Topic 7: Propagation

Telecommunication Systems Fundamentals

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Concepts in this Chapter

- ***Propagation mechanisms***
- ***Analytical Models***
  - *Free-Space propagation*
  - *Ground-Effect. Reflection.*
  - *Diffraction. Fresnel's zones*
  - *Attenuation: gases, rain, vegetation*
- ***Empirical Models***
  - *ITU-R*
  - *Okumura-Hata*
  - *Cost 231*

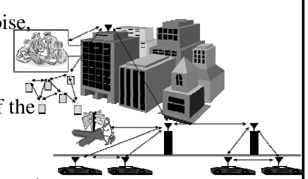
Theory classes: 2.5 sessions (5 hours)
Problems resolution: 0.5 session (1 hours)

Bibliography

Transmisión por Radio. J. Hernando Rábanos. Editorial Universitaria Ramón Areces

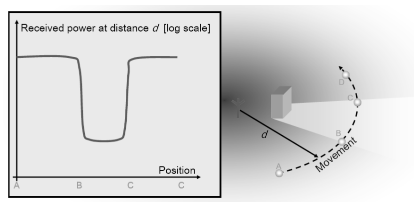
Mobile Channels Characterization

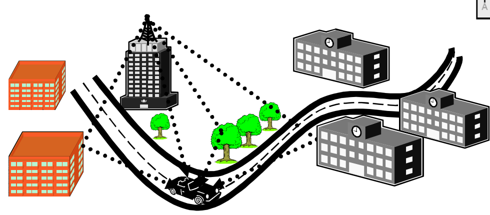
- When Tx signal propagates through wireless channels (may be mobile)
  - The received signal suffers a large variety of perturbation that require a somehow complex mathematical model to describe them
  - Quality of the received signal y quite worse than its counterpart in guided transmission (cable, fiber optic, etc.)
  - There are multitude of adverse effects: reflection, multipath, noise, interference, inter-symbol interference, …
- Such complexity of the radio channel affects:
  - Design of the receivers to cope with variability of the quality of the received signal
  - Maximum distance (coverage) for a transmitter to a receiver
  - The channel is shared among many users in the same frequency and location
  - The design and signaling of the network that has to cope with "unreliable" signal
- The behavior of the channel can be modeled into two scales
  - Large scale: to determine maximum range
  - Small scale: to design both Tx and Rx and to decided on margin to be left

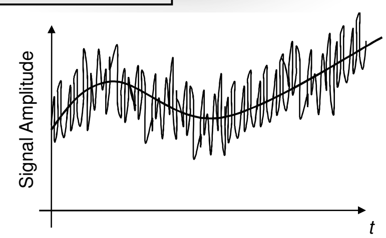


Mobile Channels Characterization

- Additionaly, if the Tx, Rx or both are moving, channel varies with tiem
- Blocking, multiple-rays (multipath), etc. May produce rapid variations (red line)
- While you also have slow variations more in accordance with the velocity of the terminals (blue line)







Channel Model and Network Planning

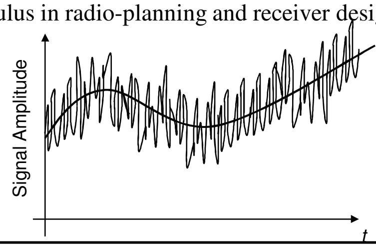
- Channel Model has an impact to
  - Understand the capacity limits of the radio transmission over it
  - To design both Tx and Rx to overcome channel degradation

Channel Model ➡ Channel Capacity / Receiver Design ➡ Design and Implementation of the Radio Network

- Two types of models
  - Narrow band
    - Valid up to 100KHz of bandwidth
    - It only considers space variations
  - Broadband
    - Considers also frequency distortion (time distortion) of the signal
    - It requires some kind of equalization at the receiver

Channel Model and Network Planning

- Narrow Band Model
  - It models only the attenuation at a given location (not time variations)
  - Large Scale
    - Areas around 50 – 100 wavelengths
    - Provides average value for attenuation between Tx and Rx
    - Used for radio-planning of networks
  - Small Scale
    - Faster (with location) variations of signal around Large Scale average value
    - Used for Margin calculus in radio-planning and receiver design



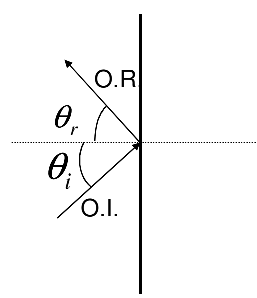
Analytical Propagation Models

- General Propagation concepts
- Terrain influence (Reflection Coefficient)
- Flat Earth model
- Curve Earth model
- Refraction
- Attenuation

Analytical Propagation Models. General Concepts

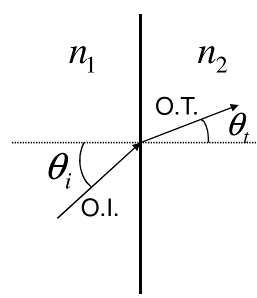
- Analytical propagation models
  - They are Large Scale Models
  - Based on Ray Tracing approach
  - Useful for point-to-point planning
  - The compute the attenuation including
    - Refraction and reflection
    - Diffraction
    - Dispersion
    - Guided-wave effect
- Characterized by
  - Exactness of the results
  - Need for detailed knowledge of the scenario
  - High computational cost
- Not recommended for
  - Mobile communications
  - Broadcasting

Reflection and Reflaction



- Reflection:
  - When a wave hits an interface between two means, a portion of the impinging power gets reflected and the rest goes through
  - Both incident and reflected waves in the same plane
  - Reflection coefficient
  - It allows passive repeaters

Snell: $\theta_i = \theta_r$



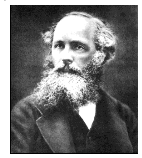
- Refraction:
  - When a wave hits an interface between two means, portion of the power that goes into the second mean travels through it with different propataion speed
  - Both incident and refracted waves in the same plane
  - Reflection coefficient

Snell: $n_1 sen\theta_i = n_2 sen\theta_t$

Electromagnetic Wave Propagation

- Different approaches to estimate the behavior of the electromagnetic propagation
  - Maxwell Equation: nice math model but quite complex to solve for specific contour conditions. Some scenarios have not closed form solution

$$\nabla \cdot \mathbf{E} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\sqrt{\varepsilon_0 \mu_0}\,\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mathbf{j} + \sqrt{\varepsilon_0 \mu_0}\,\frac{\partial \mathbf{E}}{\partial t}$$



  - Approach based on optical model

  - Empirical curve fit to measurement campaigns

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Electromagnetic Wave Propagation

- Electromagnetic propagation characteristics depend on
  - Conditions of the trajectory between Tx and Rx – obstacles (hills, buildings, vegetation, …)
  - Electrical characterization of the terrain (type of soil, smoothness, …)
  - Physical properties of the mean (humidity, gasses and vapors, …)
  - Frequency of Tx
  - Polarization
- Generally speaking, the quantity to be estimated is the attenuation
  - Basic methods to predict attenuation

Frequency Bands

Table of ITU Radio Bands			
Band Number	Symbols	Frequency Range	Wavelength Range
4	VLF	3 to 30 kHz	10 to 100 km
5	LF	30 to 300 kHz	1 to 10 km
6	MF	300 to 3000 kHz	100 to 1000 m
7	HF	3 to 30 MHz	10 to 100 m
8	VHF	30 to 300 MHz	1 to 10 m
9	UHF	300 to 3000 MHz	10 to 100 cm
10	SHF	3 to 30 GHz	1 to 10 cm
11	EHF	30 to 300 GHz	1 to 10 mm
12	THF	300 to 3000 GHz	0.1 to 1 mm

Frequency Bands

Band	Name	Min. Freq.	Max. Freq.	Max. λ	Min. λ
ELF	Extremely Low Frequency	-	3 kHz	-	100 km
VLF	Very Low Frequency	3 kHZ	30kHz	100 km	10 km
LF	Low Frequency	30 kHz	300 kHz	10 km	1 km
MF	Medium Frequency	300 kHz	3 MHz	1 km	100 m
HF	High Frequency	3 MHz	30 MHz	100 m	10 m
VHF	Very High Frequency	30 MHz	300 MHz	10 m	1 m
UHF	Ultra High Frequency	300 MHz	3 GHz	1 m	10 cm
SHF	Super High Frequency	3 GHz	30 GHz	10 cm	1 cm
EHF	Extremely High Frequency	30 Ghz	300 GHz	1 cm	1 mm

Frequency Bands - Microwaves

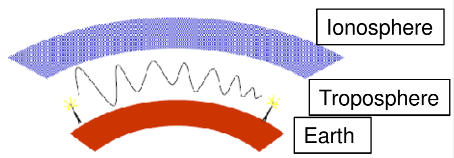
Band Name	Min. Freq.	Max. Freq.	Max. λ	Min. λ
L	1 GHz	2 GHz	30 cm	15 cm
S	2 GHZ	4 GHz	15 cm	7.5 cm
C	4 GHz	8 GHz	7.5 cm	3.75 cm
X	8 GHz	12.4 GHz	3.75 cm	2.42 cm
Ku	12.4 GHz	18 GHz	2.42 cm	1.66 cm
K	18 GHz	26.5 GHz	1.66 cm	1.11 cm
Ka	26.5 GHz	40 GHz	11.1 mm	7,5 mm
mm	40 GHz	300 GHz	7.5 mm	1 mm

Preferred Services for each Frequency Band

- From 10 KHz to 520 KHz. Naval (and aeronautical) Geo-location systems
- From 520 KHz to 1605 KHz. Audio Broadcasting – Amplitude Modulation
- From 1605 to 5850 KHz Radiotelephony
- From 5950 KHz to 26,1 MHz. Amateur Radio..
- From 26,2 to 41 MHz . Ionospheric Radio propagation. Military communications
- From 41 MHz to 68 MHz. VHF Television
- From 88 MHz to 108 MHz. Audio Broadcasting. Frequency Modulation
- From 162 MHz to 216 MHz. VHF Television
- From 216 to 470 MHz. RadioBeacons, Radiotelephony,
- From 470 MHz to 890 MHz. UHF Television
- From 890 MHz to 940 MHz. Mobile Communications
- From 960 to 1350 MHz. Radiotelephony, Radar, telecommand and telemetry
- From 1350 to 2700 MHz. Radioprobes, meteorology
- From 3GHz to 35 GHz satellite communications

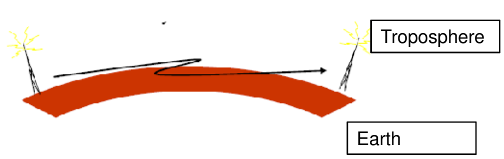
VLF Propagation

- Guided Wave effect Earth-Ionosphere
  - Ionosphere is a highly ionized layer of the atmosphere that reflects a high ratio of the VLF power. Its height is 60 – 400 km above Earth surface
  - At VLF (3kHz – 30kHz) both earth ground and ionosphere behave as good conductors
  - Distance between the two conductors (60-100Km) is comparable with the wavelength (100Km-10Km), thus the propagation model corresponds to the one in a spherical guided-wave without losses.
  - Even using physically large antennas, they are "electrically" small (comparing it against the wavelength)
  - Global coverage
  - Naval and submarine communication and navigation aids are main applications for this band. Formerly telegraphy was also an application.



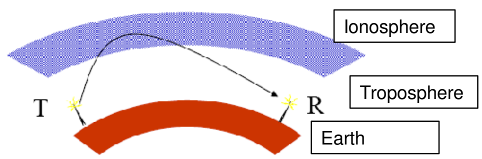
LF, MF and HF Propagation

- Earth / Surface Wave
  - LF, MF and HF (10 – 150MHz) propagation follows a model where the earth-air discontinuity guides the wave propagation
  - Antennas usually used for these bands are monopoles of 50 to 200 meters height.
  - Radio range depends on the transmitted power and it varies
    - LF: from 1000 to 5000Km
    - MF: from 100 to 1000Km
    - HF: less than 100Km
  - Usuall applications: naval communications and audio broadcasting



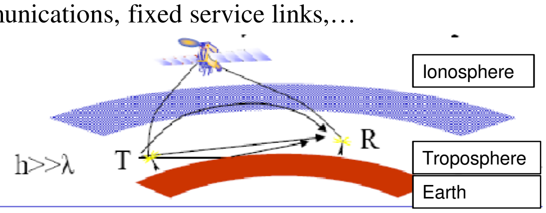
MF and HF Propagation

- Ionospheric propagation
  - Ionosphere layer of the atmosphere causes refaction of the MF and HF bands (0.3 – 30MHz) so the signal is perceived as “bouncing” on it
  - On HF band linear (horizontal and vertical) polarizations are used
  - Range with only “one-hop” can reach up to
    - MF: 0 to 2000Km
    - HF: 50 to 4000Km
  - Applications of narrow-band transmissions over long range such as naval communications, aeronautical communications both point-to-point and broadcast



VHF Propagation

- Tropospheric propagation
  - At this frequencies, above 30MHz, ionosphere becomes transparent, so propagation look more like free-space, with bounces on ground (reflections) and refraction, dispersion and attenuation at the troposphere
  - Usage of directive antennas to obtain high gains and avoid reflection on ground
  - Range varies
    - From tens of Km’s to 40.000 Km on satellite links
    - Even millions of Km in deep space communications
  - Application on audio and TV broadcast, cellular communications, radar, satellite communications, fixed service links,…

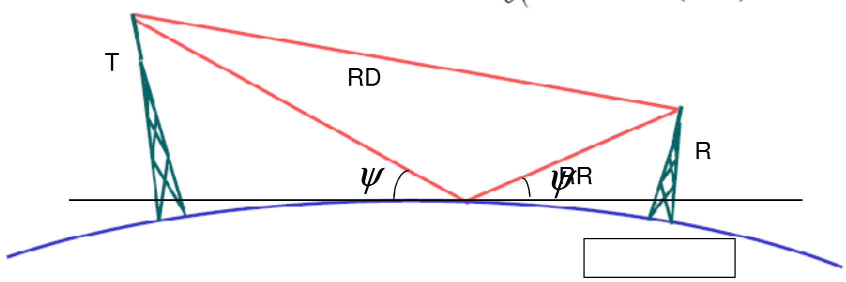


Ground Effect on Radio Propagation

- Existence of both Direct Ray and Reflected Ray

General model for propagation

$$E = E_o\left(1 + R \cdot e^{-j\Delta} + (1-R)\cdot A \cdot e^{-j\Delta}\right)$$



Ground Effect on Radio Propagation

Additional attenuation: $L_{ex} = 20\log\frac{e_0}{|e|} = 20\log\frac{1}{\left|1 + [R + (1-R)\cdot A]\exp(-jA)\right|}$

Angle: $\Delta = \frac{2\pi\Delta l}{\lambda}$

Δl : *Difference between RR and DR length*

λ : *Wavelength*

Complex Reflection Coefficient: $R = |R|e^{-j\beta}$

Both $|R|$ and β are function of:

- Frequency
- Polarization
- Electrical characteristics of the ground
- Angle ψ

Ground Effect on Radio Propagation

- Particular case:

  Large distance + low antenna height

$$\psi \to 0 \longrightarrow \beta \approx \pi \quad y \quad R = -1$$

$$|DR| \approx |RR| \longrightarrow \Delta l = \Delta = 0$$

  - RD and RR cancel each other
  - Ground propagation useful for:
    - Low height antennas (compared to λ)
    - Frequency: $f < 10$MHz

Ground Effect on Radio Propagation

- Complex Permittivity of the ground:

$$\varepsilon_0 = \varepsilon_r - j60\sigma\lambda$$

  - From this parameter, it is defined the z as a function of polarization and incidence angle ψ.
  - Ground impedance (z):
    - Vertical polarization:

$$z = \frac{\left[\varepsilon_0 - \cos^2\psi\right]^{1/2}}{\varepsilon_0}$$

    - Horizontal polarization:

$$z = \left[\varepsilon_0 - \cos^2\psi\right]^{1/2}$$

Ground Effect on Radio Propagation. Reflection Coefficient

- The Reflection Coefficient, R, of a plane surface is:

$$R = \frac{sen\psi - z}{sen\psi + z}$$

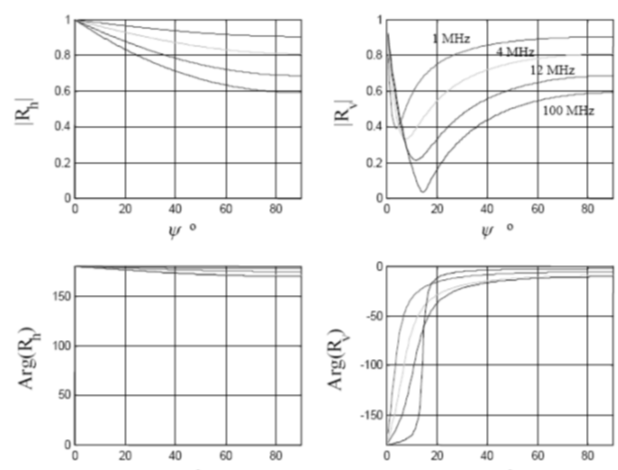
  – Vertical Polarization:

$$R_V = \frac{\varepsilon_0 sen\psi - \sqrt{\varepsilon_0 - \cos^2\psi}}{\varepsilon_0 sen\psi + \sqrt{\varepsilon_0 - \cos^2\psi}}$$

  – Horizontal Polarization:

$$R_H = \frac{sen\psi - \sqrt{\varepsilon_0 - \cos^2\psi}}{sen\psi + \sqrt{\varepsilon_0 - \cos^2\psi}}$$

Ground Effect on Radio Propagation. Reflection Coefficient

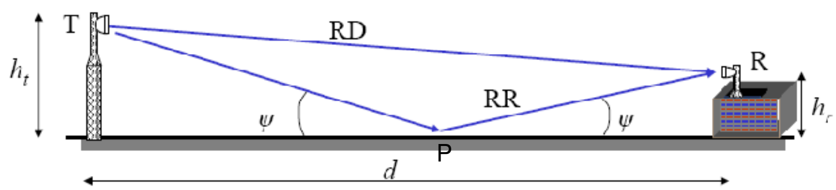


Ground moderately Dry ε_r=15, σ=12·10[-3]

- $f\downarrow$ $\sigma\uparrow$ Minima get softer and move leftwards
- $\psi\downarrow R\rightarrow -1, (R_v = 1,$ If perfect conductor)

Flat Earth Model

- Applicable only for short Tx-Rx distance and flat terrain



Angle of incidence:

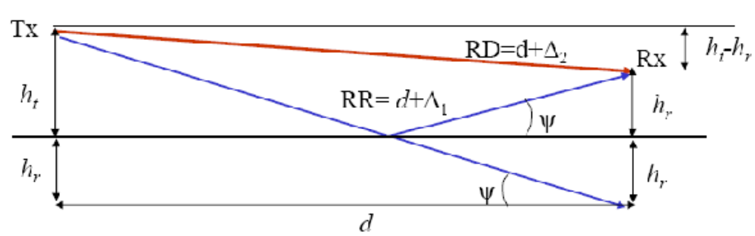
$$\psi = \arctan\left(\frac{h_t + h_r}{d}\right)$$

Path Difference:

$$\Delta l = TPR - TR = \left[d^2 + (h_t + h_r)^2\right]^{1/2} - \left[d^2 + (h_t - h_r)^2\right]^{1/2} \approx \frac{2h_t h_r}{d}$$

Phase Difference: $\Delta = \dfrac{4\pi h_t h_r}{\lambda d}$

Flat Earth Model



$$\tan\psi = \frac{h_t + h_r}{d}$$

$$\psi = \arctan\left(\frac{h_t + h_r}{d}\right)$$

$$(d+\Delta_2)^2 = (h_t - h_r)^2 + d^2 \underset{\Delta_2^2 \approx 0}{\Rightarrow} \Delta_2 = \frac{(h_t - h_r)^2}{2d}$$

$$(d+\Delta_1)^2 = (h_t + h_r)^2 + d^2 \underset{\Delta_1^2 \approx 0}{\Rightarrow} \Delta_1 = \frac{(h_t + h_r)^2}{2d}$$

$$\Delta l = \Delta_1 - \Delta_2 = \frac{(h_t + h_r)^2}{2d} - \frac{(h_t - h_r)^2}{2d} = \frac{2h_t h_r}{d}$$

Flat Earth Model

General equation for propagation is:

$$e = e_0 \left| \left\{ 1 + |R|(1-A)\cdot \exp[-j(\Delta+\beta)+A\cdot \exp(-j\Delta)] \right\} \right|$$

Calculus for A (Bullington):

$$A = \frac{-1}{1 + j\left(2\pi d/\lambda\right)(sen\psi + z)^2} \qquad A < 0.1$$

Flat Earth Model

If we neglect the Surface Wave:

$$e = e_0 \left| \left\{ 1 + |R|\cdot \exp[-j(\Delta+\beta)] \right\} \right| = e_0 \left[1 + |R|^2 + 2|R|\cdot \cos(\Delta+\beta)\right]^{1/2}$$

Thus the basic loss of propagation becomes:

$$l_b = \frac{\left(\frac{4\pi d}{\lambda}\right)^2}{1 + |R|^2 + 2|R|\cos(\Delta+\beta)}$$

$$L_b = L_{bf} + L_{ex} = 20\log\left(\frac{4\pi d}{\lambda}\right) - 20\log\left(1 + |R|^2 + 2|R|\cos(\Delta+\beta)\right)$$

Flat Earth Model

- In the particular case of

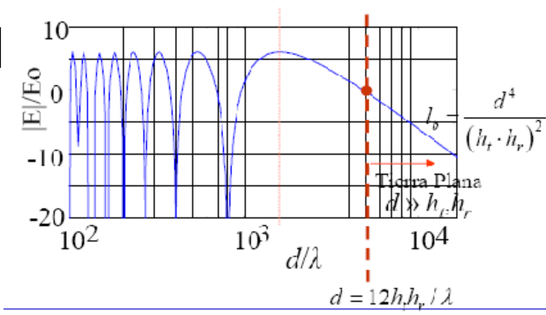
$$d >> h_t, h_r \Rightarrow \psi \to 0, \quad |R| \to 1, \quad y \quad \beta \to \pi$$

$$e = e_0\sqrt{2(1-\cos\Delta)} = 2e_0\left|sen\frac{\Delta}{2}\right| = 2e_0\left|sen\frac{2\pi h_t h_r}{\lambda d}\right| \qquad \frac{|e|}{|e_0|} \approx \frac{4\pi \cdot h_t \cdot h_r}{\lambda d}$$

4 !!

$$l_b = \frac{\left(\frac{4\pi d}{\lambda}\right)^2}{\left(\frac{4\pi \cdot h_t \cdot h_r}{\lambda d}\right)^2} = \frac{d^4}{(h_t \cdot h_r)^2}$$

Flat Earth



Flat Earth Model

- For frequencies bellow 150MHz the surface wave has to be considered
  - This wave can be included in the flat earth model by substituting antenna heights, h_t and h_r, by the new ones h_t' y h_r' defined as

$$h_t' = \left(h_t^2 + h_0^2\right)^{1/2} \qquad h_0 = \frac{\lambda}{2\pi}\left[(\varepsilon_r - 1)^2 + (60\sigma\lambda)^2\right]^{-1/4} \quad horizontal \quad polar.$$

$$h_r' = \left(h_r^2 + h_0^2\right)^{1/2} \qquad h_0 = \frac{\lambda}{2\pi}\left[(\varepsilon_r + 1)^2 + (60\sigma\lambda)^2\right]^{1/4} \quad vertical \quad polar.$$

  - The parameter h_0 is non-negligible only for vertical polarization and frequencies bellow 150MHz
  - Otherwise it can be set to zero

Flat Earth Model

h_0 values for different types of grounds and frequencies. Vertical Polarizationvertical

Type of Ground	Frequency (MHz)			
	30	60	100	150
A: Sea Watter	87	31	14	8
B: Wet Soil	9	4	3	2
D: Dry Soil	6	3	2	1
E: Very Dry Soil	3	2	1	-

Flat Earth Model

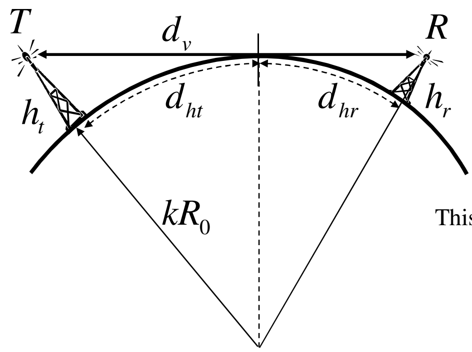
Accordingly, propagation losses are

$$l_b = \frac{d^4}{(h_t' h_r')^2}$$

- Expressed on dBs $$L_b = 40\log d(km) - 20\log(h_t' \cdot h_r') + 120$$
  - Frequency independent
  - Proportional to the distance to the 4th power

Curved Earth Model

- When link length is larger than the *Radioelectric In-Sight Distance* (d_v):
  - d_v = sum of the distances to the horizont



$$(kR_0 + h_t)^2 = d_{ht}^2 + (kR_0)^2 \Rightarrow d_{ht}^2 \approx 2kR_0 h_t$$

$$\begin{cases} d_{ht}(km) = 3.57\sqrt{kh_t(m)} \\ d_{hr}(km) = 3.57\sqrt{kh_r(m)} \end{cases}$$

This in-sight distance incresaes with $\sqrt{k}$

$$d_v = 3.57\left(\sqrt{kh_t} + \sqrt{kh_r}\right)$$

$$\text{Ej}: \; d_v(k = 4/3) = 4.1\left(\sqrt{h_t} + \sqrt{h_r}\right)$$

Curved Earth Model

- Objective = compute propagation losses assuming:
  - Straight trajectory
  - Earth radios modify to become kR_0.

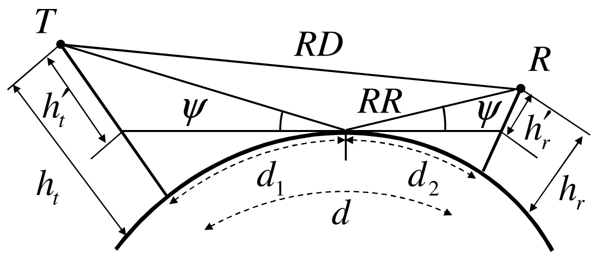
- Map the curved earth model to the flat one:

$$L_b = L_{bf} - 10\log\left[1 + |R|^2 + 2|R|\cos(\beta + \Delta)\right]$$

- To do that:
  - 1. Heights h_t' and h_r', and the phase difference Δ are computed
  - 2. Check that earth does not block the link
  - 3. Update the reflection coefficient R:
    - Using divergence
    - Using terrain roughness.
  - 4. Compute propagation losses

Curved Earth Model

- Reflection model:
  - Direct Ray + Reflected Ray



- Data:
  - Link length d(km), absolute antenna height (h_t, h_r) and k factor for the earth radios

Curved Earth Model

- Four equation with four unknowns let us to find the reflection point

$$\begin{cases} h_t' = h_t - \dfrac{d_1^2}{2kR_0} \\ h_t' = h_r - \dfrac{d_2^2}{2kR_0} \\ \dfrac{h_t'}{h_r'} = \dfrac{d_1}{d_2} \\ d = d_1 + d_2 \end{cases} \Rightarrow d_1^3 - \frac{3d}{2}d_1^2 - \left[kR_0(h_t + h_r) - \frac{d^2}{2}\right]d_1 + kR_0 h_t d = 0$$

$$d_1 = \frac{d}{2} + p\cos\left(\frac{\pi + \phi}{3}\right) \begin{cases} p = \dfrac{2}{\sqrt{3}}\left[6.37k(h_t + h_r) + \left(\dfrac{d}{2}\right)^2\right]^{\frac{1}{2}} \\ \phi = \cos^{-1}\left[\dfrac{12.74k(h_t - h_r)d}{p^3}\right] \end{cases}$$

Curved Earth Model

- Once distances d_1 and d_2 (km) are computed, antenna heights are to be calculated

$$h_t' = h_t - \frac{4d_1^2}{51k}; \quad h_r' = h_r - \frac{4d_2^2}{51k}$$

- And the incidence angle $\psi(mrad) = \frac{h_t' + h_r'}{d}$
- Reflection theory is valid if $\psi > \psi_{\lim}(mrad) = (5400/f)^{1/3}$
- Path difference is $\Delta l(m) = \frac{2h_t'h_r'}{d} \cdot 10^{-3}$
- And therefore the phase difference is $\Delta(rad) = \frac{\pi \cdot f \cdot \Delta l}{150}$

Curved Earth Model

- The reflection over a spherical surface produces a divergence that reduces the effective reflection coefficient
  ➔ Efficient Reflection Coefficient

$$R_e = R \cdot D \qquad D = \left[1 + \left(\frac{5}{16k}\right)\frac{d_1^2 d_2}{dh_t'}\right]^{-1/2} \quad (D < 1)$$

- In addition to the correction of the Reflection Coefficient, it can be included an addition attenuation due to the roughness of the terrain

$$R_e = R \cdot D \cdot e^{-\frac{\gamma^2}{2}}$$

where $\gamma = \frac{4\pi\sigma_z sen(\psi)}{\lambda}$

and σ_z is the standard deviation of the terrain irregularities

Curved Earth Model

- Using all the above factors

$$|e| = |e_0| \cdot \left[1 + |R_e|^2 + 2R_e \cos(\beta + \Delta)\right]^{1/2}$$

  - Where Δ is computed from h_t', h_r'
  - and R_e is accordingly updated

- Thus the basic propagation loss

$$L = L_{bf} - 10\log\left[1 + |R_e|^2 + 2R_e \cos(\beta + \Delta)\right]$$

Tropospheric Propagation: Refraction

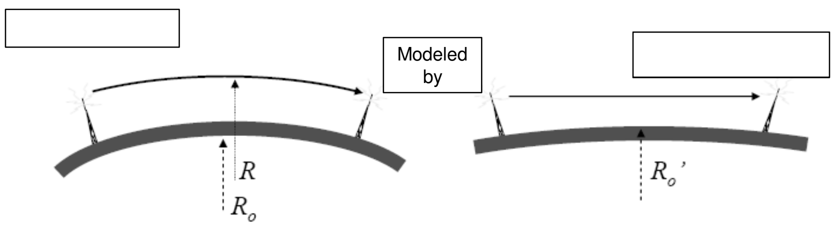
- Atmospheric layers are not uniform
  ➔ Refraction (refraction index varies with height)
  ➔ Non-straight trajectory – but curved

  - On satellite links: it affects to the pointing of the antenna to the satellite
  - On earth links: it affects to the potential blocking of obstacles

  - *f > 10GHz* gases and vapors (oxigen and water vapor mainly)
    ➔ Electromagnetic energy absortion
  - Atmospheric attenuation and rain produce additionaly an increase of the noise temperature of the Rx antenna, and some de-polarization of the signal

Tropospheric Propagation: Refraction

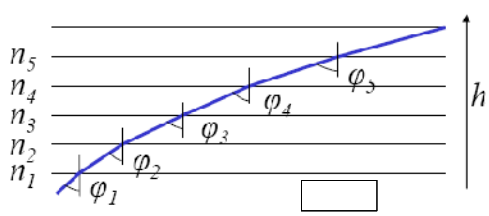
- To simplify the analysis, the Earth radius is changed and straight propagation is assumed
- It has to be computed
  - How much the trajectory is curved ➔ computing the new equivalent Earth radius
  - How to apply the flat earth model



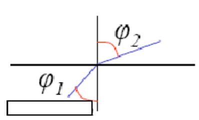
Tropospheric Propagation

Refraction Index: Ray Trajectory

$\uparrow h \Rightarrow \downarrow n$ The ray suffers sucesive diffractions that curve it away form the straight line propagation



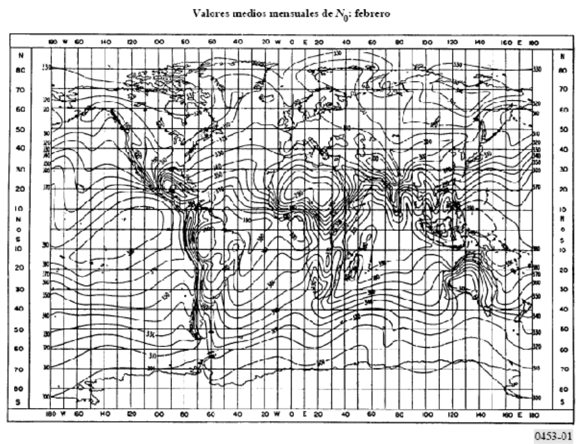
$$n_1 sen\varphi_1 = n_2 sen\varphi_2 = ... = const$$



$n_1 > n_2 \Rightarrow sen\varphi_2 > sen\varphi_1 \Rightarrow$ The ray gets curved

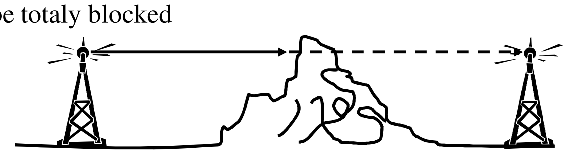
Tropospheric Propagation

- Refraction Index for February

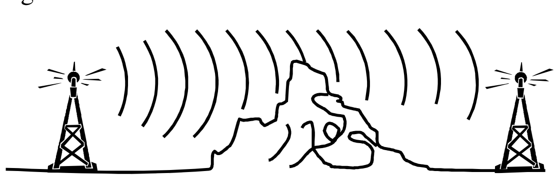


Diffraction

- What happens when the ray hits an obstacle?
  - If an optical propagation approach were used, the transmission woulb be totaly blocked



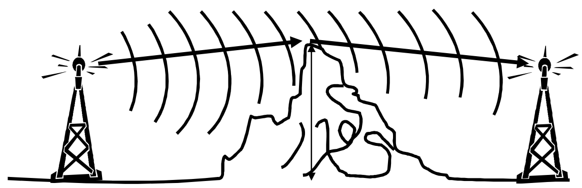
  - It is observed that there is still energy received even in the non-lin-of-sight scenario



Diffraction

- Diffraction is the effect (dispersion and curvature) on the propagation of a plane-wave due to an obstacle which dimensions are comparable to the wavelength

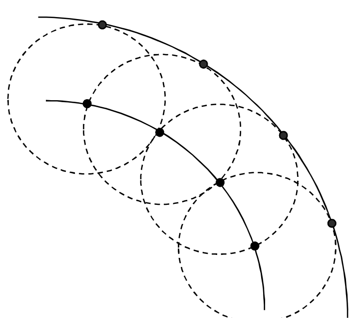
- When the dimensions of the obstacle are larger than the wavelength propagation keeps on straight line

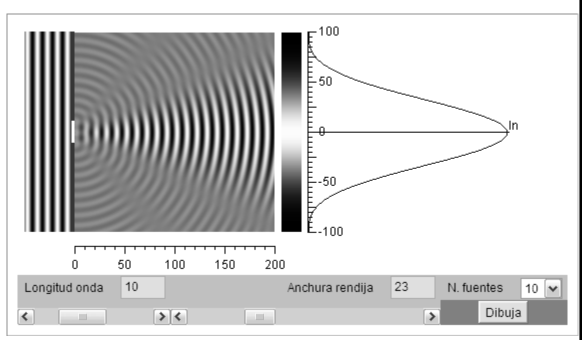


$$h \approx \lambda$$

Diffraction

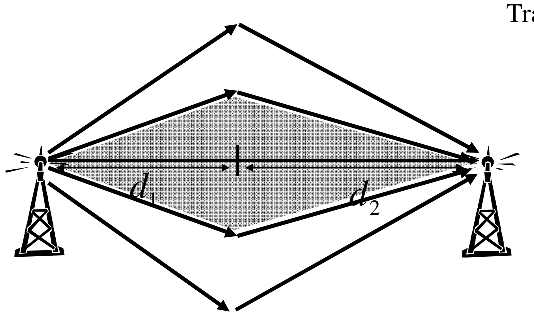
- Huygens' principle generalization: "*Each spatial point of an electromagnetic field becomes a secondary source of radiation*".





Diffraction

- Fresnel's Zones:
  - Maximum succession (constructive interference) y minimum (destructive interference)



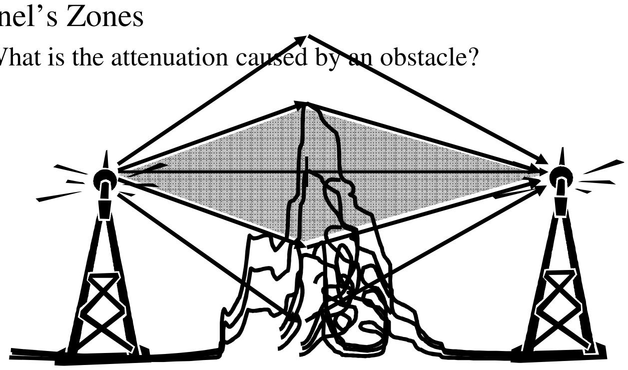
Trajectories with oposed phases define the different zones

1st Fresnel's Zone: Constructive (phase diff. < π)

2nd Fresnel's Zone: Destructive (π < phase diff. < 2π)

Diffraction

- Fresnel's Zones
  - What is the attenuation caused by an obstacle?



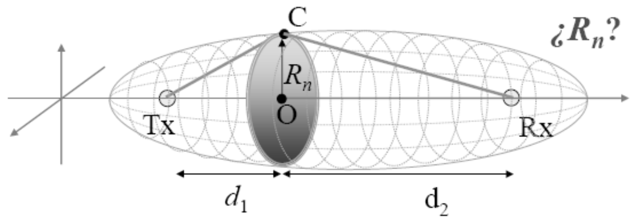
Positive Effect: elimination of the destructive contribution

Negative Effect: feasible link

Very Negative Effect

Diffraction

- Computation of the Fresnel's Zones:



  - Phase Difference $T_xCR_x - T_xR_x = n\pi = n\frac{\lambda}{2}$

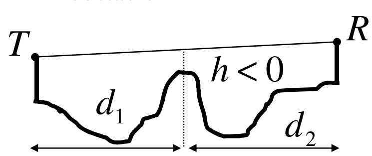
$$R_n = \sqrt{\frac{n\lambda d_1 d_2}{d}}$$

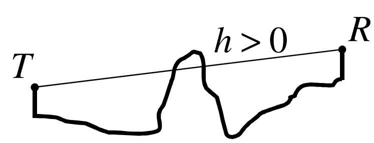
Diffraction

- If the first Fresnel's zone is free of obstacles there is no need to compute the influence of terrain on the propagation losses

$$R_1 = \sqrt{\frac{\lambda d_1 d_2}{d}}$$

- When the direct ray goes near an obstacle or it is block by it, there is an additional propagation loss
  - We define height margin, *h,* as the distance between the ray and the obstacle



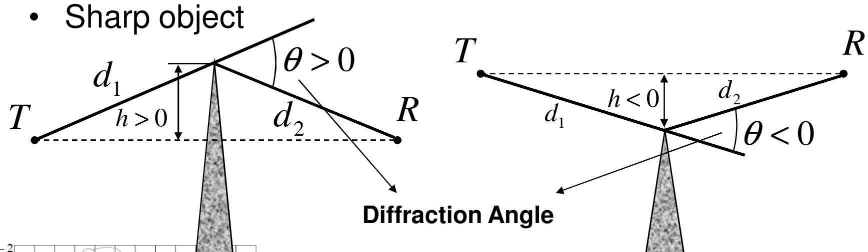


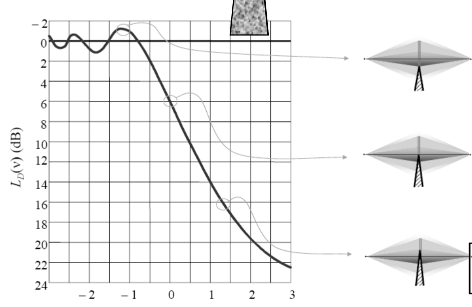
Diffraction

- An accurate model for the propagation loss due to obstacles is quite complex
- In practice, approximate methods are employed with a enought accuracy respect actual losses
- These methods depend on the terrain type between Tx and Rx
  - Terrain with low undulation: low irregularities, curved Earth model
  - Isolated obstacles: one or few aisolated obstacles
  - Undulated terrain: small hills where there is no one clearly higher than the rest

Diffraction

- Sharp object





- Normalized margin

$$\nu = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)} = \theta\sqrt{\frac{2d_1d_2}{\lambda(d_1+d_2)}}$$

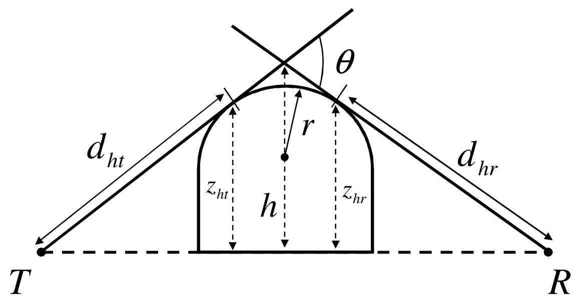
- Losses

$$L_D(\nu) \approx 6.9 + 20\log\left(\sqrt{(\nu-0.1)^2+1}+\nu-0.1\right) \quad \text{si } \nu > -0.78$$

Diffraction

- Rounded obstacle: one object is considered "rounded" if its area is smaller than

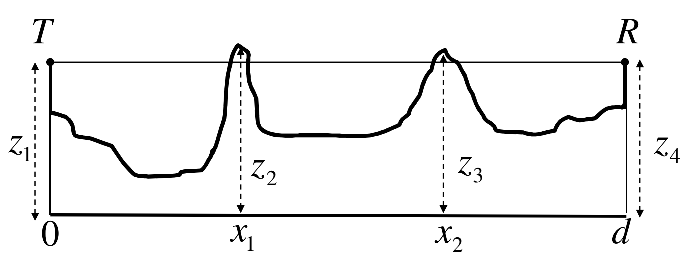
$$\Delta = 0.04\left(r\lambda^2\right)^{1/3}$$



$$A = L_D(\nu) + T(m,n)$$

Diffraction

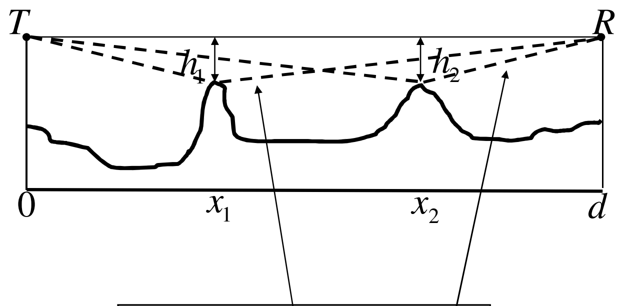
- If two obstacles in the path



- Three different situations
  - Empirical model (EMP)
  - Epstein-Peterson model
  - Recommendation UIT-R P.526 model

Diffraction

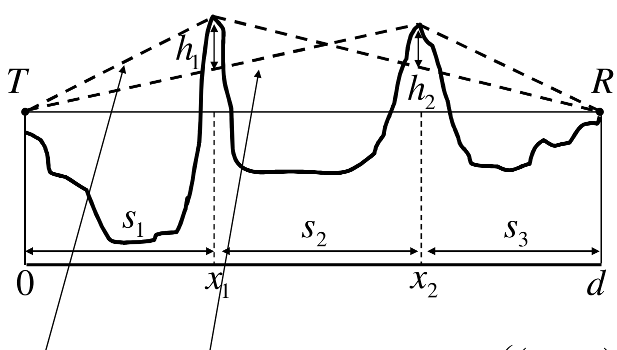
- Two obstacles isolated: empirical model
  - None obstacle blocks the direct ray, but the margin is not enough (-0.7≤ ν ≤0)



$$L_D = L_D(\nu_1) + L_D(\nu_2)$$

Diffraction

- Two obstacles isolated: Epstein-Peterson model
  - The two obstacles block the direct ray, but they have similar heights

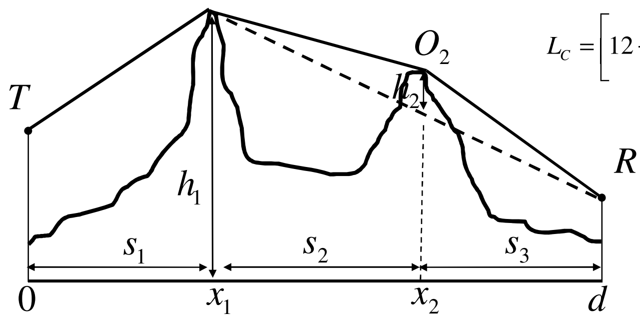


$$L_D = L_D(\nu_1) + L_D(\nu_2) + L_C$$

$$L_C = 10\log\left(\frac{(s_1+s_2)(s_2+s_3)}{s_2(s_1+s_2+s_3)}\right)$$

Diffraction

- Two obstacles isolated: UIT-R P.526 model
  - One of the obstacles is clearly higher than the other



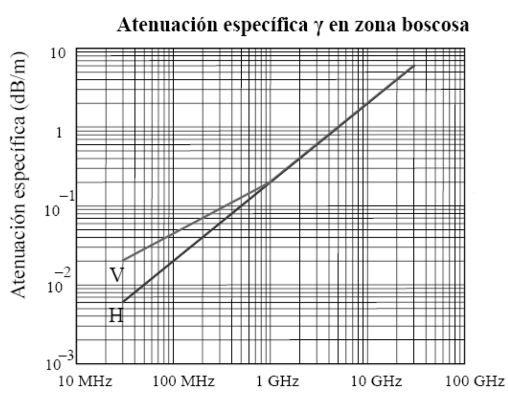
$$L_C = \left[12 - 20\log\left(\frac{2}{1-\alpha/\pi}\right)\right]\left(\frac{\nu_2}{\nu_1}\right)^{2\nu_1}$$

$$\alpha = tg^{-1}\left[\frac{s_2(s_1+s_2+s_3)}{s_1 s_3}\right]^{1/2}$$

$$L_D = L_D(TO_1R) + L_D(TO_1O_2R) + L_C$$

Attenuation due to Vegetation

- If there is a forestall zone in between the Tx and Rx, there is an additional loss due to the energy absorption of the vegetation when the ray goes through it



Vertical
Horizontal
Polarization

Attenuation due to Vegetation

- If non the Tx nor the Rx are in forestal zones, but
  - Part of the trajectory crosses forestal areas (l_{veg}) ,
  - And the frequency is bellow 1GHz.

$$L_{veg} = l_{veg} \cdot \gamma$$

- When either the Tx or the Rx are in forestal area:
  - And part of the trajectory crosses forestal area *d*,
  - if L_m is the loss without any forestation along the ray

$$L_{veg} = L_m \left[1 - e^{-\frac{d \cdot \gamma}{L_m}} \right]$$

- When the attenuation is high (i.e. high frequencies) diffraction should be considered
  - $f > 1$GHz ➔ diffraction, dispersion, reflections, …

Attenuation Due to Gases and Atmospheric Vapors

- Due to absorption of energy by 0_2 and H_2O molecules
  - High impact for $f > 10$ GHz.
  - For low inclination paths, near to ground, for a distance *d*:

$$A_a = \gamma_a \cdot d$$

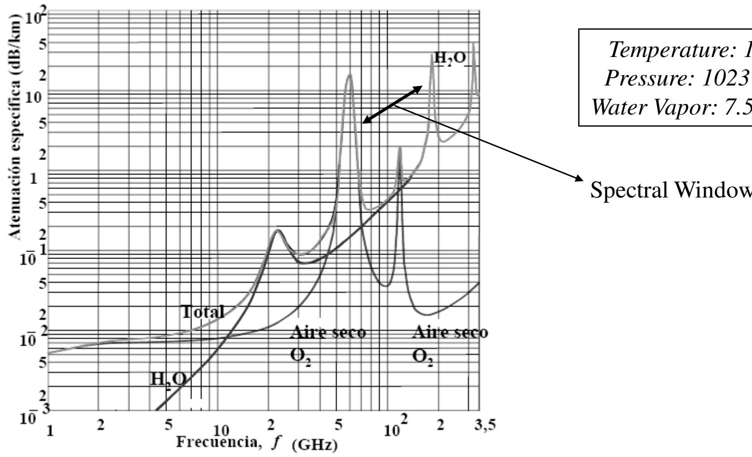
- where is the specific attenuation (dB/m), that can be computed as

$$\gamma_a = \gamma_0 + \gamma_w$$

Oxigen Water Vapor

Attenuation Due to Gases and Atmospheric Vapors

- Specific Attenuation γ_a



Temperature: 15ºC
Pressure: 1023 hPa
Water Vapor: 7.5 g/m3

Rain Attenuation and Depolarization

- Rain attenuation is a factor to consider on Fixed Service (terrestrial) links and Satellite links
  - High impact at $f > 6$ GHz.
  - Rain attenuation exceeded during a time percentage *p%*

$$A(R,p) = \gamma(R,P) \cdot L_{ef}$$

Efective Length: $$L_{ef} = \frac{d}{1 + d/d_0}$$

$$d_0 = 35 \cdot e^{-0.015 R_{0.01}}$$

$$R_{0.01} = 100 (mm/h)$$

Specific Attenuation: (dB/km)
- Rain intensity *Rp*(mm/h)
- Time percentage *p*(%)

$$\gamma = k \cdot R_p^{\alpha}$$

k, α } Depends on *f* and polarization

- De-polarization loss factor

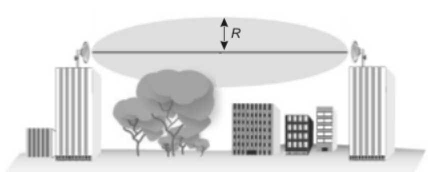
$$L_{polarizacion} = \left| \bar{e}_{tx} \cdot \bar{e}_{rx}^* \right|^2$$

Empirical Models for Propagation Losses

- Outdoor
  - UIT-R P.1546 Recommendation
  - Okumura-Hata Model
  - COST-231 Model
  - Propagation through an heterogeneous mean
  - Longley-Rice Model
  - Other models

Empirical Models. Introduction

- Previous methods to compute the propagation losses
  - Require knowledge of the terrain – hills, houses, forest, …
  - They may be appropriate to fixed point-to-point links

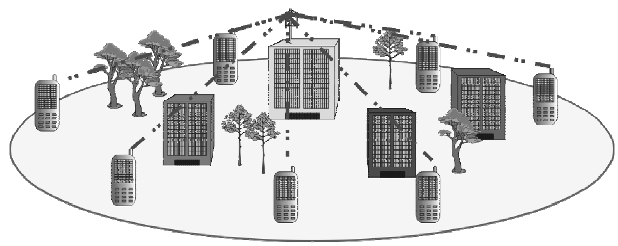


- Distance
- Obstacles, diffraction
- Reflections

Prediction of the Propagation Losses

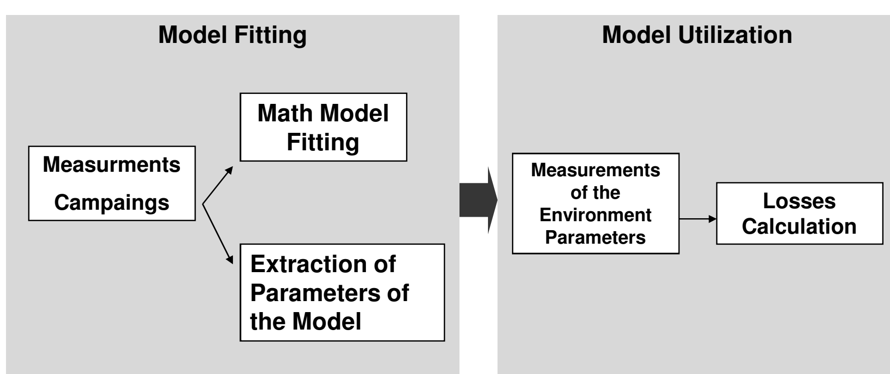
Empirical Models. Introduction

- But, what if we want to predict the attenuation for a region, not for a specific point?



  - Prediction for each radial: 12 minimum
  - Long process with high computational cost
  - In urban environment: modeling of obstacles quite complex, and usually not enough information, and changing

Empirical Models. Introduction



Outdoor Empirical Models

- Initially, several decades ago, they were presented by tables and graphs
- Because the usage of software to semi-automatic radio planning, it is more convenient to fit a closed form mathematical model

- Basic Properties
  - Fitting of closed form equations to multiple (large number of) measurements
  - Easy and fast estimation, but with large error margin

- Most used models
  - UIT-R P.1546 (Rural)
  - Okumura-Hata
  - COST 231

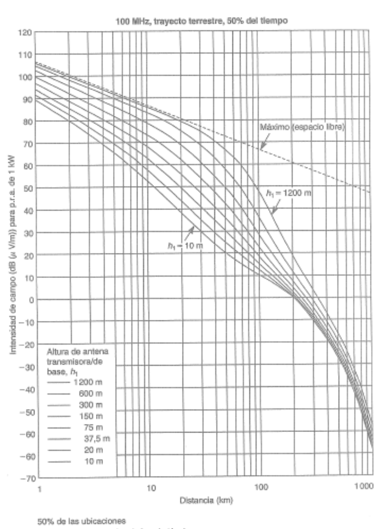
UIT-R P.1546 Recommendation

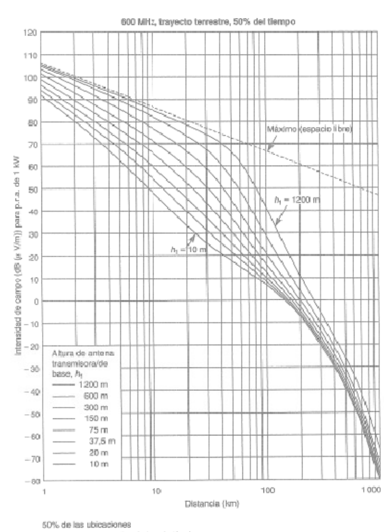
- Presentation as normalized graphs
- Prediction of the electrical field intensity (V/m)
- Designed for fixed service point-to-point links in rural areas
- International standard used by public administrations all over the world – especific usage on cross-borders interference calculations
- Limits
  - Frequency from 30 to 3.000 MHz
  - Distance form 1 to 1.000 Km

UIT-R P.1546 Recommendation

- Curves
  - Electrical field as function of the distance (dBuV/m)
  - Normalized frequencies (100, 600 and 2000 MHz)
  - Different propagation scenarios: land, warm ocean, cold ocean
  - Tx antenna height: from 10 to 1200 m
  - Rx antenna height: 10 m.
  - Value of intensity exceeded 50% of locations for 1%, 10% and 50% of the time
- Methodology includes a specification to convert it into a numerical value (software)
  - Interpolation
  - Extrapolation
  - Correction terms

UIT-R P.1546 Recommendation





UIT-R P.1546 Recommendation

- Graphs usage
  - When one or more parameters of the system under consideration do not match the graphs ➔ Correction
  - The obtained value never should be larger (lower attenuation) than
    - Land: free space attenuation
    - Sea, with distance *d* and *T* percentage of time:

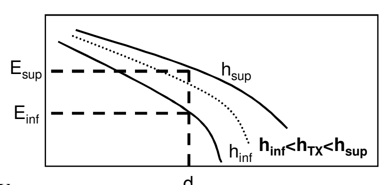
$$E_{se} = 2.38 \cdot [1 - \exp(-d/8.94)] \cdot \log(50/T)$$

  - Basic corrections
    - Tx power
    - Tx antenna height
    - Tx frequency
    - RX antenna height
    - Short trajectory over urban/suburban terrain
    - Height margin of the Rx
    - Percentage of locations
    - Percentage of time

UIT-R P.1546 Recommendation

- Example of corrections
  - Tx antenna height
    - $\mathbf{h_{TX}}$ is defined as: *height of the antenna, expressed in meters, from the radiation center of the antenna above the average level of the terrain at distance between 3 and 15 Km from the Tx to the Rx*
    - If the antenna height does not match the one in the graph ➔ logarithmic interpolation

$$E = E_{inf} + (E_{sup} - E_{inf}) \cdot \log(h_{TX}/h_{inf}) \cdot \log(h_{sup}/h_{inf})$$



  - Frequency
    - If the frequency is different form 100, 600 or 2000 MHz, but it is in between one the these values ➔ logarithmic interpolation

UIT-R P.1546 Recommendation

- Example of corrections
  - Location percentage
    - Example: design objective is to guaranty 90% of locations
    - A given statistical distribution of the received electrical field is assumed
      - Statistical distribution depending on one, or several, parameter, provided on tables by ITU-R. Example: log-normal distribution with parameter σ_L.
    - The parameter σ_L is found in corresponding ITU-R table depending on scenario (urban, rural, etc).
    - The value of the electrical field exceeded *L%* of the location is

$$E(q) = \overline{E} + \sigma_L G^{-1}(L/100) \quad \text{for } 1 \le L \le 50$$

$$E(q) = \overline{E} - \sigma_L G^{-1}(1 - L/100) \quad \text{for } 50 \le L \le 99$$

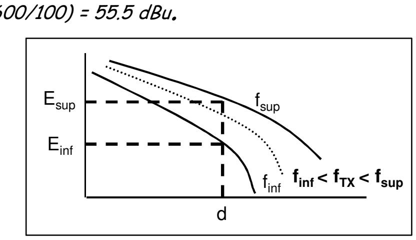
Servicio	*Desviación típica σ_L (dB)*		
	100 MHz	*600 MHz*	*2000 MHz*
Radiodifusión analógica	8,3	9,5	
Radiodifusión digital	5,5	5,5	5,5
Móvil urbano	5,3	6,2	7,5
Móvil suburbano y áreas montañosas	6,7	7,9	9,4

- where
  - E is the mean value of the field
  - G^{-1} is a specific function given in the recommendation

UIT-R P.1546 Recommendation

- Example 1: Estimation of the intensity of the electrical field at a distance d = 10 Km, antenna height h_{TX} = 20 m, and a frequency 450 MHz.
  - *From the ITU-R graphs, we can read the field intensity at 100 and 600 MHz:*
  - *E_{inf} = 58 dBu. E_{sup} = 55 dBu.*
  - *Interpolation:*

E = 58 + (55-58) log(450/100)/log(600/100) = 55.5 dBu.



UIT-R P.1546 Recommendation

- Example 2:
  Given a cellular system
  - In an urban area
  - working at f = 450 MHz
  - Mean value of the field intensity is Em = 30 dBu.

  It is needed the value of the field intensity that is exceeded at 90% of the locations

  For this service:
  σ_L = 1,2 + 1,3 log 450 = 4,6 dB.
  Additionally: $G^{-1}(1-0.9)$ = 1,28.

  Therefore,
  E = 30 – 4,6·1,28 = 24 dBu.

Okumura-Hata Model

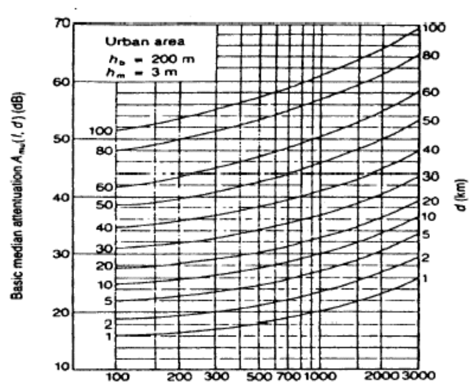
- Objective: define simple closed-form mathematical model for the propagation attenuation applicable to the radio planning of cellular networks, specially for urban areas
- Starting point: a quite large measurement campaing done in Japan
- Okumura: graphs providing mean values for electromagnetic filed in urban areas, for
  – Several antenna heights
  – Frequency bands of 150 MHz, 450 MHz and 900 MHz.
  – EIRP = 1 KW.
  – Rx antenna height: 1,5 m.

Okumura-Hata Model

- The previous graphs, were complemented by correction factors for:
  - Undulation of the terrain
  - Heterogeneity of the terrain
  - Rx antenna height
  - Tx EIRP
  - Streets orientation
  - Buildings density
- Hata: development of closed-form mathematical expressions for the normalized Okumura graphs

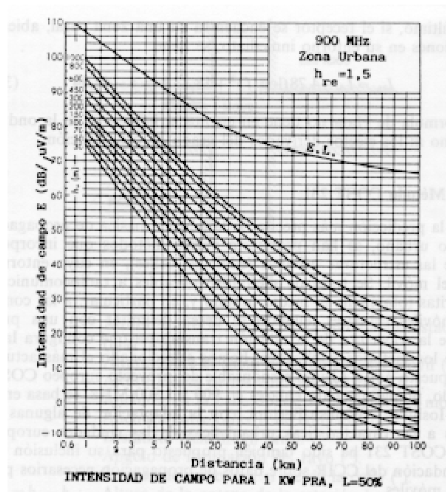
Okumura-Hata Model

- Okumra graphs for the frequency variation



Okumura-Hata Model

- Okumura graph for the received field intensity (f=900MHz)



Okumura-Hata Model

- Closed-Form model: logaritmic fitting of the graphs
- Losses for urban environment:

$$L_{Oku} = A + B\log(d) + C$$

$$A = 69.55 + 26.16\log\left(f_{0|MHz}\right) - 13.82\log\left(h_b\right) - a\left(h_m\right) \quad B = 44.9 - 6.55\log\left(h_b\right)$$

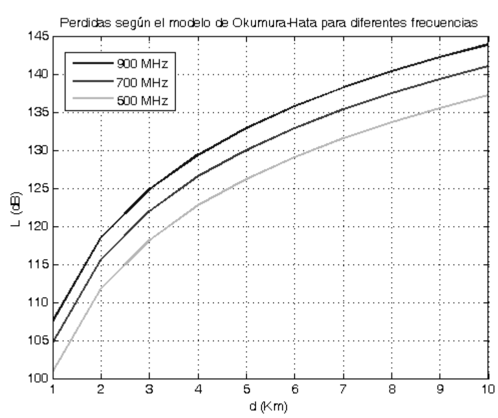
	$a(h_m) =$	$C =$
Metropolitan areas	$8.29\left(\log\left(1.54h_m\right)\right)^2 - 1.1$ for $f_0 \le 200$ MHz $3.2\left(\log\left(11.75h_m\right)\right)^2 - 4.97$ for $f_0 \ge 400$ MHz	0
Small/medium-size cities	$\left(1.1\log\left(f_{0\|MHz}\right) - 0.7\right)h_m - \left(1.56\log\left(f_{0\|MHz}\right) - 0.8\right)$	0
Suburban environments		$-2\left[\log\left(f_{0\|MHz}/28\right)\right]^2 - 5.4$
Rural areas		$-4.78\left[\log\left(f_{0\|MHz}\right)\right]^2 + 18.33\log\left(f_{0\|MHz}\right) - 40.94$

Okumura-Hata Model

- Where
  - f = frequency MHz
    - Limits: $150 < f < 1500$MHz
  - h_t = Effective Tx Antenna Height (m)
    - Limits: $30 < h_t < 200$m
  - h_r = Effective Rx Antenna Height (m)
    - Limits: $1 < h_r < 10$m
  - d = Distance (Km)
- Note: model valid only up to 1500 MHz
- Adaptation Hata-COST231:
  - Extension of the model for upper band in cellular networks (between 1800 and 2000 MHz)

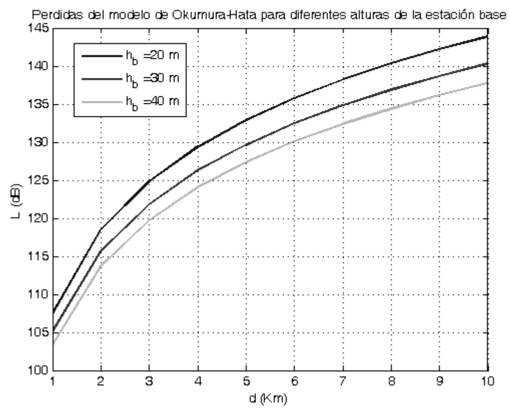
Okumura-Hata Model

- Results



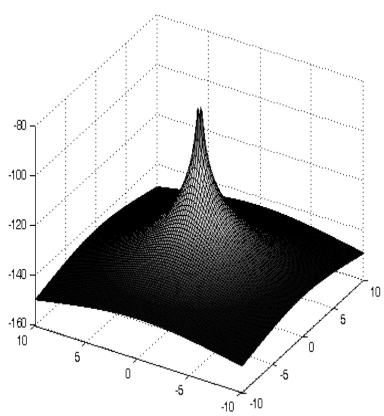
Okumura-Hata Model

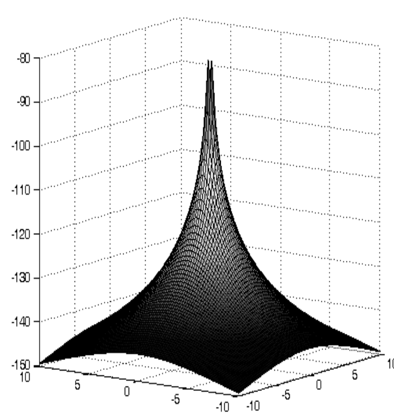
- Results



Okumura-Hata Model

- Results



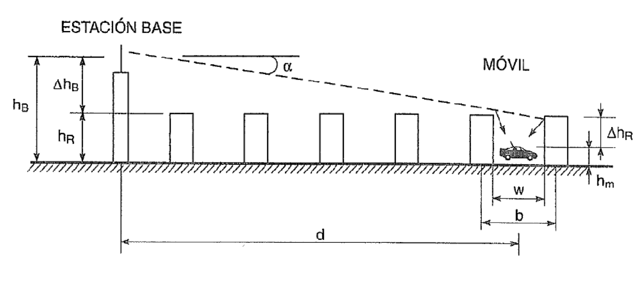


COST-231 Model

- Okumura-Hata model does not include any parameter about the terrain.
- To achieve more precision, models considering next parameters have been considered
  - Streets structure
  - Buildings dimension
  - Al the parameters in the Okumura-Hata model
- The most updated model is the COST231, which was adopted as UIT-R recommendation
- Valid for non-line-of-sight scenarios

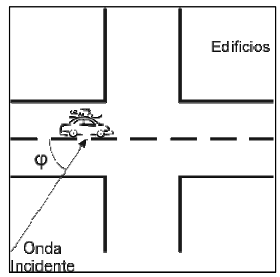
COST-231 Model

- Parameters
  - BS antenna height
  - MS antenna height
  - Average height of buildings
  - Broadness of the street where the MS is located
  - Distance between center of buildings
  - BS-MS distance
  - Angle of incidence

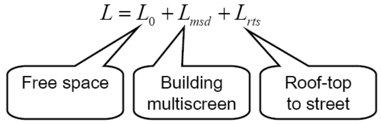


COST-231 Model

- Parameters:
  - Angle with respect the street axis
  - BS height above the average building height
  - Average buildings height above MS antenna height



$$L = L_0 + L_{msd} + L_{rts}$$



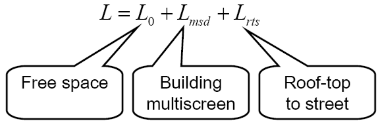
COST-231 Model

- Closed form math model
  - $L_0 = 32.45 + 20 \log(f) + 20 \log(d)$
  - $L_{rts} = -8.2 - 10 \log(w) + 10 \log(f) + 20 \log(\Delta h_R) + L_{ori}$

    where L_{ori} depends on the angle between the ray and the street axis

- L_{mds} = estimation of the diffraction produced by multiple obstacles

$$L = L_0 + L_{msd} + L_{rts}$$



Applicability limits:

$800 < f < 2.000$ MHz

$4 < h_B < 50$ m

$1 < h_m < 3$ m

$0.02 < d < 5$ km

Models Comparison

- *An estimation of propagation losses is to be done for a big city for the radio planning of a cellular network at 900 MHz.*
  - *Base Station height is 35m while the mobile stations have an antenna at 1,5m hight.*
  - *The averge height of the buildings is 5 floors*
  - *The average broadness of the streets corresponds to a 2 lines each direction, plus 3 meters for the sidewalk each side. Two parking lines are also considered*
  - *Average distance between building is 45m.*

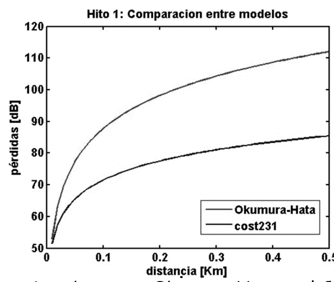


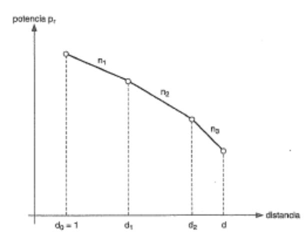
Figure: comparison between Okumura-Hata and Cost231 models

Propagation over an Heterogeneous Mean

- Some scenarios are better considered as concatenation of different areas with different electromagnetic properties
- Each section is better modeled by a different mathematical model

$Lb(d) = k \cdot d^n$

Lb = losses expressed on natural units.
k = constant.
D = distance.
n = parameter depending of the mean



- To add the effect of different models the following model can be used (example for three sections)

$$
\begin{array}{ll}
p_r(d) = p_r(1) \cdot d^{-n_1} & d \le d1 \\
p_r(d) = p_r(1) \cdot d_1^{-n_1+n_2} \cdot d^{-n_2} & d_1 \le d \le d_2 \\
p_r(d) = p_r(1) \cdot d_1^{-n_1+n_2} \cdot d_2^{-n_2+n_3} \cdot d^{-n_3} & d \ge d_2
\end{array}
$$

Propagation over an Heterogeneous Mean

- The exponent on the previous model, *n,* takes a value from 1.4 and 5, as function of the environment

Environment	**Exponent, n**
Free Space	2
Urban	2.7-3.5
Urban with large buildings	3-5
Indoor with LOS	1.6-1.8
Indoor without LOS	2-3
Suburban	2-3
Industrials areas	2.2

Longley-Rice Model

- Also known as ITS Irregular Terrain Model
  - Based on electromagnetic theory and statistical analysis of the terrain characteristics and measurement campaign
  - Outcome: average value for attenuation as function of the distance, and a model for the variation with time and space
  - It contains a point-to-point model and a area prediction model.
- System parameters: associated to the radio equipment and independent of the environment
  - Frequency between 20MHz and 40GHz
  - Distance between 1Km and 2000Km
  - Antenna height between 0.5m and 3000m above the terrain
  - Polarization: horizontal and vertical

Longley-Rice Model

- Parameters describing statistically the environment
  - Average undulation of the terrain (Δh):

Forma del terreno	Δh (m)
Plano o superficie del agua	0
Llanura	30
Colinas	90
Montañas	200
Montañas escabrosas	500
Para un nivel promedio usar Δh = 90 m	

  - Atmosphere refractivity: determines the “bending” or “curvature” of the radio propagation
    - Other models include this parameter in the effective curvature of the Earth, typically 4/3 (1.333).
    - Longley-Rice model includes directly the refractivity value
      - Range from 250 to 400 Units of n (corresponding to effective Earth curvature between 1.232 and 1.767).
      - Effective curvature of the Earth of 4/3 (=1.333) corresponding to a refractivity of 301 Units of n. (recommended value for average atmospheric conditions)
      - Relation between parameters “k” and “n” : $N_s = 179.3 \cdot Ln\left[\frac{1}{0.046665}\left(1 - \frac{1}{K}\right)\right]$

Longley-Rice Model

- Environment parameters
  - Dielectric constant of the terrain
    - Relative permittivity or dielectric constant (ε).
    - Conductivity:

Tipo de suelo	Permitividad relativa	Conductividad (S/m)
Tierra promedio	15	0.005
Tierra pobre	4	0.001
Tierra buena	25	0.020
Agua dulce	81	0.010
Agua salada	81	5.000
En la mayoría de los casos usar las constantes de tierra promedio.		

  - Climate: 7 models for climate
    - Equatorial (Ex. Congo)
    - Subtropical Continental (Ex. Sudan)
    - Subtropical Maritime (Ex. Africa shore)
    - Desert (Ex. Sahara)
    - Warm Continental
    - Warm Earth – Maritime (Ex. UK and EU)
    - Warm Maritime Sea

Clima	Ns (N-unidades)
Ecuatorial	360
Continente subtropical	320
Marítimo subtropical	370
Desierto	280
Continental temperado	301
Marítimo temperado, sobre la tierra	320
Marítimo temperado, sobre el mar	350
Para condiciones promedio usar el clima continental temperado y Ns = 301 N-unidades	

Longley-Rice Model

- Statistical Parameters
  - Time variation: (of the atmospheric changes and other effects)
  - Location variation
  - Other variations or “hidden variables”

Other Models

- Walfish-Bertoni
- Durkin
- Sakagami-Kuboi
- Ibrahim-Parsons

Summary of Models

Model	Out / Indoor	Frequency Range	Applicability
UIT-R P.1546	Outdoor	3000MHz	Broadcast
Okumura-Hata	Outdoor	1500(2000)MHz	Urban
COST-231	Outdoor	2000MHz	Any
Heterogeneus Mean	Outdoor	Any	Any
Longley-Rice	Outdoor	40GH<	Any although it is quite complex

Summary of Concepts in this Chapter

- We have seen different models to predict the radio propagation loss
- First classification:
  - Deterministic models, where you need to know accurately the environment
  - Empirical models: average estimation is fitted to a measurements campaign previously done
- Several useful Outdoor empirical models depending on
  - Frequency
  - Terrain
  - Rural or Urban environment
  - Distance
- Models Trade-off between complexity and accuracy
- Software tools include propagation models to greatly simplify radio planning