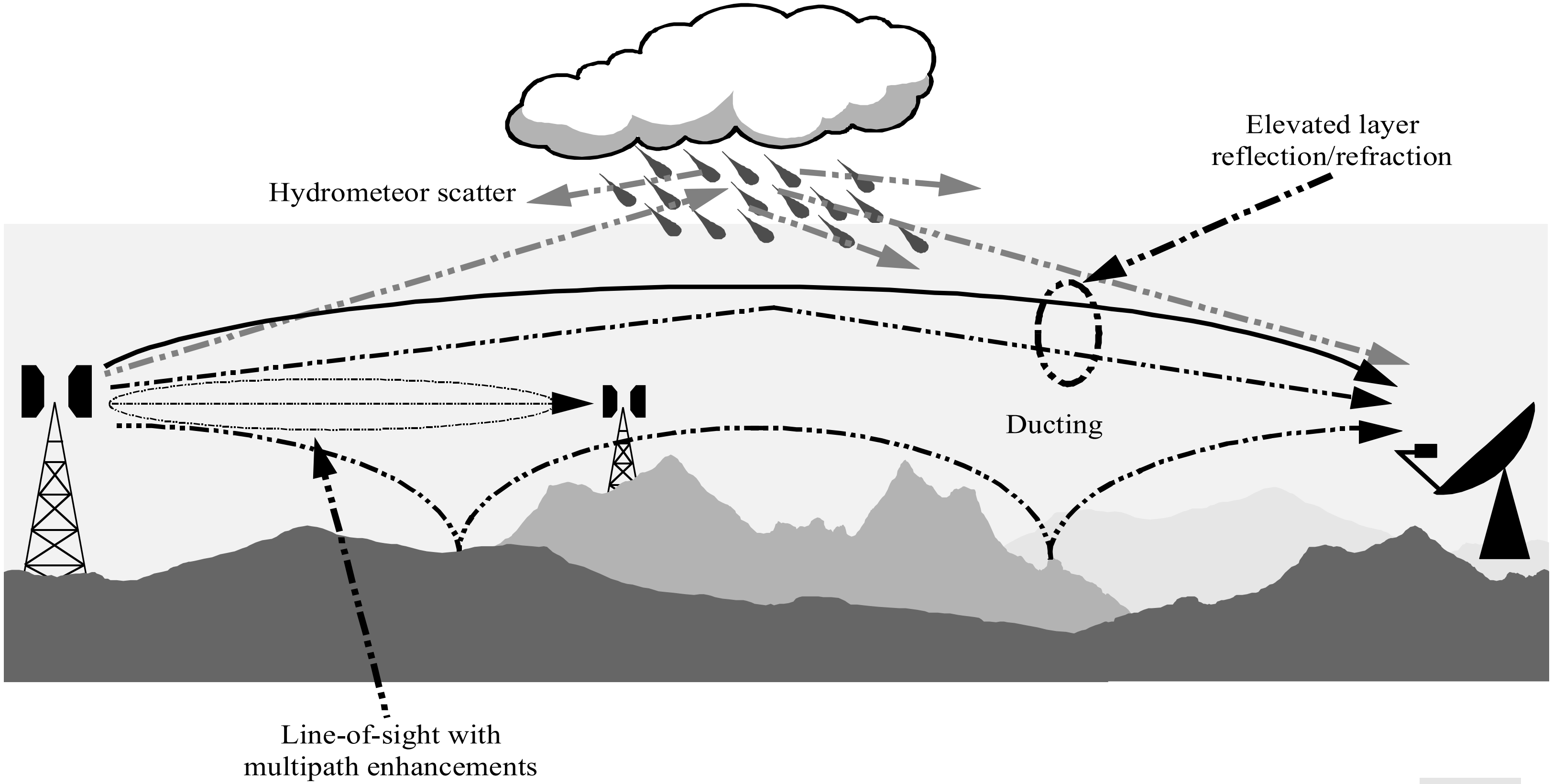
FIGURE 1

Long-term interference propagation mechanisms



Outdoor propagation: short-term modes

Anomalous (short-term) interference propagation mechanisms



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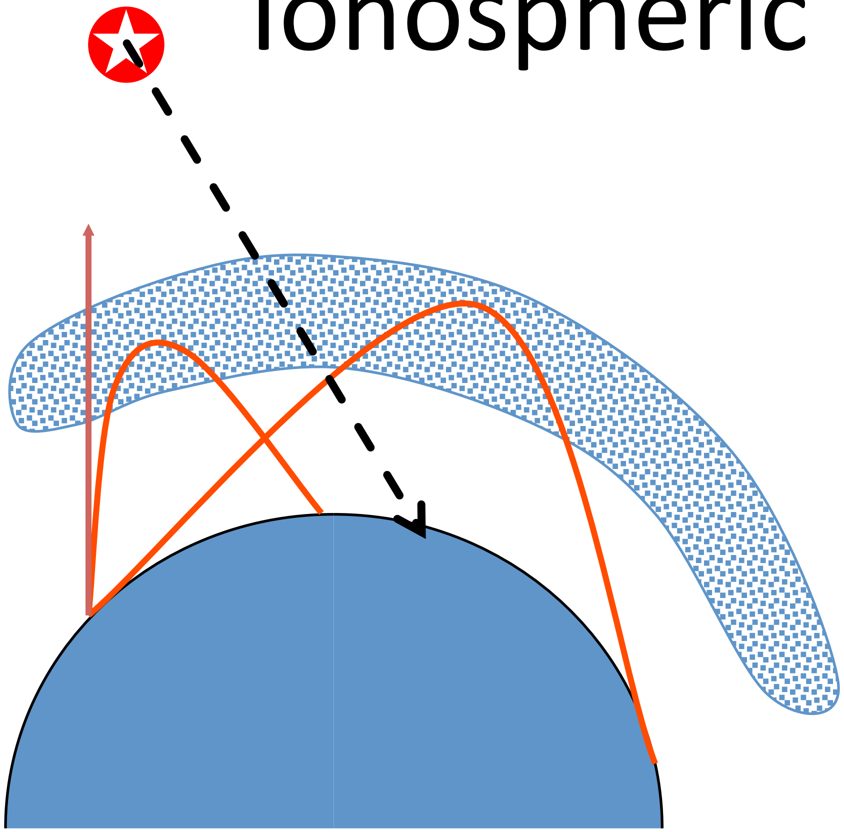
Ionospheric “reflections”



Ionospheric reflectivity depends on time, frequency of incident wave, electron density, solar activity, etc. Difficult to predict with precision.

- The ionosphere is transparent for microwaves but reflects HF waves
- There are various ionospheric layers (D, E, F1, F2, etc.) at various heights (50 – 300 km)
- Over-horizon communication range: several thousand km
- Suffers from fading

Reflection: what it does?

- At an interface between two dissimilar media the wave returns into the medium from which it originated
- Changes the direction, magnitude, phase and polarization of the incident wave
  - Depending on the
    - reflection coefficient,
    - wave polarization,
    - shape of the interface

- Reflection may be specular
  (*i.e.,* mirror-like)
  or diffuse (*i.e.,* not retaining the image, only the energy)
  according to the nature of the interface.
    - Demonstration (laser pointer)

Boundary conditions

- Tangential components of E (and H) at both sides of the border are equal to each other

- With ideal conductor, tangential component of E is zero at the border

Reflection coefficient

- = The ratio of the complex amplitudes of the reflected wave and the incident wave

$$R_{HP} = \frac{\sin\psi - \sqrt{\varepsilon_c - \cos^2\psi}}{\sin\psi + \sqrt{\varepsilon_c - \cos^2\psi}}$$

$$R_{VP} = \frac{\varepsilon_c \sin\psi - \sqrt{\varepsilon_c - \cos^2\psi}}{\varepsilon_c \sin\psi + \sqrt{\varepsilon_c - \cos^2\psi}}$$

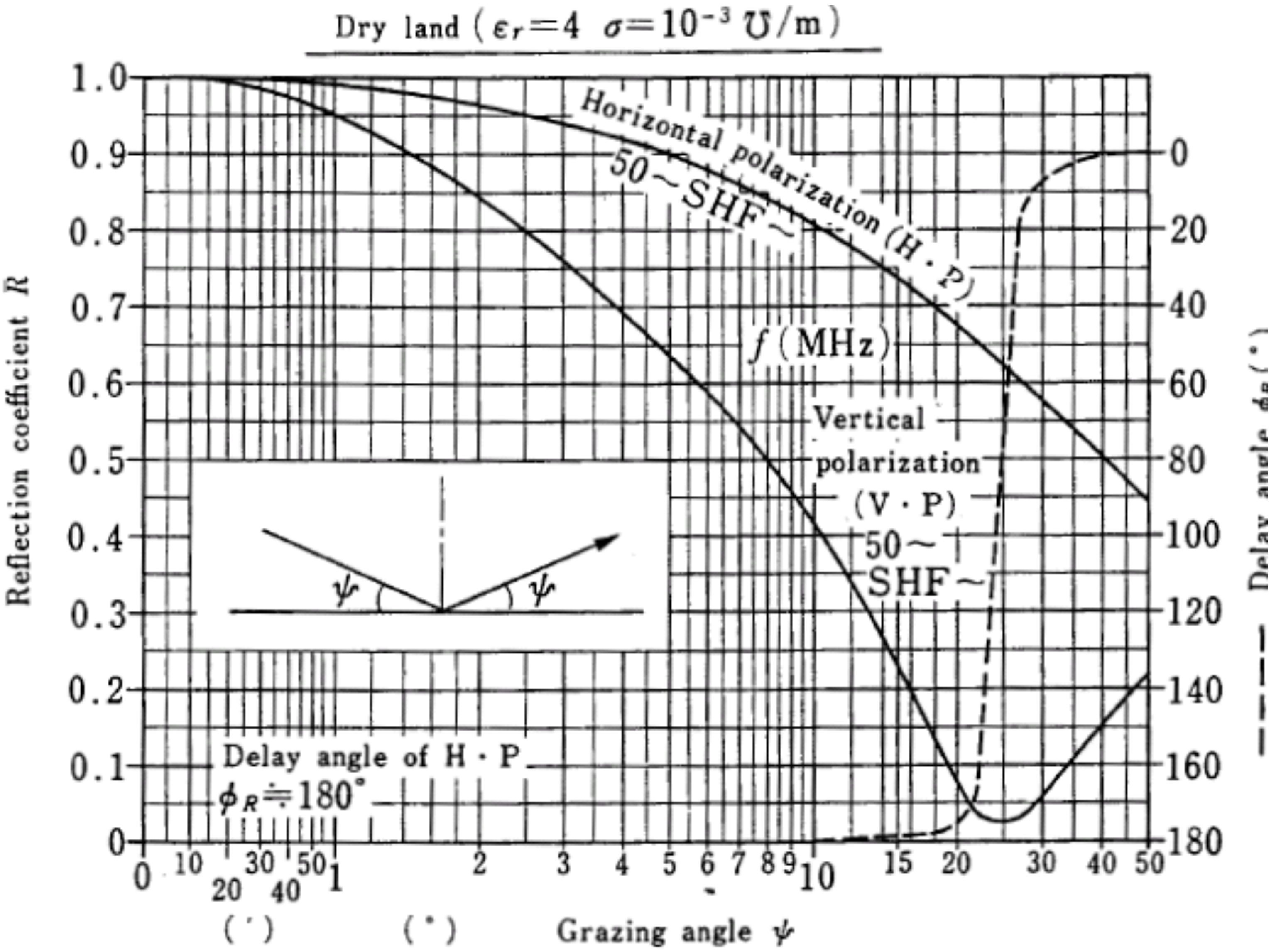
$\varepsilon_c = \varepsilon_r - j60\sigma\lambda$ (complex dielectric const.)

ψ : grazing angle (complementary angle of incidence)

ε_r : dielectric const. of reflection surface

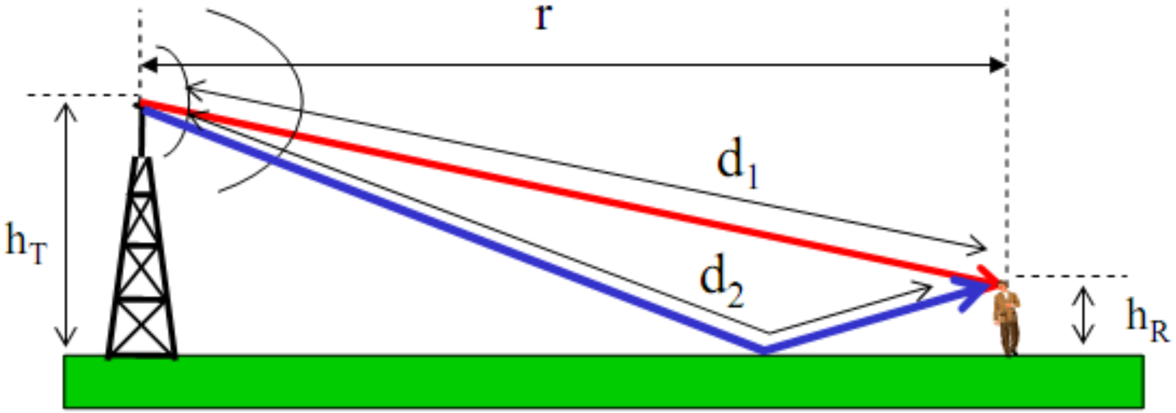
σ : conductivity of reflection surface, 1/ohm.m

λ : wavelength, m



Java applett on reflection:http://www.amanogawa.com/archive/wavesA.html

Reflection, 2-ray model 1



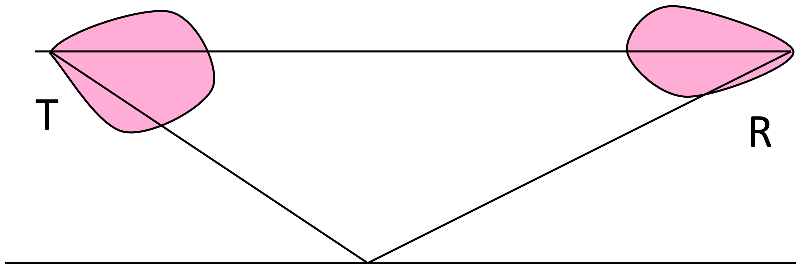
At the receiver, superposition between the direct ray and a ray reflected on the surface of the earth can arise.

For the received power, the following applies:

$$P_R = P_T \frac{1}{r^2}\left(\frac{\lambda}{4\pi}\right)^2 L_{ZS}(r, h_T, h_R) G_T(\theta_T, \phi_T) G_R(\theta_R, \phi_R) \qquad (9)$$

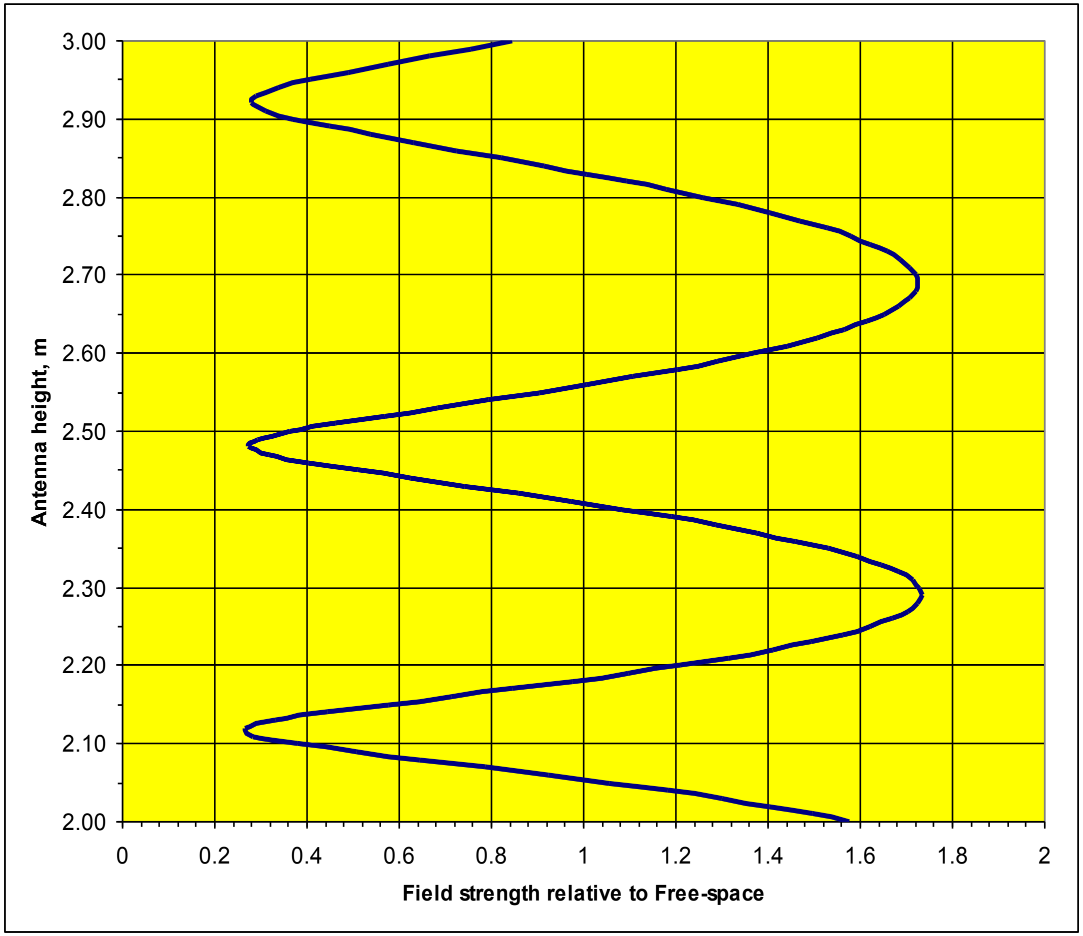
- with the term $\frac{1}{r^2} L_{ZS}$ describing the attenuation resulting from the two rays

Source: Kurner T; 1st COST2100 Training School, Wroclaw, Feb 2008



- The received direct and reflected waves differ due to
  - Path-lengths difference
  - Transmitting antenna characteristics
  - Receiving antenna characteristics
    - The antenna directive radiation pattern may have different magnitudes and phases for different angles (for the direct ray and for the reflected ray)

Example 2: height



Variable:

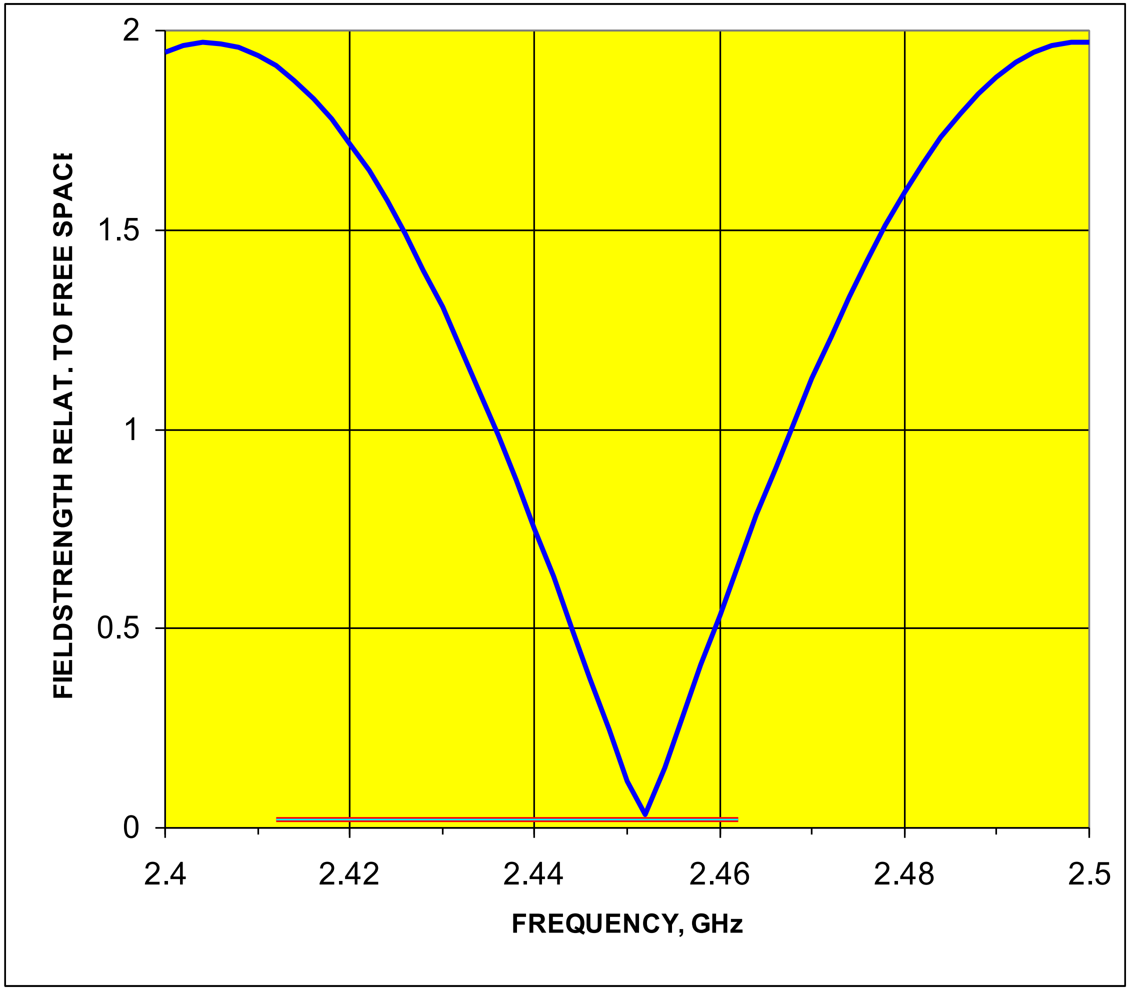
H2 = 2 - 3m
Step = 1 cm

Fixed parameters:

F = 2.4GHz
H1 = 1m
D = 3m
|R| =1
Arg(R) = 180^0

- Simulation of Height dependence

Example 3: frequency



Variable:

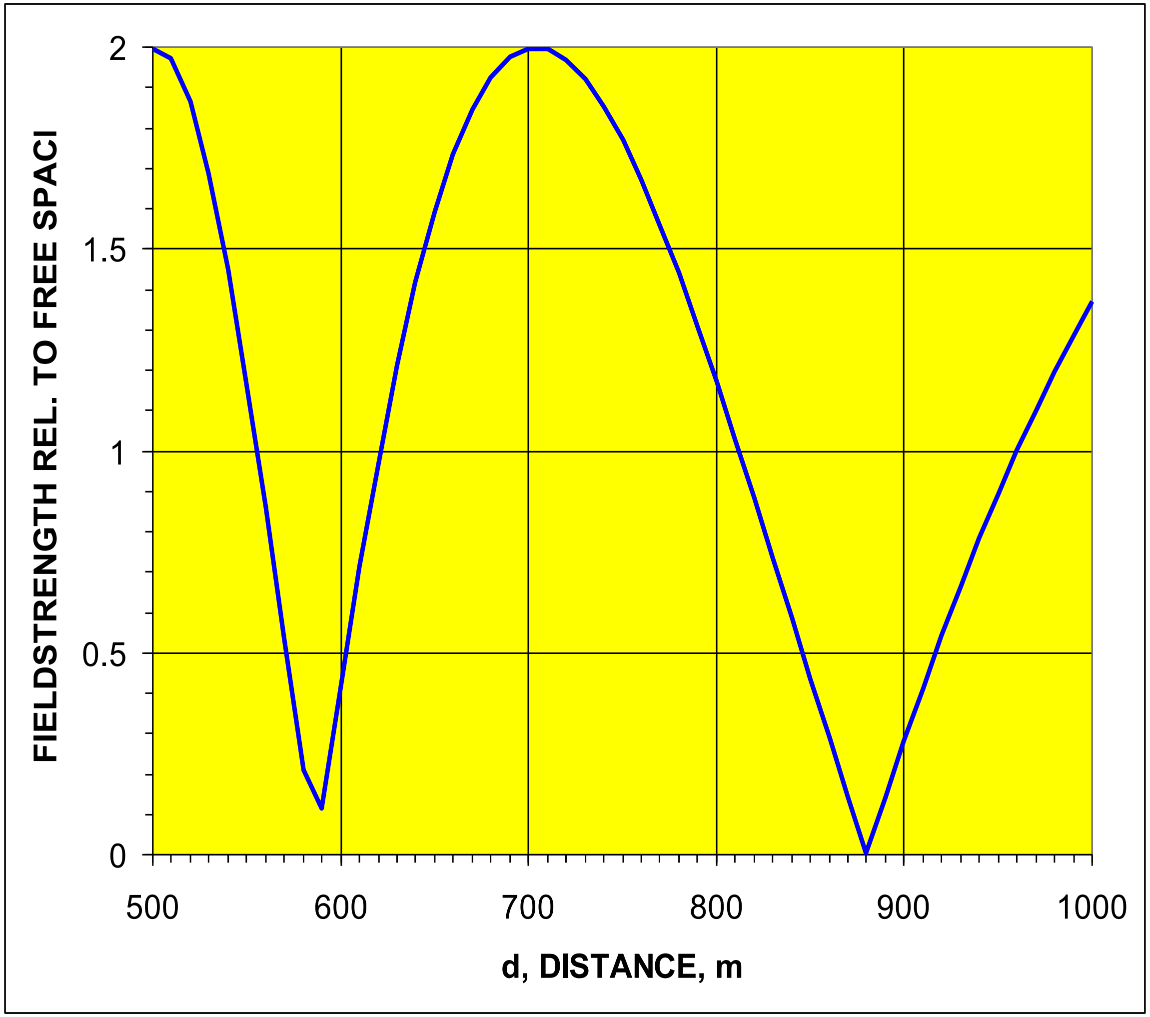
F = 2.4 - 2.6 GHz
Step = 2 MHz

Fixed parameters:

H1 = 14 m
H2 = 12 m
D = 104 m
|R| =1
Arg(R) = 180^0

- Simulation of [Frequency]() dependence

Example 1: distance

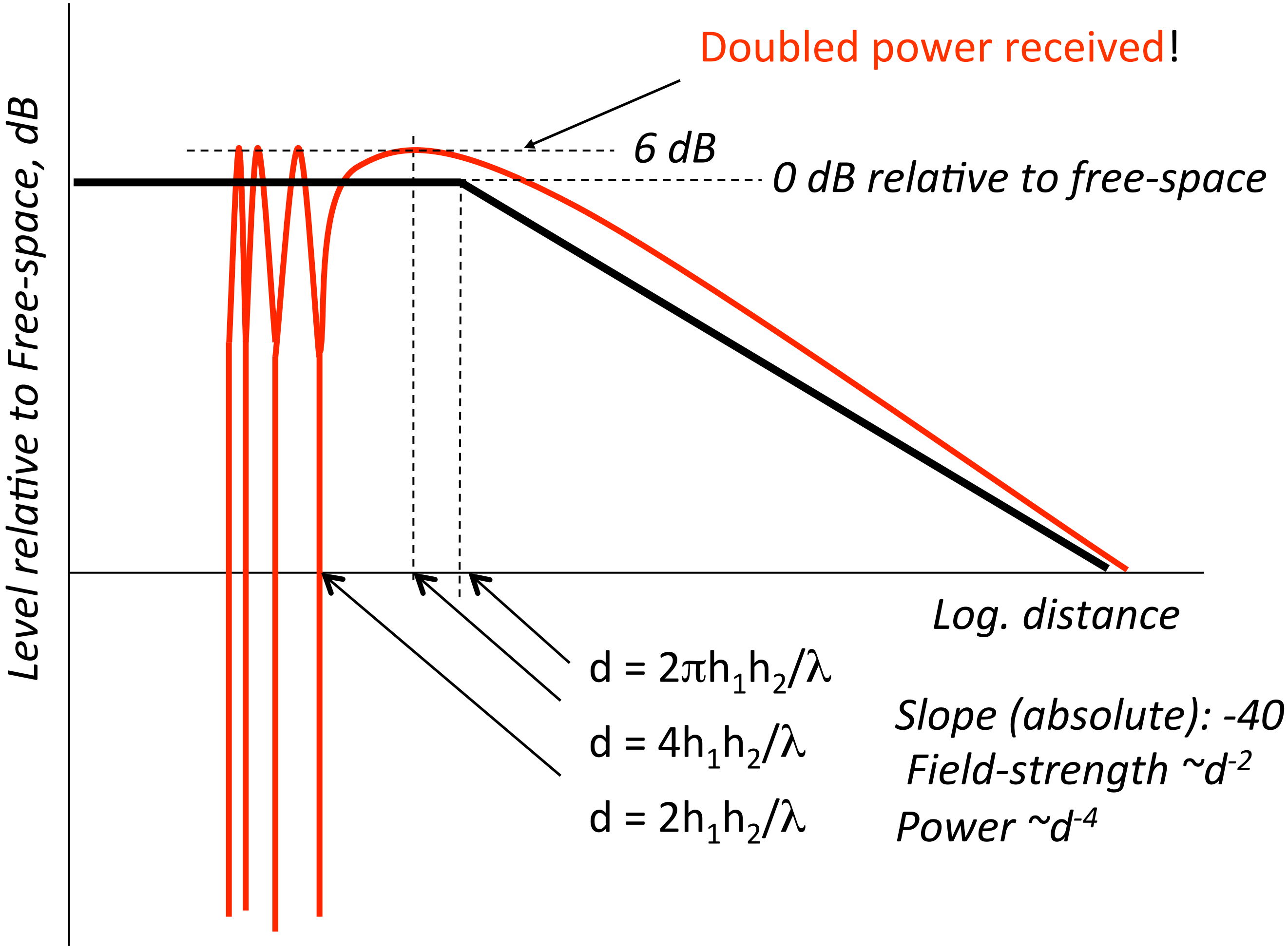


Variable:
d = 500-1000m
Step = 10m

Fixed parameters:
F = 2.4 GHz
H1 = 11m
H2 = 10m
|R| = 1
Arg(R) = 180^0

- Simulation of Distance dependence

Distance Dependence

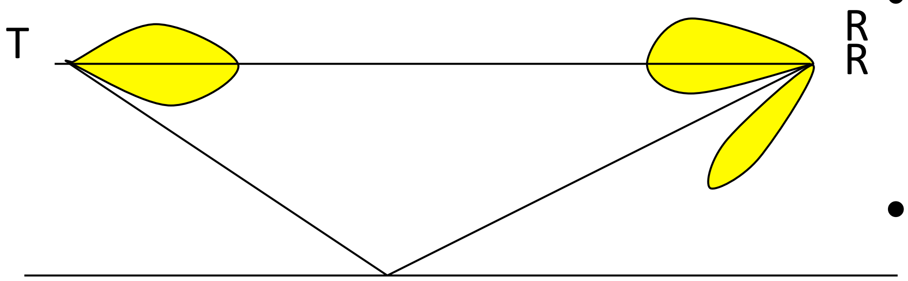


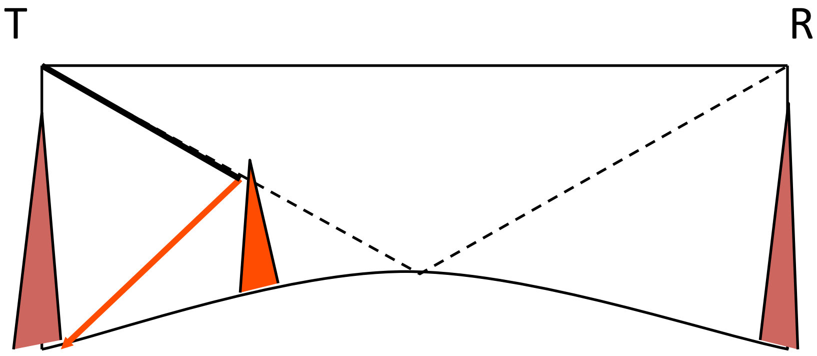
Slope (absolute): -40 dB/dec

Field-strength ~d^{-2}

Power ~d^{-4}

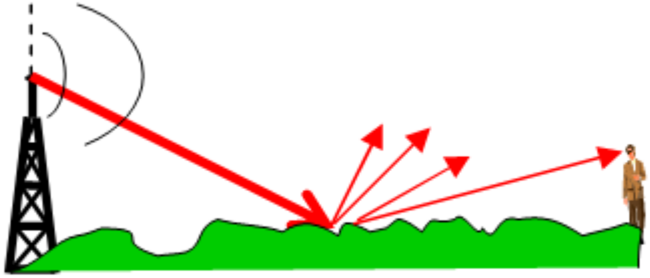
Avoiding negative reflection effects





- Controlling the directive antenna gain at the transmitter and/or receiver
- Blocking the reflected ray at the transmitter-reflector path and/or reflector – receiver path
- Combine constructively the signals using correlation-type receiver
  - Antenna diversity (~10 dB)
  - Dual antennas placed at λ/2 separation

Scattering

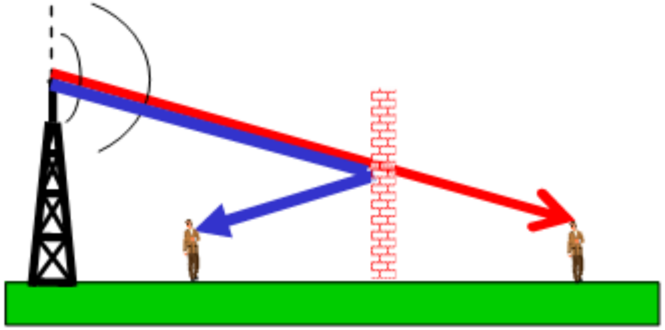


scattering

- a phenomenon in which the direction (or polarization) of the wave is changed when the wave encounters propagation medium discontinuities smaller than the wavelength (e.g. foliage)

  Results in a disordered or random change in the energy distribution

Absorption

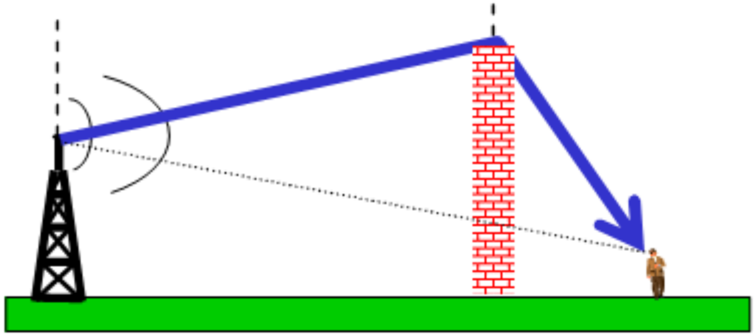


Reflection & absorption

= the conversion of the transmitted EM energy into another form, usually thermal.

- The conversion takes place as a result of interaction between the incident energy and the material medium, at the molecular or atomic level.
- One cause of signal attenuation due to walls, precipitations (rain, snow, sand) and atmospheric gases

Diffraction

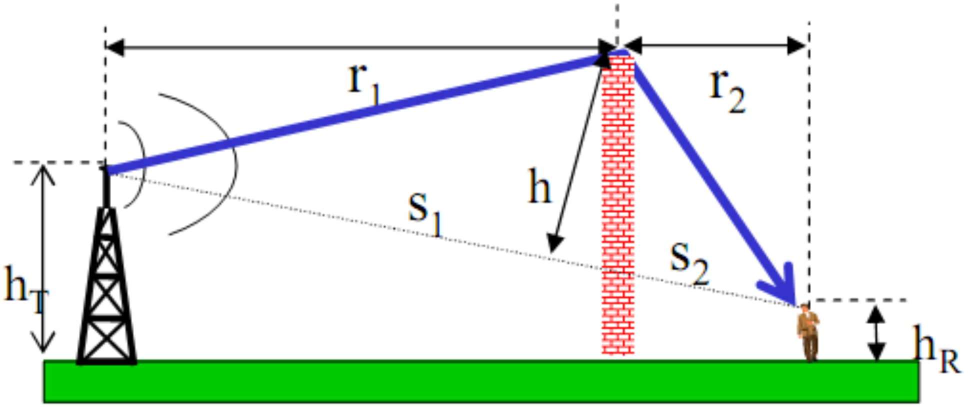


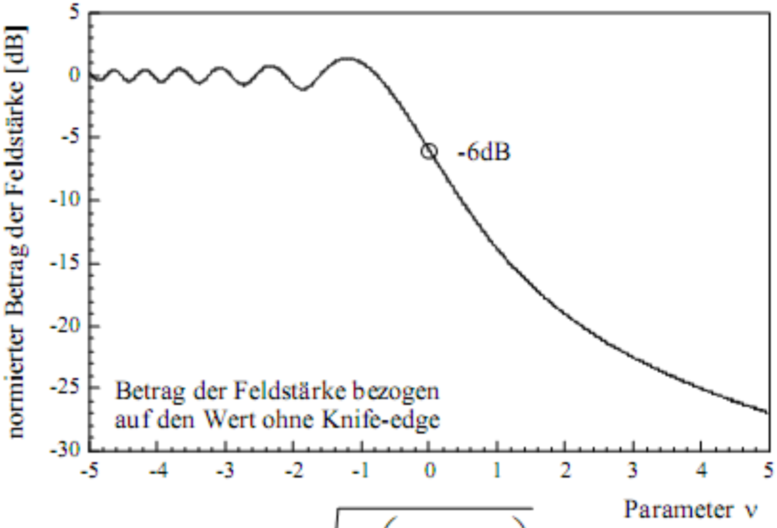
diffraction

- = the mechanism the waves spread as they pass barriers in obstructed radio path (through openings or around barriers)

  important when evaluating potential interference between stations sharing the same frequency.

Knife-Edge diffraction 2



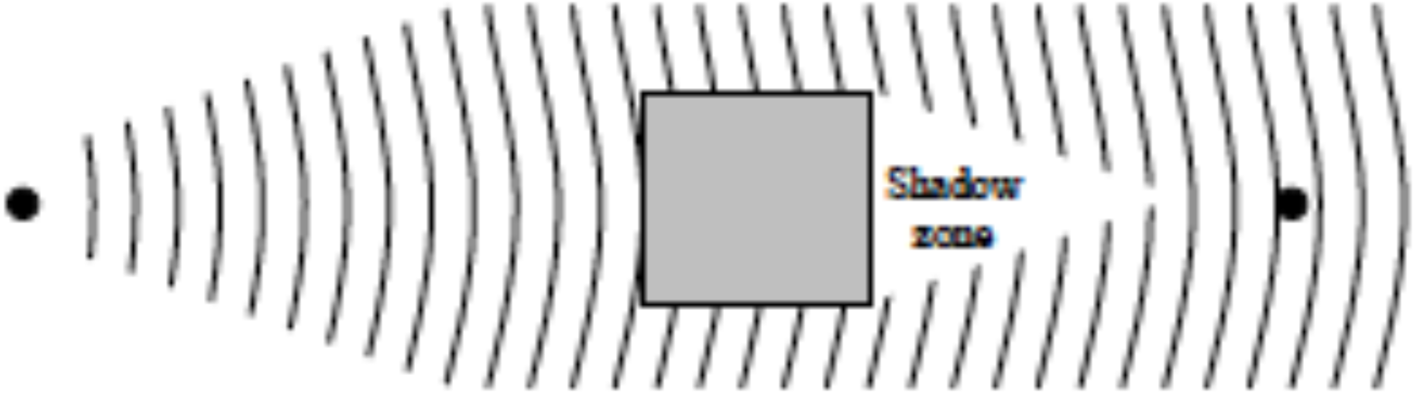


$$L_B / dB = 6.9 + 20*\log\left(\sqrt{(v-0.1)^2+1}+v-0.1\right) \qquad (13)$$

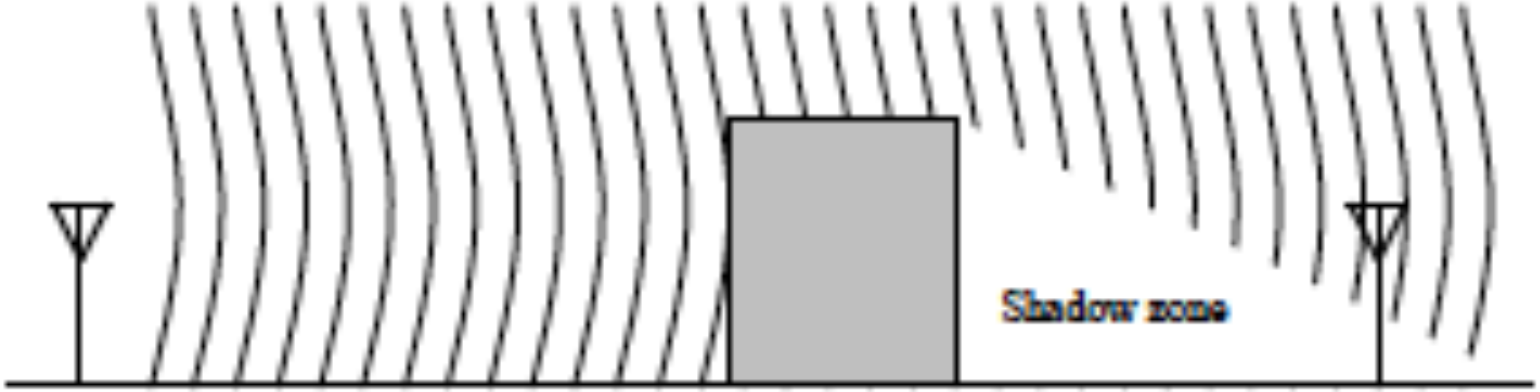
$$v = h*\sqrt{\frac{2}{\lambda}\left(\frac{s_1+s_2}{r_1 r_2}\right)} \qquad (14)$$

In practice, the diffraction loss L_B is also multiplied by an additional empirical correction factor k. Typical values for k are in the range of k = 0.2 ... 0.5 .

Source: Kurner T; 1st COST2100 Training School, Wroclaw, Feb 2008



a. Top view



b. Side view

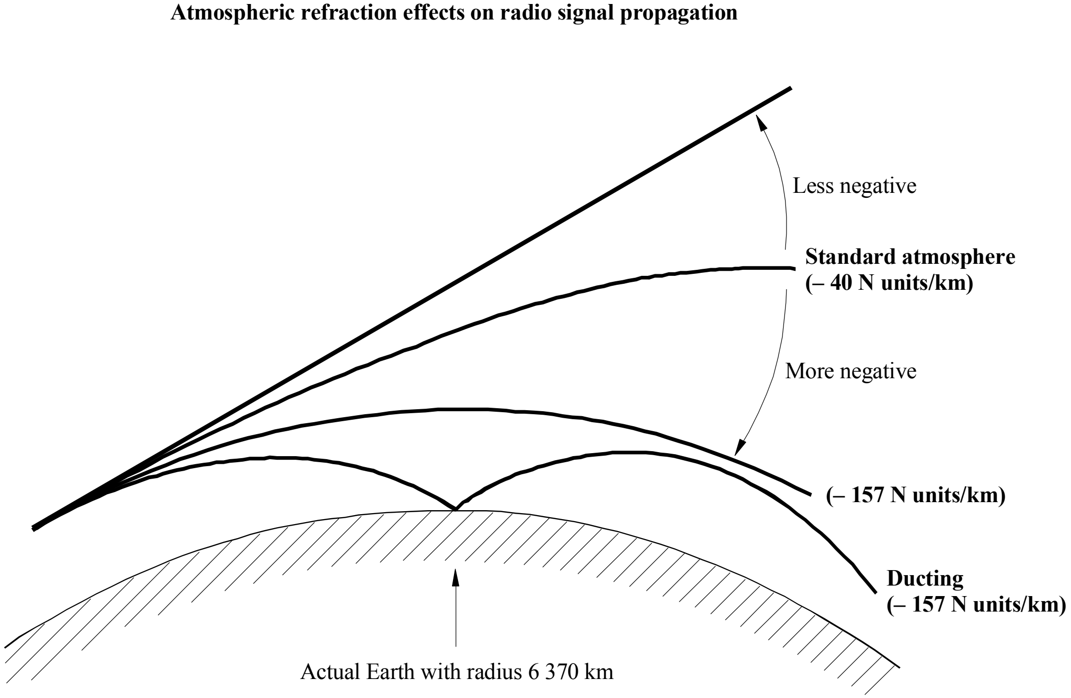
Figure 1-13. Diffraction of a wave around a building

Source: R. F. Linfield: Radio Channel Capacity Limitations; ITS-NTIA

Refraction

- = redirection of a wavefront passing through a medium having a refractive index that is a continuous function of position (*e.g.,* a graded-index optical fibre, or earth atmosphere) or through a boundary between two dissimilar media
  - For two media of different refractive indices, the angle of refraction is approximated by Snell's Law known from optics

Super-refraction and ducting



Important when evaluating potential interference between terrestrial/ earth stations sharing the same frequency

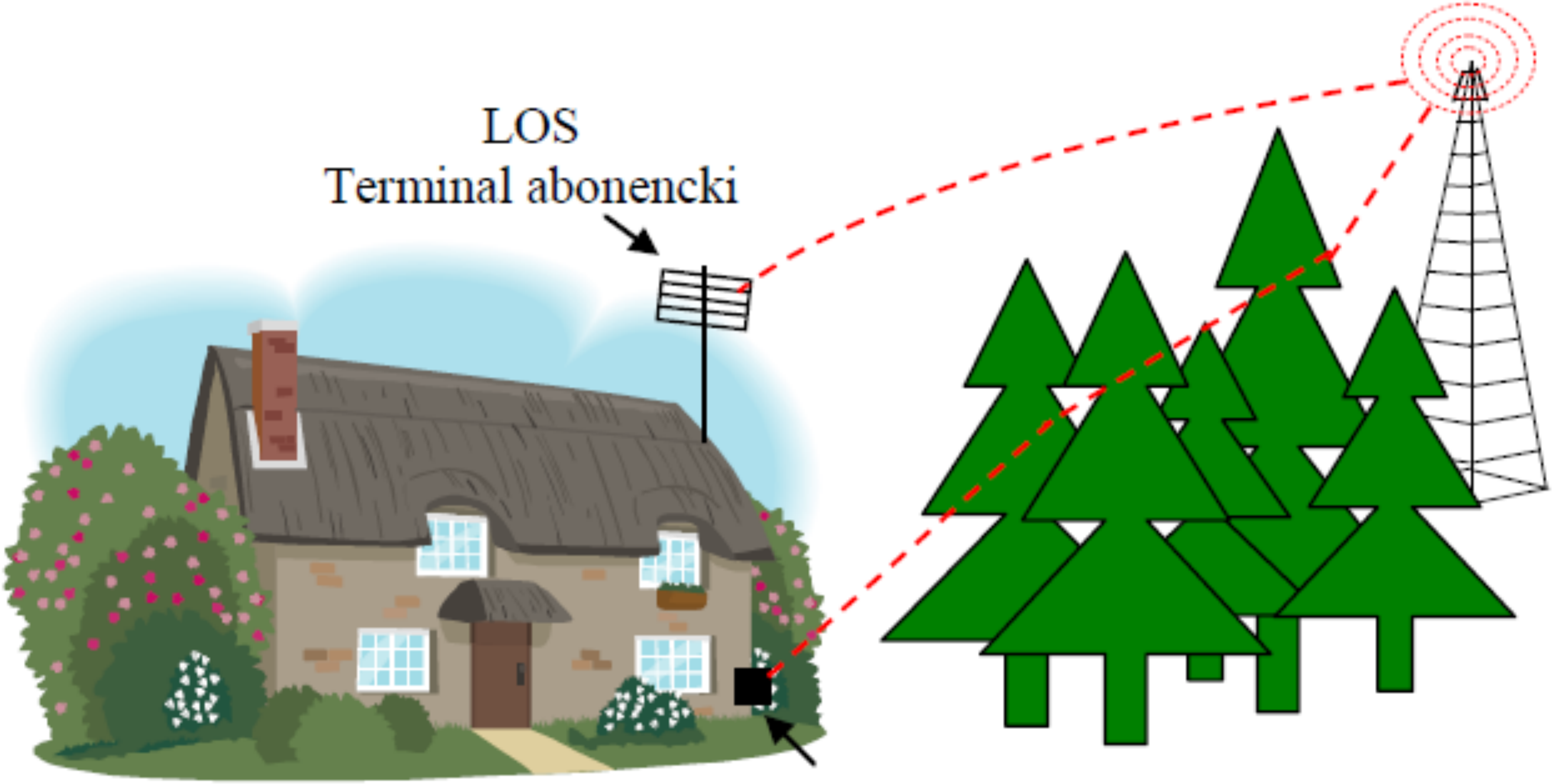
- coupling losses into duct/ layer
  - geometry
- nature of path (sea/land)
- propagation loss associated with duct/layer
  - frequency
  - refractivity gradient
  - nature of path (sea, land, coastal)
  - terrain roughness

Standard atmosphere: -40 N units/km (median), temperate climates
Super-refractive atmosphere: < -40 N units/km, warm maritime regions
Ducting: ≤ -157 N units/km (fata morgana, mirage)

Non-LOS propagation

- – when the 1st Fresnel zone is obstructed and/ or the signal reached the receiver due to reflection, refraction, diffraction, scattering, etc.
  - An obstruction may lie to the side, above, or below the path.
    - » Examples: buildings, trees, bridges, cliffs, etc.
    - » Obstructions that do not enter in the 1st Fresnel zone can be ignored. Often one ignores obstructions up to ½ of the zone

LOS-NLOS



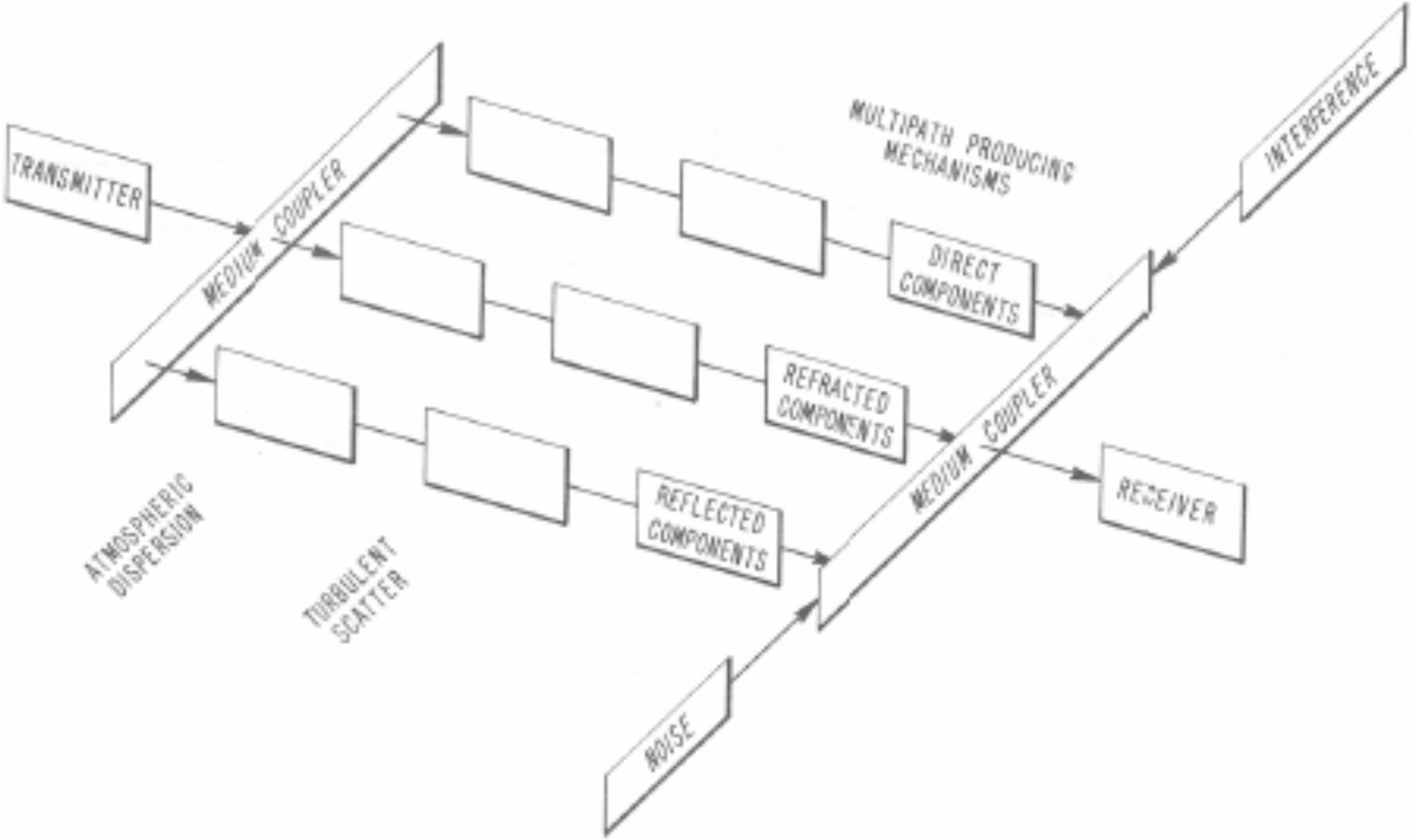
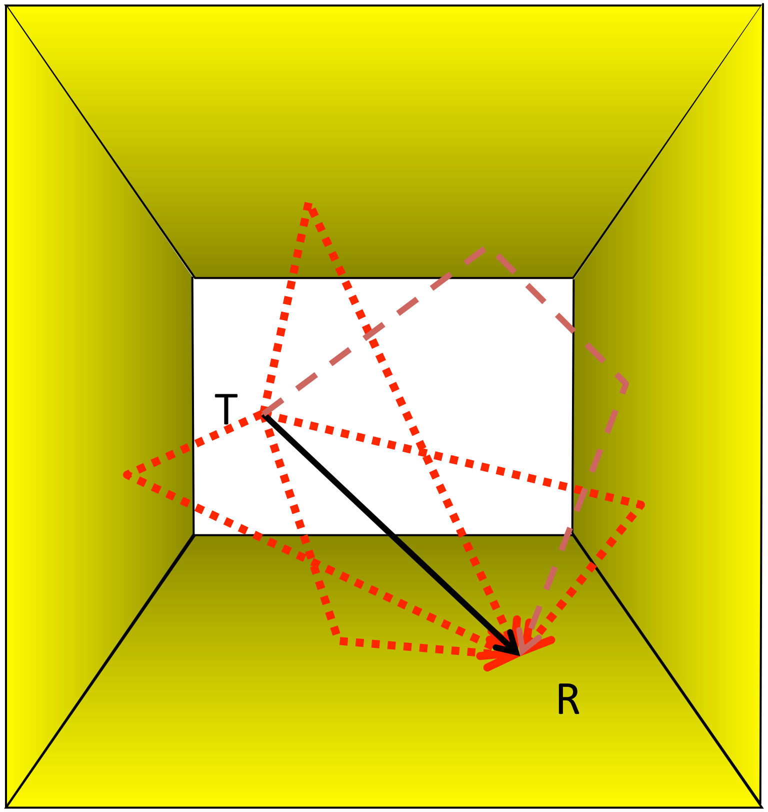


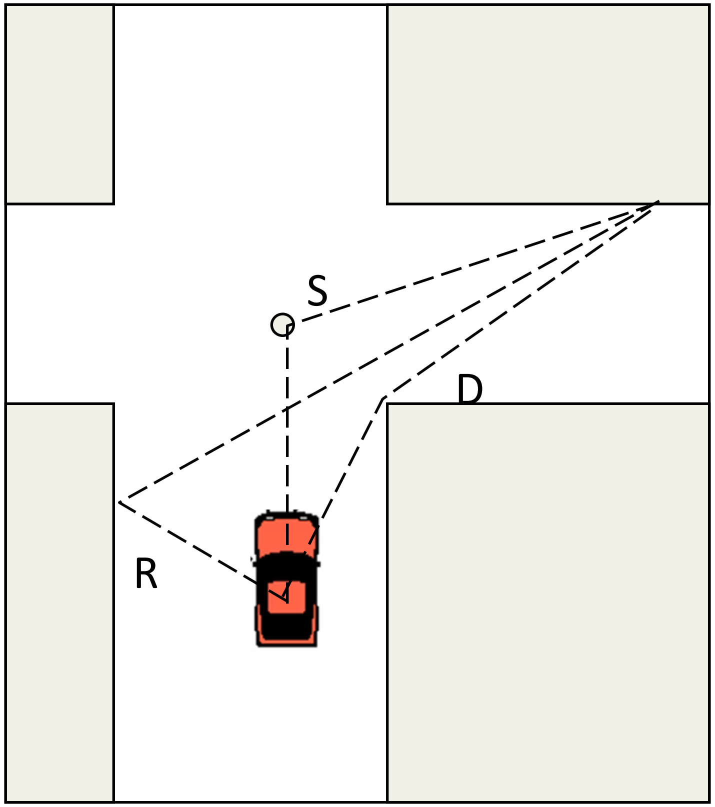
Figure 5. The radio channel.

Source: R. F. Linfield: Radio Channel Capacity Limitations; ITS-NTIA

Multipath propagation



Indoor



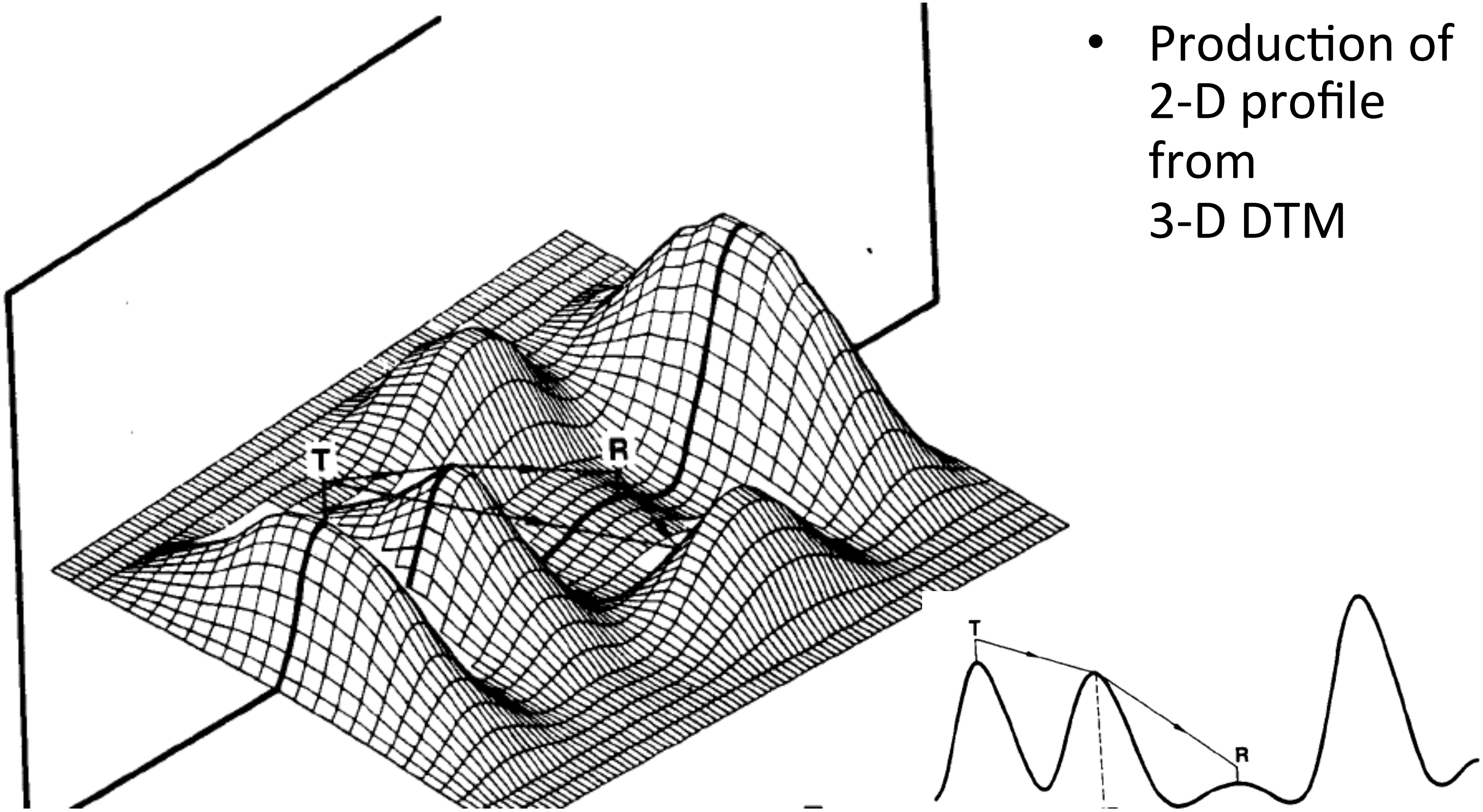
Outdoor: reflection (R), diffraction (D), scattering (S)

- The effects of multipath include phase shifting of the signal and constructive and destructive interference. This causes *Rayleigh fading*, with standard statistical distribution known as the *Rayleigh distribution*.
- Rayleigh fading with a strong line of sight content is said to have a *Rician distribution*, or to be *Rician fading*.

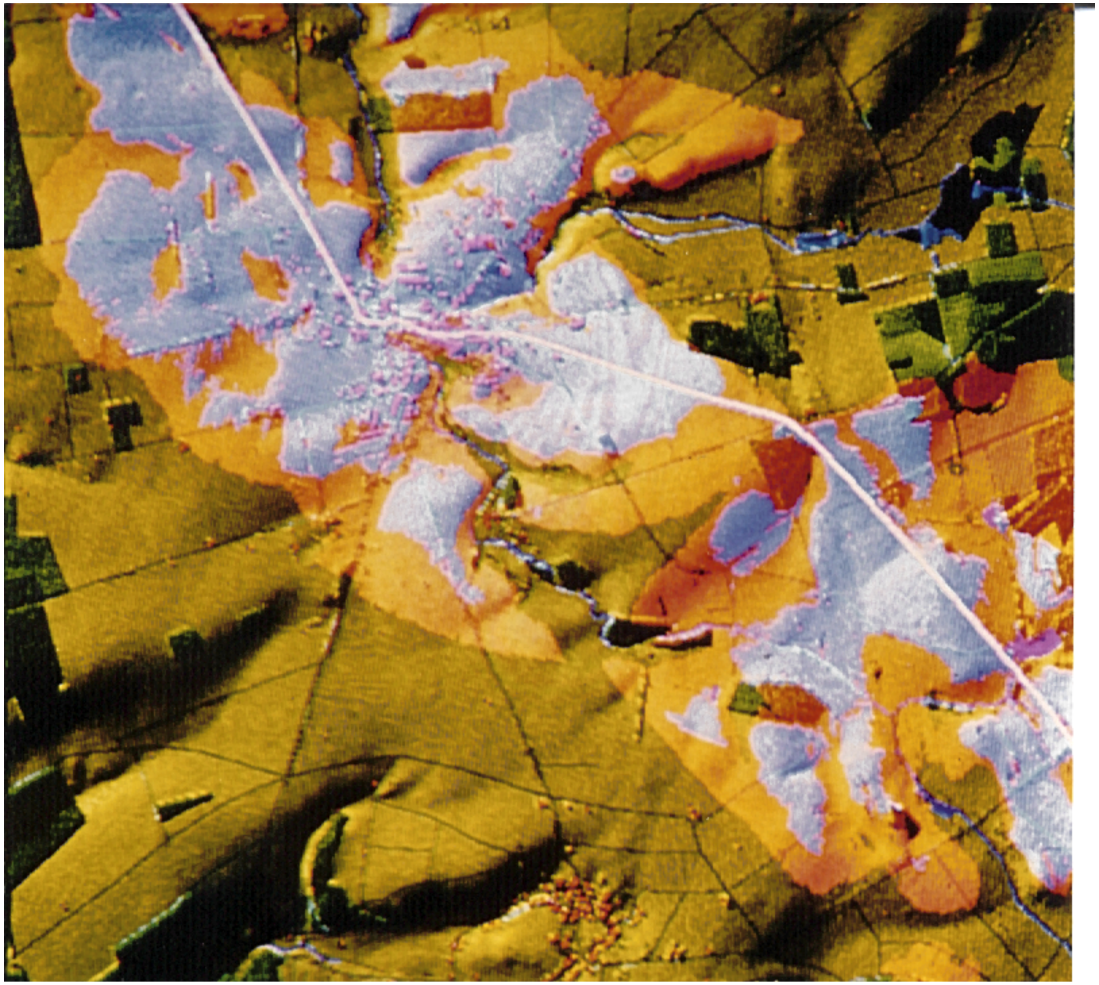
SISP

- SISP – Site Specific propagation models based on an analysis of all possible rays between the transmitter and receiver to account for reflection, diffraction & scattering
- Requires exact data on the environment
  - Indoor: detailed 3D data on building, room, equipment
  - Outdoor: 3D data on irregular terrain infrastructure, streets, buildings, etc. (Fresnel-Kirchoff or Deygout theoretical constructions)
  - Large databases
    - Satellite/ aerial photographs or radar images,

- Production of 2-D profile from 3-D DTM

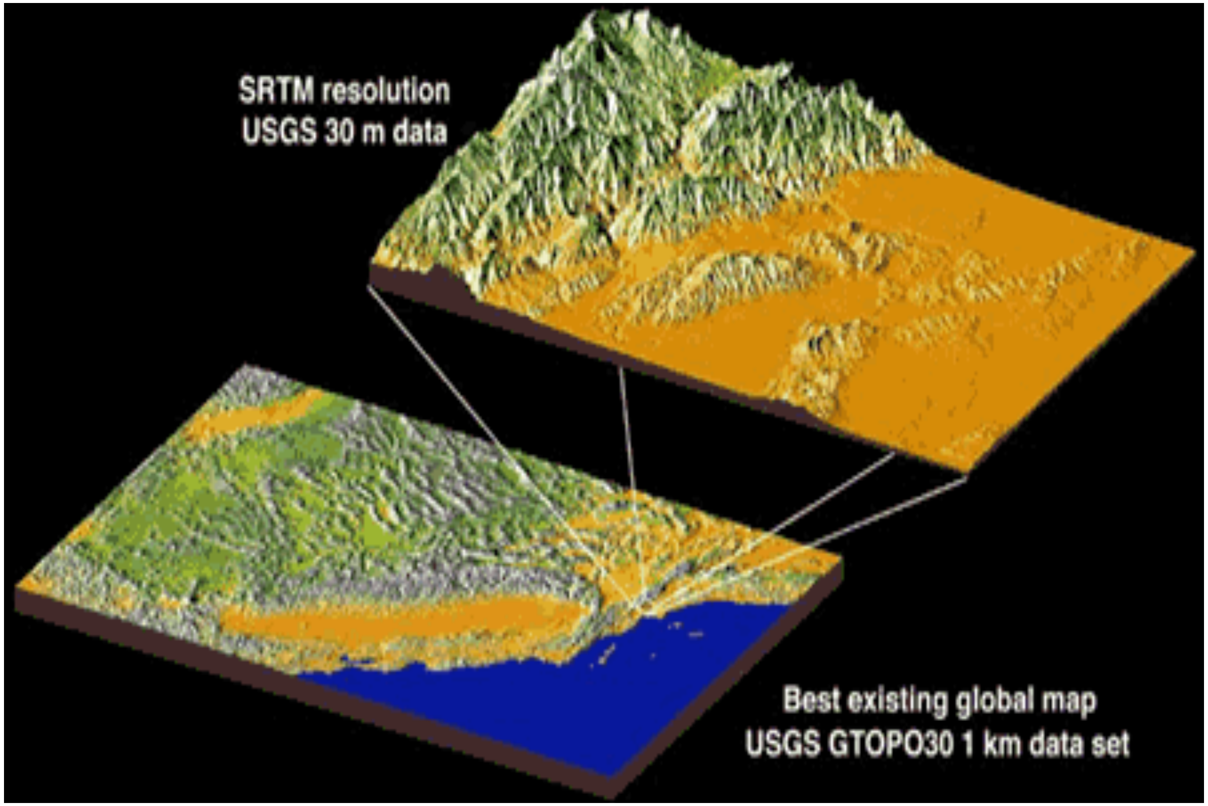


Signal coverage map



- Example of computer-generated signal-level distribution superimposed on a terrain map
  - Light-blue = strong signal
- Radio mobile software
  – a separate lecture

Digital terrain elevation maps



Most of DTM & DTED were created from paper maps

Recently, they were also produced from radar data collected from satellite

Best resolution: 1 arc-sec (~30 m)

30 times as precise as the best global maps in use today. First such maps were planned for 2004.

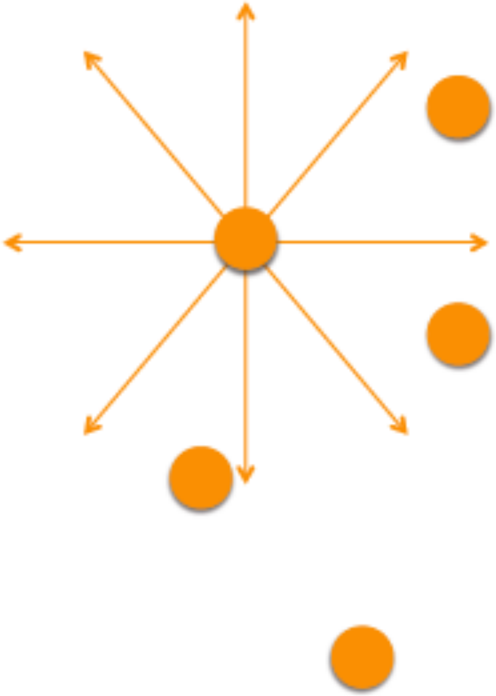
Source: NASA (http://www2.jpl.nasa.gov/srtm/)

Real wireless traces

Gather wireless link statistics (delivery rate, RSSI, LQI) over longer period of time on real hardware. Use this information directly in wireless simulation.

CURRENT STATE OF THE ART

Gathering real wireless traces



- ☐ Fix topology
- ☐ One sender at a time, all other nodes receivers
- ☐ High data rate (~20 ms)
- ☐ Each packet has ID
- ☐ Log each sent packet at sender with ID
- ☐ Log each received packet at receiver with ID, RSSI and LQI (at least ID!)
- ☐ Switch senders, repeat for all nodes

Using real wireless traces

- Result from gathering real wireless traces:

sender 1	packet ID 1, time = 0	packet ID 2, t =20ms	acket ID 3, t = 40 ms	...
node 2	RSSI=-55dBm, LQI=108	RSSI=-54dBm, LQI=108	SSI=-56dBm, LQI=109	...
node 3	RSSI=-44dBm, LQI=105	🟥	SSI=-44dBm, LQI=106	...
node 4	RSSI=-50dBm, LQI=110	RSSI=-51dBm, LQI=109	🟥	...
...	...	...	..	...

- Simulation: sender 1 sends a packet at time t=22 ms to all nodes
- Find in table sender, best fitting time (i.e. ID 2)
- Node 2 and 4 receive the packet, node 3 misses it

Real wireless traces – Discussion

- Advantages
  - Captures all properties of the real wireless channels
  - Low complexity
  - Fast execution
  - Techniques exist for “stretching” real traces into longer (infinite) ones
- Disadvantages
  - High memory requirements
  - Fixed topology, fixed environment
  - Does not capture inter-node interference
- Relatively new model, requires further refinement and investigation!

Recent NIT Contributions

- Propagation beam launching method Wypior.pptx
- Acceleration of propagation predictions over irregular terrain.ppt

What we have learned

- Radio physics co-decide on the system performance
- The best transmitter, receiver, antennas, cables, etc. may not work as expected if the relevant propagation effects are ignored or incorrectly taken into consideration
- The propagation mechanisms of the wanted signal and unwanted signals must be carefully analyzed

Aditional Material

- www.piast.edu.pl (PIAST free simulation tool)
- http://www.cplus.org/rmw/english1.html (Radio Mobile free simulation tool)
- file:///Users/ryszard/Desktop/2012%20ICTP%20Feb/CRCCovPredict.webarchive (free simulation tool)
- SEAMCAT® (Spectrum Engineering Advanced Monte Carlo Analysis Tool)
  http://www.ero.dk/ (SEAMCAT - free simulation tool)
- R. Struzak: Microcomputer Modelling, Analysis and Planning in Terrestrial TV Broadcasting: Digital Terrain Maps, Spectrum-related Data Banks and Computer Simulation Help to Examine TV Broadcasting Networks and Find a Place for New Stations; TiTI, 3/2013; pp. 8-40; http://www.itl.waw.pl/publikacje/kwartalnik-titi;
- ITU-R CACE/745 Radiowave Propagation SG 3 Circular: 22 Revised Recommendations;15 Aug. 2015; www.itu.int

Thank you for your attention