

Mobile communication networks

Propagation models

**Politecnico di Torino
2006**



Propagation laws

in mobile communication environment

Several elements to be considered in a hostile environment

- **field strength distance decay (3rd-4th power law) depending on the environmental conditions**
- **fast fading (Rayleigh statistics)**
- **slow shadowing fading (Log-Normal statistics of local mean values)**
- **delay spread and Doppler effect**

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Propagation conditions characterised by several environment characteristics (see figure). For the typical bands used in mobile communications (hundreds of MHz) the most significant are those reported in the above figure:

- Natural obstacles (natural or artificial) create a multi path behaviour
- Movements of the mobile station

Statistical considerations are to be used to describe the overall behaviour.

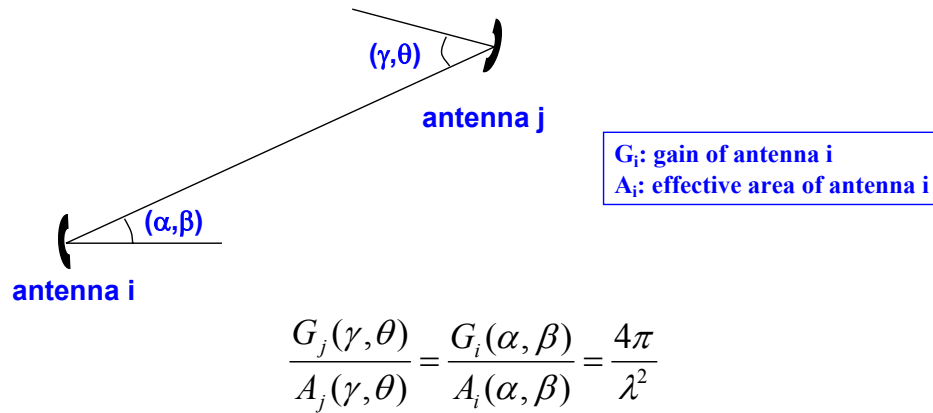
In field measures are used to validate propagation models.

We will see how short-term fluctuations take place around average values which are, by turn, subject to longer-term statistical modifications (*shadowing*).

Some basic concepts are now introduced before proceeding to the coverage estimate in a real environment.

Propagation model in free space

relationship between antenna gain and effective area



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The effective area A of a receiving antenna is the area through which the antenna intercepts the power on the receiving side: the power that will be converted in an electrical signal transmitted over the cable connecting the antenna with the base station.

The antenna gain G is the ratio between the power emitted in a given direction and the power emitted in the same direction by an isotropic antenna.

The formula in the figure is valid for any kind of antenna. It will be used to derive the free-space propagation models explained in the following figures.

Propagation model in free space

received power and free space attenuation

Mean power density generated by an isotropic source (input power P_T) at a distance d

$$p(d) = \frac{P_T}{4\pi d^2}$$

Received power at the antenna site (located at distance d from the transmitting antenna)

$$P_R = p \cdot A_R$$

isotropic case ($G=1$)

$$P_R = P_T \cdot \left(\frac{\lambda}{4\pi d}\right)^2$$

Free space attenuation: the ratio between P_T and P_R with isotropic antennas

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

$$L_{free}(dB) = 20 \cdot \lg 4\pi + 20 \lg \left(\frac{d \cdot f}{c}\right)$$

$$f = c/\lambda$$

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The average power density generated by an isotropic source and measured by a receiver posed at a distance d from the source may easily be written in function of the area of a sphere with a radius equal to the distance d .

Using the formula giving the rate between the antenna gain and the effective area, the power received by an isotropic antenna can be deduced.

In the free space (no obstacles, vacuum conditions) the power decays with the square power of the distance.

Free-space attenuation is the rate between the the transmitted power and that received at the distance d when an isotropic antenna is used.

In free space, power decreases with the square of the distance (6dB of reduction if the distance is doubled). The free space conditions are fulfilled when the transmission takes place in the vacuum (no losses due to the propagation medium) without any diffraction and reflection phenomenon.

Propagation model in the free space

received power with non isotropic antennas

Received power with
non-isotropic antennas

$$P_R = P_T \cdot G_T \cdot A_R / 4\pi d^2 = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi d}\right)^2$$

Power ratio between
non-isotropic antennas

$$L = \frac{P_T}{P_R} = \frac{L_{free}}{G_T \cdot G_R}$$

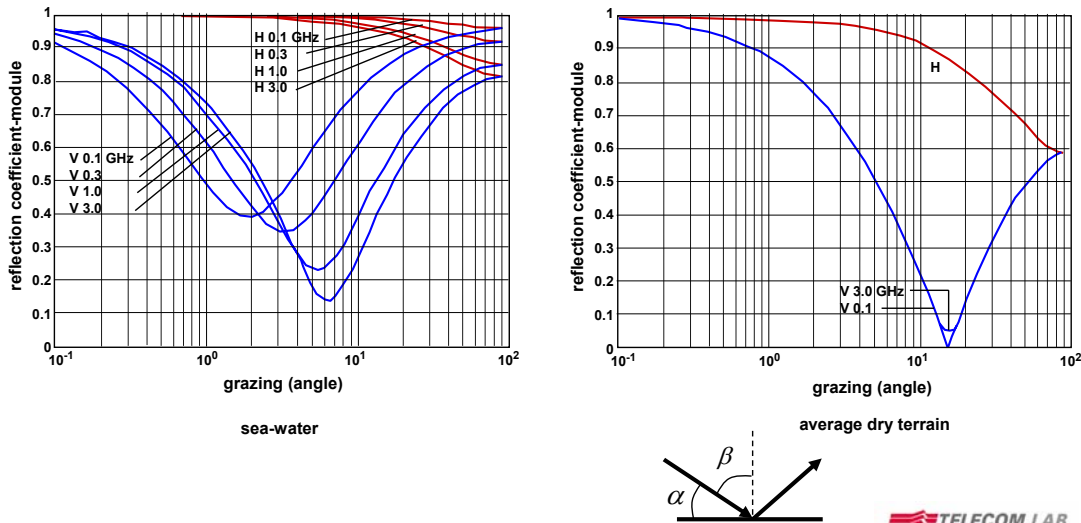


$$L(dB) = L_{free}(dB) - G_T(dB) - G_R(dB)$$

Similar formulas can be derived when antennas are non-isotropic. Attenuation is still tied to the square of the distance.

Still attenuation is tied to the square of the distance between the two antennas, but in this case, the antenna gain of the receiving and transmitting side are to be introduced.

Direct and reflected waves module



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A surface is said a *reflection* surface whenever its dimensions are *wide* with respect to the wave length λ of the incident waveform.

The reflected wave (reflected by a given surface) may be modelled by using a complex reflection coefficient **R**. From a geometrical viewpoint the reflection angle coincides with the incident angle and the reflected waves lies on the same plane of the incident wave (Snell law).

R is typically split into three components:

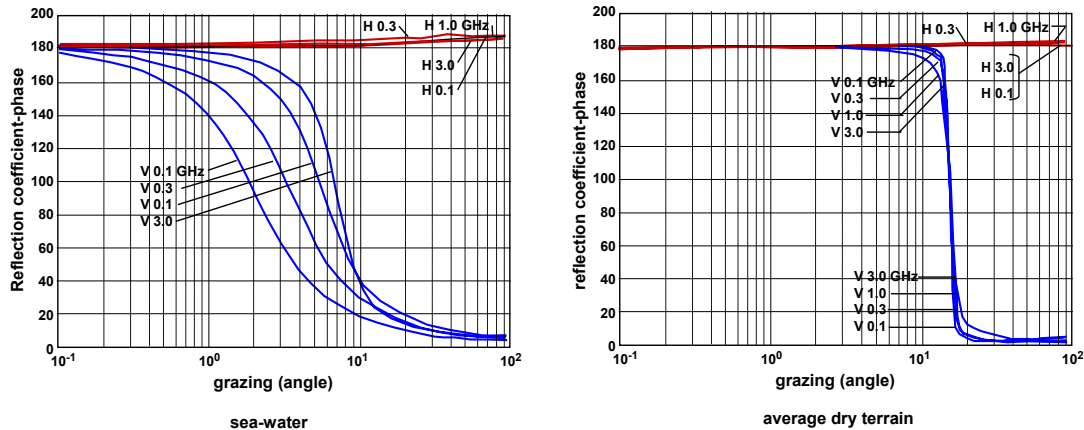
- **R_f** the complex component (Fresnel coefficient) which may be applied to a perfectly flat and unlimited surface
- **R_s** the real component depending on the real extension of the surface
- **R_d** the second real component depending on the form of the surface (e.g. convex)

The module of **R_f** is depicted for different values of the frequency for both horizontal and vertical polarisations (H and V). Two kinds of surfaces are considered: sea water (blue line, continuous and dashed for vertical and horizontal polarisations respectively) and dry terrain (red line, continuous and dashed for vertical and horizontal polarisations respectively) ..

$|R_f|$ is drawn in function of the grazing angle $\alpha = \pi/2 - \beta$ (β is the incidence angle).

The vertical polarisation shows the most significant behaviour: its module reaches a minimum value and in $\alpha = \pi/2$ takes the same value of the horizontal case. The minimum value decreases with the increasing of frequency and the minimum takes place for decreasing values of α (from 1° to 7° in the considered range for the sea water case).

Direct and reflected waves phase



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The phase of the reflection coefficient shows a similar behaviour. For small values of α , the phase sticks around 180° for both polarisations (vertical and horizontal).

In the case of horizontal polarisations, the phase always maintains its value, independently from the value of α , while it depends heavily on α in case of vertical polarisation in the dry terrain case, where a shift of 180° is generated for values of α ranging between 10° and 20°.

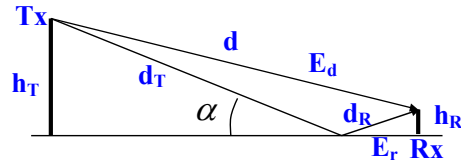
Conversely, the vertical polarisation is heavily affected by the value of the grazing angle. Dry terrain introduces a sharp variation of the phase for the vertical polarisation for values of the grazing angle between 10° and 20°.

Direct and reflected waves

received field; small grazing angle α

Resulting field at the receiving side
(direct+reflected rays)

$$\underline{E} = \underline{E}_d + \underline{E}_r$$



$$\underline{E} = \underline{E}_d \cdot (1 - e^{-j\Delta\phi})$$

- α small $\Rightarrow \mathbf{R}_r = -1$ (module=1; phase 180°)
- $\Delta\phi$: phase difference due to the path difference between direct and reflected rays

$$\Delta\phi = \frac{2\pi}{\lambda} \cdot \Delta l \quad (\text{rad})$$

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The intensity of the received signal depends on both direct and reflected rays. With α sufficiently small (see previous figures) the reflection parameter $\mathbf{R}_r$ shows values of the module equal to 1 and a phase equal to 180° almost independent from frequency, polarisation and type of surface. A small value of α is the typical situation arising for the communication between the base station and the mobile terminal antenna, due to the different height values of the respective antennas.

Hence, on the receiving side, the phase difference between the two rays depends only on the different path length arising between the direct and reflected ray.

Direct and reflected waves received field

Some simplifications are possible when $d \gg h_T, h_R$:

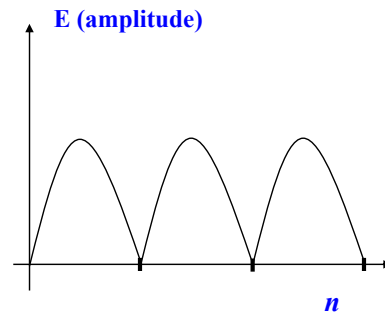
$$\Delta l = \frac{2h_T \cdot h_R}{d}$$

Hence, the related phase difference:

$$\Delta\phi = \frac{4\pi h_T h_R}{\lambda d}$$

Taking the module of the received field, it can be seen that it vanishes for all the values h_R such that:

$$h_R = \frac{n\lambda d}{2h_T} \quad n = 1, 2, 3, \dots$$



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As a consequence, on the receiving side, direct and reflected waves work either in a constructive or in a non-constructive way in function of the difference of the path lengths.

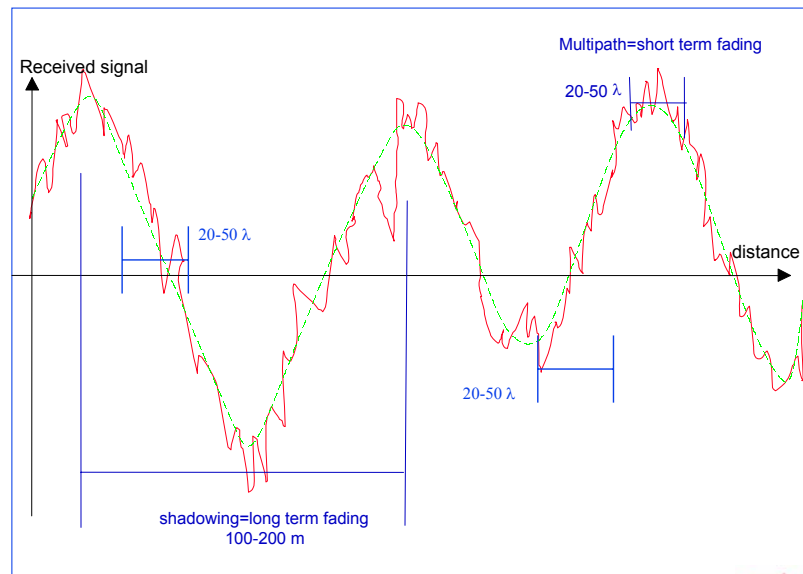
In the figure, the exercise is run varying the height of the receiving antenna. It is assumed that the reflection coefficient has a value equal to 1 for the reflected wave. Zeroes of the receiving signal obviously arise also by varying the distance d (moving mobile).

Zeroes in the spectral dimension may be revealed by keeping fixed heights, and distance and varying λ .

The real situation is by far more complex: the received signal derives from the contribution of many reflected rays: those resulting from the presence of many obstacles intercepting the emitted signal between source and destination points components of the multiple path).

The sum of the contributions is often represented through the Rayleigh distribution, a good model of the fast fading behaviour.

Statistical description



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The shadowing and the multipath effects are the most important elements conditioning the propagation in a real environment.

The context complexity cannot be represented through deterministic models, reproducing shadowing and multiple paths in each specific situation, taking also into account the mobile terminal movements. On the other hand, the same geometry of the environment assumes random configurations, beyond the mobile movements.

Typically, two components are identified: long and short term shadowing.

Short term fluctuations, due to multiple paths, take place around mean values that are considered to be constant within certain spatial limitations, at least for a given time.

These *steady state* areas show a size ranging between 20-50 times λ .

Long-term fading

- **Local means are random variables**
- **Log-Normal distribution. With local mean expressed in (dB) the p.d.f. is:**

$$p(m_d) = \frac{1}{\sigma_d \sqrt{2 \cdot \pi}} \cdot \exp \left(- \frac{(m_d - \mu_d)^2}{2 \cdot \sigma_d^2} \right)$$

- **Where:**
 - m_d = local mean in dB
 - μ_d = average value of m_d (dB)
 - σ_d = standard deviation of m_d
- μ_d and σ_d fully characterise the phenomenon, to evaluate:
 - Coverage areas
 - Interference arising between iso-frequency cells

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The long term shadowing (local means variations) depend on the topological conditions, antenna height, frequency, distance: the so called connection configuration.

Long term shadowing is evaluated through in field measurements, over paths of the order of hundreds meters, by averaging, as said, over sizes of 20-50 times λ . Measures must be repeated in order to have the necessary statistical accuracy in different environment conditions.

It is assumed that an average value exists and that it is constant (average value of the local means, steady state conditions). It is typical of each environment characteristic (urban, sub urban, open area)

m_d (random variable) is the mean local value of the field intensity expressed in dB ($\mu V/m$).

μ_d is the mean value of the random variable m_d . Knowing μ_d and the relative standard deviation σ_d is enough to represent the statistic of the mean local values (as for any *normal* distribution, these two parameters are exhaustive).

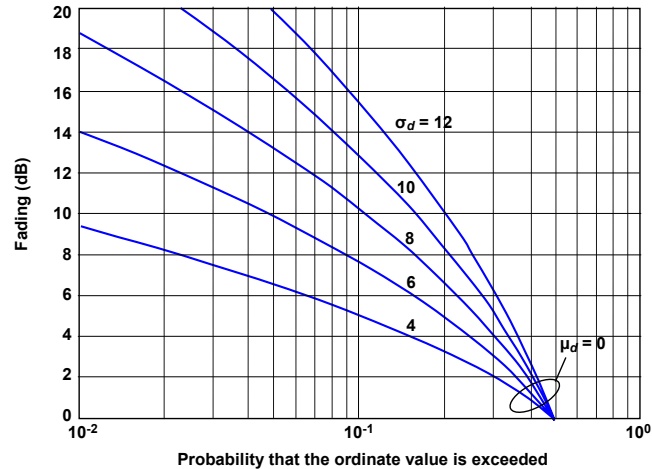
For cellular applications may be useful to evaluate the probability that, in the area where such statistics hold, the local mean value overcomes a given threshold m_0 :

$$P(m_0) = \int_{m_0}^{\infty} p(m_d) \cdot dm_d$$

The complementary of the cumulative distribution, normalised over

μ_d , supplies the probability that the long term fading overcomes a given value along the space segment (hundred of meters) over which the analysis is performed. An example is reported in the subsequent figure for some values of the standard deviation.

Long-term fading complementary cumulative



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Within a given area S , over which the service must be guaranteed, the measure reflecting the degree of coverage of the service is the portion F of S where the local mean value m_d overcomes a given threshold m_0 .

In probabilistic terms, F (named service area) may be calculated as:

$$F = \frac{1}{S} \int_S P(m_0) dA$$

Each elementary area dA is characterised by the characteristic values μ_d and σ_d that fully characterise the phenomenon.

Beyond its analytical representation, the numerical solution can be found by splitting area S in elementary areas, each characterised by constant values of μ_d and σ_d : those used to calculate $P(m_0)$.

Short-term fading

- Signal within paths ranging around $20-50 \lambda$ (steady state condition)
- Mean level (m_d) constant (under defined hypothesis)
- The p.d.f follows a Rayleigh distribution:

$$p(r/m_d) = \frac{\pi r}{2m_d^2} \cdot \exp\left(-\frac{\pi r^2}{4m_d^2}\right)$$

- The Rayleigh distribution is invoked for:
 - Performance of modulation schemes (S/N, BER)
 - Definition of diversity techniques
- Rice distribution for the cases where a fundamental component (higher amplitude) arises

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Short-term fading is mainly due to reflected waves and the mobile movements. Typically it is modelled by means of the Rayleigh distribution, whose probability density function is:

$$p(r) = \frac{r}{\sigma^2} \cdot \exp\left(-\frac{r^2}{2\sigma^2}\right)$$

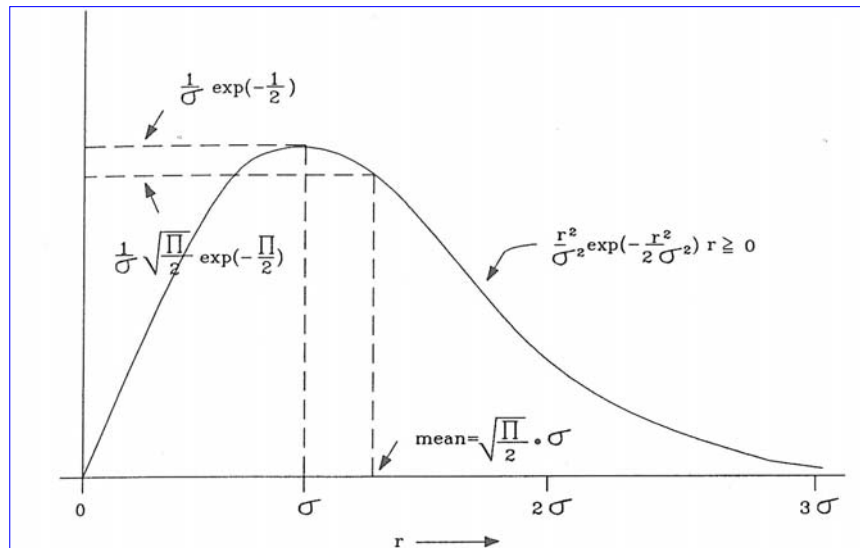
Since the short-term fading takes place around (is conditioned to) a given value of the local mean m_d and being the average value and standard deviation of the Rayleigh distribution tied to each other in this form:

$$m = \sigma \sqrt{\pi/2}$$

σ^2 must assume a consistent value, namely the value of $2m_d^2/\pi$ (consistent with the mean value m_d of the local mean (over $20-50\lambda$) of the long term fluctuations to which it is conditioned). From this consideration, the formula in the figure is deduced.

It has to be underlined that the assumption of having a constant value for m_d derives from the assumption that the *multipath* components have the same amplitude and a uniform distribution of the associated phase between $-\pi$ e $+\pi$, which corresponds to a uniform distribution of the angles of arrival ($0 - 2\pi$).

Rayleigh distribution



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The Rayleigh distribution is characterised by an average value which is very close to the standard deviation and by a distribution tail more evident than the one characterising the normal distribution. The fading reaches high values for $r \gg 3\sigma$.

Often the Rayleigh distribution is used in a normalised form. The normalised variable is:

$$\rho = r / \sqrt{\langle r^2 \rangle}$$

Where $\langle r^2 \rangle$ is the mean square deviation of the distribution.

$$\langle r^2 \rangle = 4m_d^2 / \pi$$

The normalised distribution is then:

$$p(\rho / m) = 2\rho \cdot e^{-\rho^2}$$

The resulting fading characteristics

Resulting fading
(short+long term) through
a convolutional process

$$p(r) = \int_0^{\infty} p(r / m_d) \cdot p(m_d) dm_d$$

Criteria for the evaluation
of the local mean through
measurements (need of
filtering short term
contributions)



- choice of a suitable path length over which the signal is averaged
- choice of the independent samples within the path (the basis for the local mean calculation)
- suitable path length minimising the variance of the mean estimation: $20-50\lambda$
- minimum number of samples: 50 (estimation within 1dB from the real value with a confidence level of 90%)

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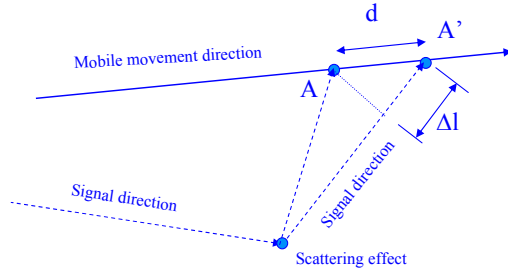
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Defining the local means requires that the measurement paths are really chosen in such a way that they have a statistical significance.

The experience is typically accumulated through in-field experience and repeated evaluation of the resulting accuracy.

The figure shows some of the criteria typically adopted and how the resulting fading may be calculated.

Doppler shift



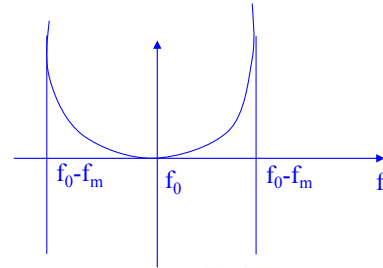
Spectral density around the transmitted frequency f_0 due to a multiplicity of contributions to Rx with Rayleigh distribution of the amplitudes and uniform distribution of the arrival angles between 0 and 2π

$$d = v \cdot \Delta t$$

$$\Delta l = d \cdot \cos \alpha$$

$$\Delta \Phi = -\frac{2\pi}{\lambda} \cdot \Delta l = -\frac{2\pi \cdot v \cdot \Delta t}{\lambda} \cdot \cos \alpha$$

$$\Delta f = -\frac{1}{2\pi} \cdot \frac{\Delta \Phi}{\Delta t} = \frac{v}{\lambda} \cos \alpha$$



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Doppler effect calculated for an angle α between the direction of the propagation ray and the direction of the mobile movement. The minimum value of $\Delta f = 0$ is obtained when directions are orthogonal. The maximum value is given when the two directions coincide:

$$f_m = f_0 \cdot v / c$$

In general Δf depends on $\cos \alpha$. It may be shown that the power spectral density of the vertical component of the electric field has the form of the figure (Rayleigh distribution of the amplitude and uniform arrival angles between 0 and 2π). Also the rate at which a given threshold is passed (level crossing rate) results to be tied to the Doppler effect. It may be calculated under the hypotheses that angles of arrival have a uniform distribution and the various components of the multipath are independent. The level crossing rate is:

$$N(\rho) = \frac{v \cdot \sqrt{2\pi}}{\lambda} \cdot \rho \cdot e^{-\rho^2}$$

Where ρ is the normalised attenuation previously introduced.:

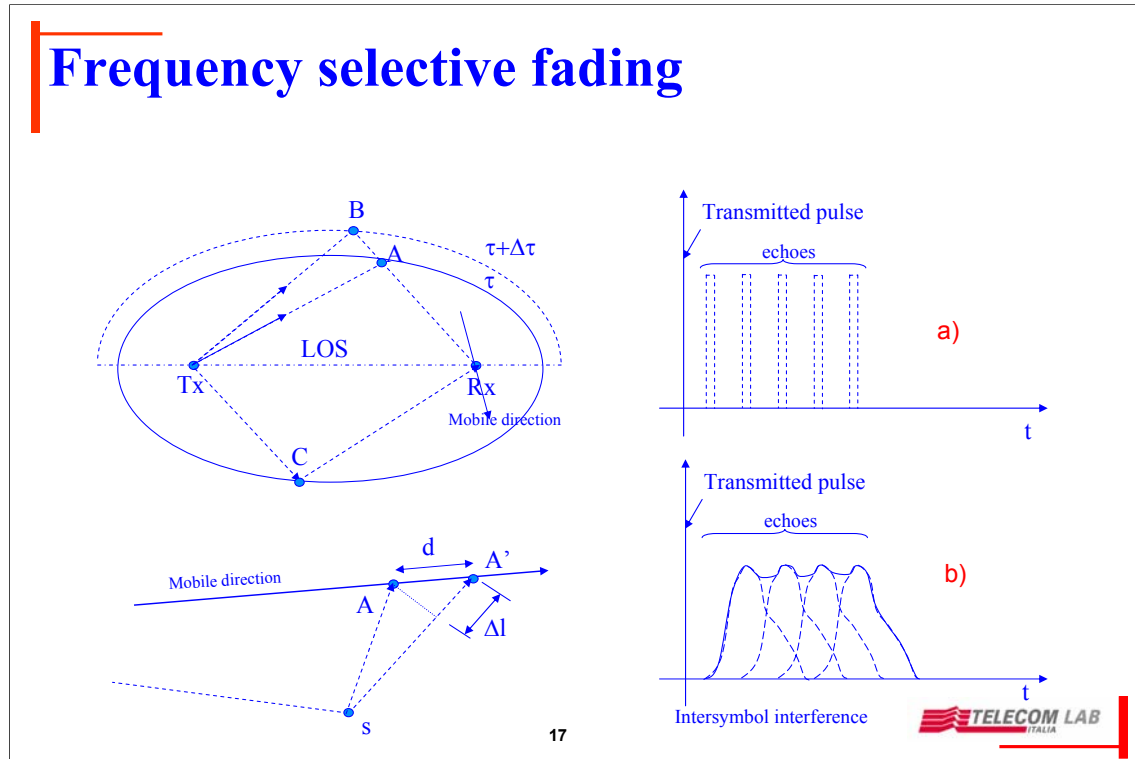
$$\rho = r / \sqrt{\langle r^2 \rangle}$$

Once the level crossing rate is known, the mean duration of the level ρ of attenuation (lasting time of the fast fading in function of their level) is:

$$\bar{\tau}(\rho_0) = \frac{e^{-\rho_0^2}}{N(\rho_0)}$$

where the numerator is the probability that the attenuation is greater than ρ (portion of time in which the receiver experiences at least a level ρ of attenuation) $\rho \geq \rho_0$.

Frequency selective fading

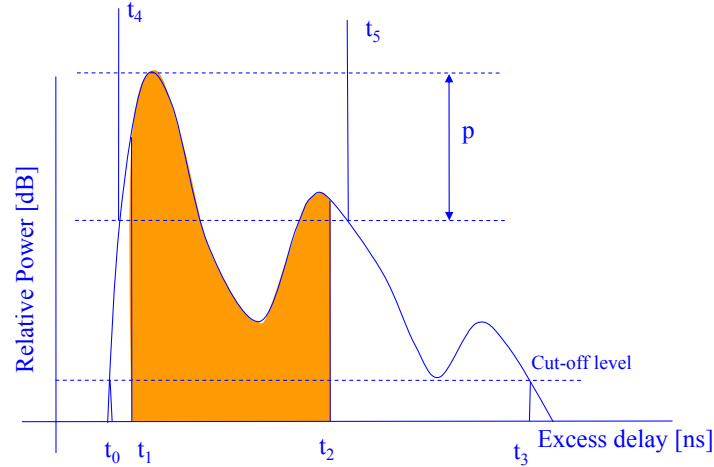


For wide band channel, it is often useful to represent the distribution of the delay undergone by the signal in a multi path situation, namely the delay accumulated before reaching the receiver, due to diffusion and reflection effects. The delay distribution completes the channel characterisation (for instance, through it, one can calculate the inter symbol interference in wide band digital transmission).

For a given position of the mobile terminal and the base station, all the objects located over an ellipsis with foci Rx and Tx, will produce, through reflections, the same delay at the receiving side. In the figure, obstacles in A and B will produce different delays, time separated proportionally to the length of segment AB. In the general case, many echoes will be present corresponding to an emitted signal. Figure a and b correspond to cases where inter symbol interference is present or not. This depends on the channel bandwidth.

A complete representation of the phenomenon, would require the deep study of the radio channel behaviour (response) in the presence of an impulse waveform. In function of this response, the delay distribution can be studied.

Impulse Response Definition (ITU-R Rec. P. 1145)



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The impulse response is a complex function. The figure represents the value of the relative power, by adopting the definitions normalised in ITU-R. The curve represents the *delay profile* resulting from the various echoes in a real environment. This profile coincides with the module of the impulse response:

$$P(t; \tau) \approx |h(t; \tau)|$$

Where, in the more general form the following holds:

$$h(\tau) = \sum_{i=0}^{N-1} a_i \cdot \exp(-j\theta_i) \cdot \delta(\tau - \tau_i)$$

The delay profile then represents the amplitude of echoes that, from a given instant on (hence for a given position of the mobile) reach the mobile itself.

The mean value of the energy and the average delay associated to the impulse response are:

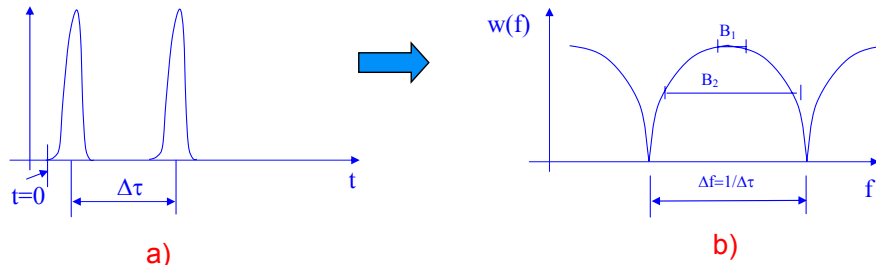
$$P_m = \int_{t_0}^{t_3} P(t) \cdot dt \quad T_D = \frac{1}{P_m} \cdot \int_{t_0}^{t_3} (t - t_0) \cdot P(t) \cdot dt$$

Other parameters are the delay dispersion and the delay width (the latter represents the delay interval within which a fraction q of the overall energy P_m is transmitted):

$$\sigma_T = \sqrt{\frac{1}{P_m} \int_{t_0}^{t_3} t^2 \cdot P(t) dt - \left[\frac{1}{P_m} \int_{t_0}^{t_3} t \cdot P(t) dt \right]^2} \quad W_q = (t_2 - t_1)_q$$

The representation is valid in a given instant t : the impulse response varies in function of the mobile movements. These movements will induce some fluctuations (fast fading) of the related amplitudes, hence fluctuations of the delay profiles.

Band Distortion



$$w(t) = \int_{-\infty}^{\infty} z(t - \tau) \cdot h(t, \tau) d\tau$$

Examples:

$\Delta\tau = 1 \mu s$	$\Delta f = 1 \text{ MHz}$
$\Delta\tau = 10 \mu s$	$\Delta f = 100 \text{ kHz}$
$\Delta\tau = 50 \mu s$	$\Delta f = 20 \text{ kHz}$

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The same phenomenon can be represented in the frequency domain.

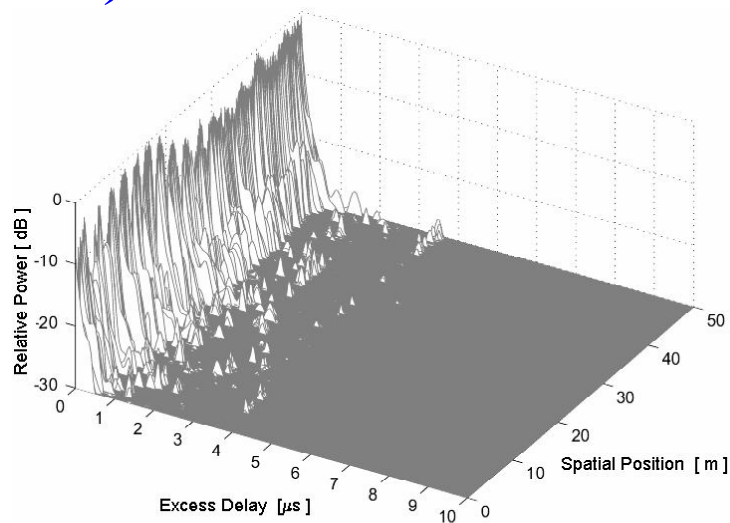
The figure represents an ideal situation, where only two echoes exist. They have the same amplitude and a relative delay of $\Delta\tau$. Through an appropriate use of the Fourier transform, it is possible to demonstrate that the two representations of the figure are equivalent (in different domains).

Being $\Delta f = 1/\tau\Delta$, it is easy to evaluate the selectivity in frequency corresponding to a given relative delay between the echoes. The latter (distortion) must then be put in relation with the channel bandwidth.

Since, for instance, $\Delta\tau = 1 \mu s$ (typical delays for an urban environment) corresponds to a $\Delta f = 1 \text{ MHz}$, a system like the GSM, characterised with a band of 200kHz, is substantially not affected by the produced distortion. Conversely, reasonably independent from For instance, $\tau\Delta$ implies a $\Delta f \pm 1 \text{ MHz}$. The distortion will have conversely an important effect on the UMTS which shows a channel band of 5 MHz.

However, in an open context (e.g. mountains) where propagation echoes may reach $50 \mu s$ ($\Delta f = 20 \text{ kHz}$) also the GSM system is sensitive to the band distortion.

Delay Profiles measured outdoor (urban area)

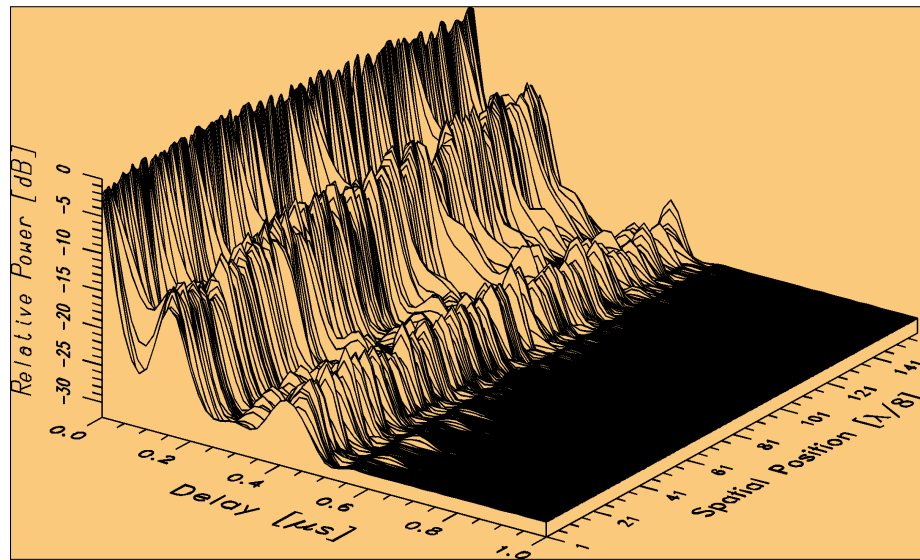


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Typical values in an urban environment: 1 – 5 μs

Delay Profiles measured indoor (*corridor*)

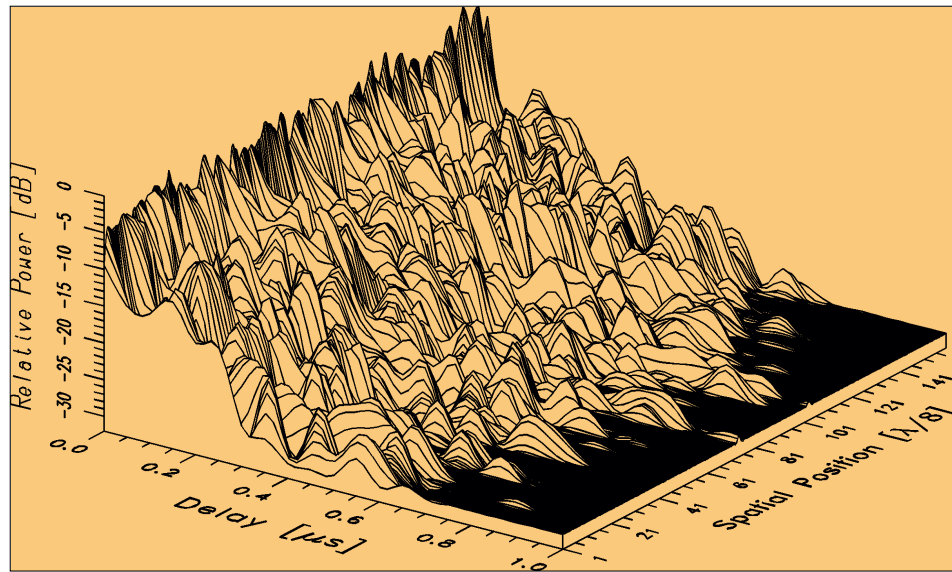


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Typical delay values:
 $0.1 - 0.5 \mu\text{s}$

Delay Profiles measured indoor (*Car Parking*)



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Typical delay values:
 $0.2 - 0.8 \mu s$

Diffraction effects - Fresnel approach

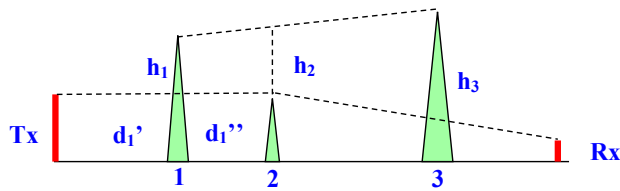
Received power exponentially dependent on the frequency:

$$f^{0.7}; \quad d < 20 \text{ Km}; \quad 400 \text{ Hz} < f < 1000 \text{ Hz}$$

Impact of the environment conditions:

Factors:

- Terrain characteristics
- Building density and building height
- Vegetation conditions
- Width and orientation of the streets



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The presence of obstacles requires the need of considering the impact of the diffraction phenomenon. In the general case, many obstacles can be situated between the Rx and Tx terminations. Many methods have been proposed to evaluate the induced attenuation. The Epstein-Peterson and the Deygout models are the most effective for a practical use. Both decompose the attenuation in a given number of elementary contributions, reflecting the one-obstacle case, well known in the literature as *blade* model.

In the Epstein-Peterson model, the obstacle configuration represented in the figure, is studied through three applications of the one-obstacle model. This give rise to an attenuation $A(i)$ generated by the i -th obstacle, located between the obstacles $(i-1)$ and $(i+1)$. For $A(i)$ empirical formulas are adopted as estimates of the Fresnel integral. For instance, for $h_i' \leq 0.7$ the following formula can be used:

$$A(i) = 6.9 + 20 \cdot \lg \left[\sqrt{(h_i' + 0.1)^2 + 1} - (h_i' + 0.1) \right] \quad i = 1, 2, 3$$

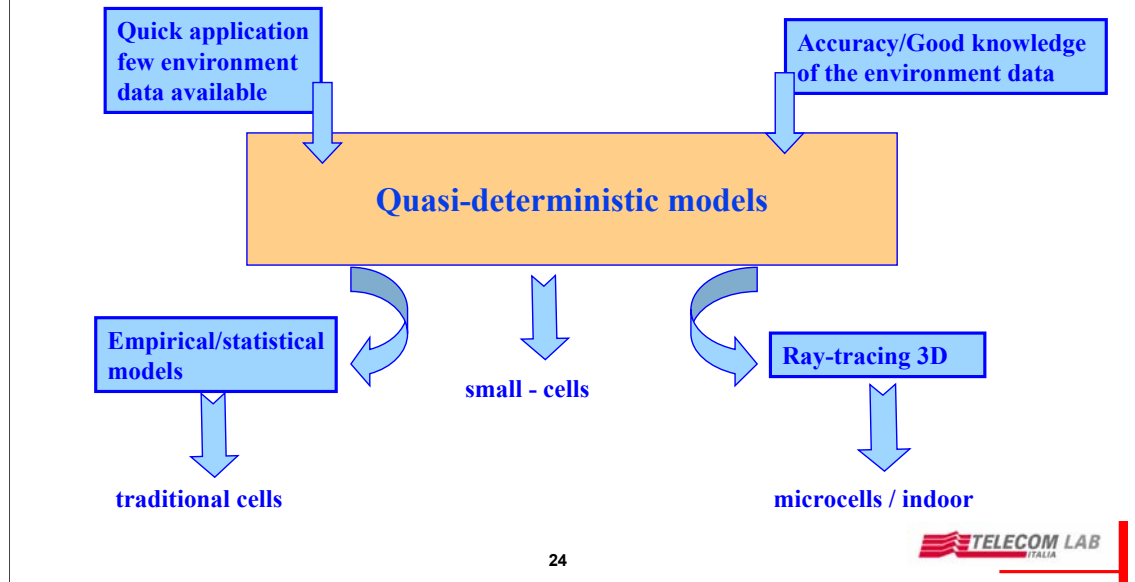
Where h_i' is the Fresnel parameter: h_i is negative whenever the i -th obstacle is below the straight line connecting Rx and Tx in the case of a single obstacle (or, equivalently, connecting obstacles $(i-1)$ and $(i+1)$ in case of multiple obstacles).

$$h_i' = \frac{-h_i}{\sqrt{\lambda \cdot \frac{d_i' \cdot d_i''}{d_i' + d_i''}}}$$

The denominator is the radius of the first Fresnel zone. The overall additional attenuation is:

$$A = \sum_{i=1}^3 A(i)$$

Propagation models



The propagation model are used to study the propagation characteristics without being forced to conduct wide and expensive measurement campaigns.

Besides, through the propagation models, innovative solutions or servfice configurations can be studied with a satisfactory accuracy even when systems and services are not yet implemented or deployed in the field.

Some elements are affecting the choice of the propagation models:

- the kind of investigation to be performed
 - planning (e.g. through simulation)
 - study of the nature of the phenomenon (analysis)
- The available data, related costs and related storage requirements

The model choice often derives from trade-off between cost and model accuracy requirements.

Empirical models for the calculation of the mean values of the field strength

- **Es. : Okumura-Hata**

- **Attenuation may be calculated as (using 50 m resolution data, at least):**

$$L_{50} = 69.55 + 26.16 \cdot \log(f) - 13.82 \cdot \log(h_t) + C(U) + C(V) + (44.9 - 6.55 \cdot \log(h_r)) \cdot \log(d)$$

- *h_t and h_r effective heights of Tx and Rx in m*
- *f frequency in MHz and d distance in km*
- *$C(U)$ correction factor tied to the kind of urban structure (building density)*
- *$C(V)$ correction factor tied to the kind of vegetation*

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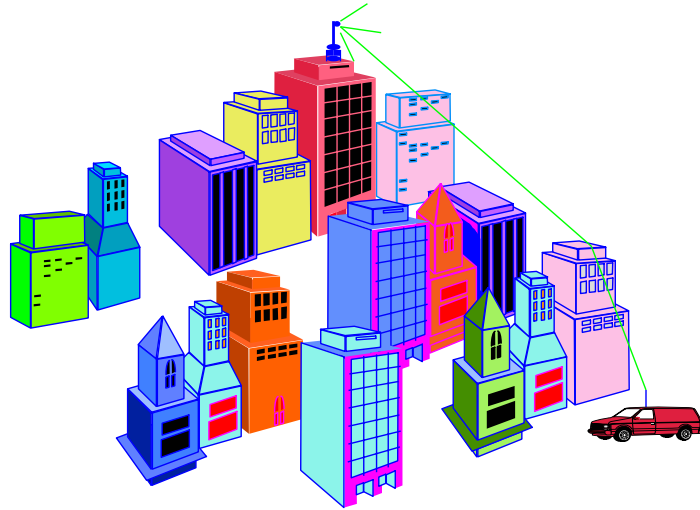
The Okumura-Hata model is extensively used to evaluate the local means in the traditional (macro cellular) coverage.

The factors used have an empirical nature. For instance, the vegetation effect is evaluated as:

$$C(V) = 0.2 \cdot f^{0.3} \cdot d^{0.6} \quad (dB)$$

where d is the vegetated distance arising along a straight line between the transmission and the receiving points.

Small cell environment



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The propagation model is built through the following steps:

- modelling of the buildings profiles (from the data bases)
- evaluation of the field intensity in the free-space
- selection of the obstacles to identify active and non-active obstacles (ITU-R model)
- evaluation of the attenuation based on the Huygens-Fresnel (or on Deygout) model.

Coverage example: Turin



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This is an example of coverage for the Torino city.

Radio coverage is directly superimposed to the data base of the territorial data (surfaces and building heights) of the service area (2m accuracy).

Field intensities are assigned different colours

It can be noted as the coverage guaranteed by the small cells (relatively low antennas) is extremely sensitive to the buildings geometry.

For these *small cells*, the coverage calculations is very heavy in comparison with the calculations needed for a macro cell, in spite of the great difference of dimensions:

- up to 35 km for the macro cells
- 3 km for the *small cell*.

Measurements: Turin

Area: torino
UTM: 394048 4989968
X axis [m]: 3500
Y axis [m]: 3500

Colour map:

h_Tx [m]: 20.0
P_Tx [dB]: 1
g [dB]: 18

EL FIELD [dBuV/m]:
(MEASUREMENTS)

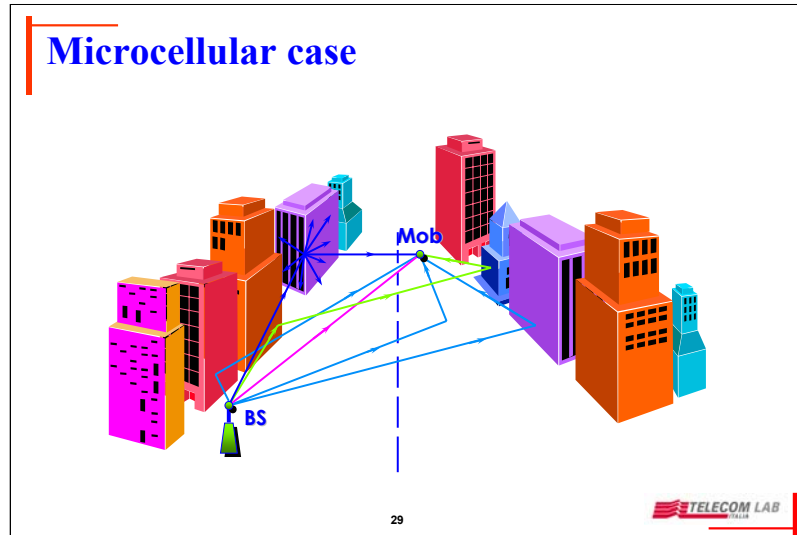
E >= 65
E >= 50
E >= 54
E >= 41
E >= 30
E < 30



The figure shows a certain number of paths where the local means have been measured for a consistency verification of the coverage data evaluated in the previous figure.

Again, different colours are assigned to different values of the field intensity.

Microcellular case

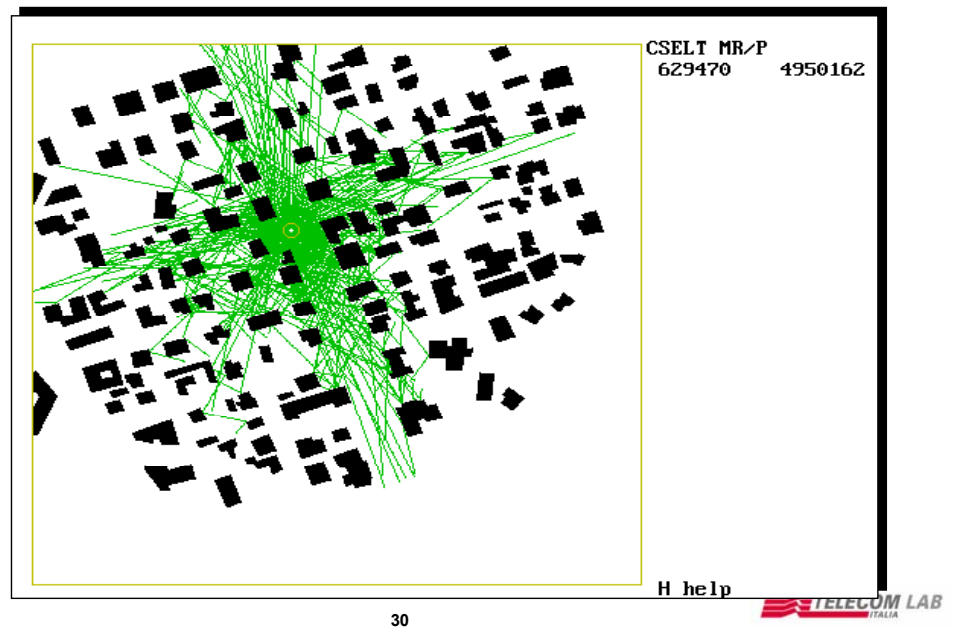


In case of microcellular coverage, the antenna is located below the roof level. The radio coverage can be evaluated by making use of geometrical models, with related reflection, diffraction and scattering mechanisms.

Three different approaches can be used in this case:

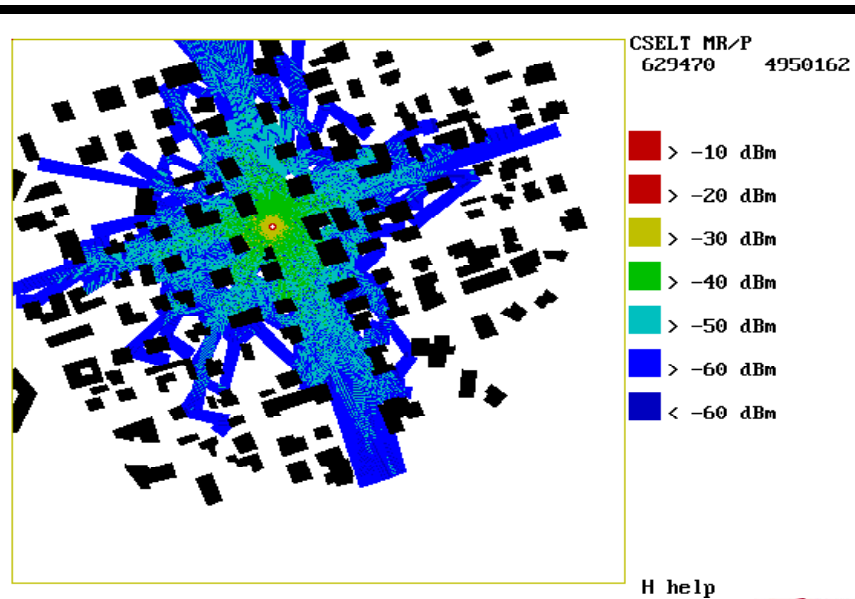
- *ray-tracing* (the most precise, but very onerous on the side of calculation time involved); for each point of the domain, the intensity and the delay structure are evaluated
- *ray-launching* (it is less accurate but it supplies a sufficient evaluation accuracy)
- empirical methods (mostly used for *indoor* propagation); this approach is the only one that can be applied in several cases, due to the absence of input data (geometrical parameters, thickness of the walls, materials) which are conversely needed for more accurate approaches.

Ray-Launching - example



An example of evaluation based on the *ray-launching* approach . The greater the distance from the antenna, the lower the accuracy of the results. In fact, great distances mean low significance of the contributions that are to be considered for the evaluation of the local means.

Ray-Launching (field evaluation)

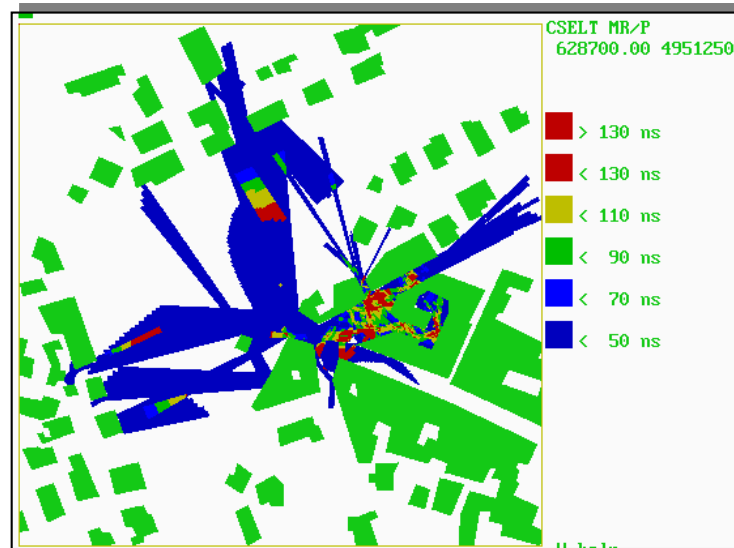


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This is the result of the procedure applied to the previous case (the resulting average calculation applied to each *pixel*).

Delay spread calculation

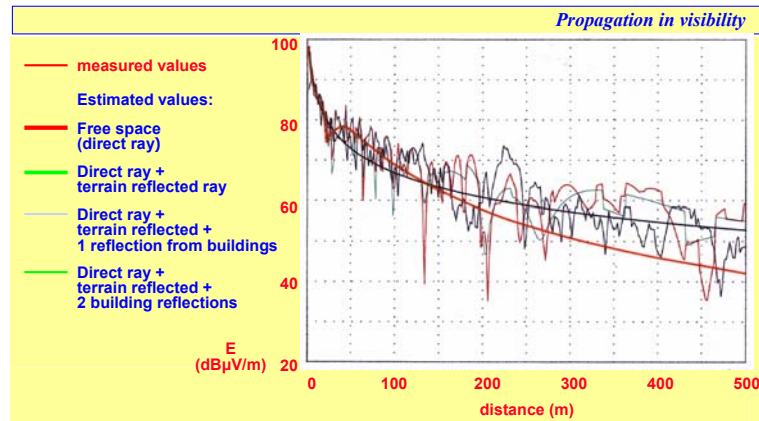


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Still in relation to the previous configuration, this figure is representing the *delay spread* of the echoes. The values have been calculated with 2D techniques (buildings have an infinite height).

If the antenna is not much below the roof level, then 3D techniques are to be used to consider the diffraction due to the roofs edges (much greater evaluation efforts are needed).

Comparison with measured data

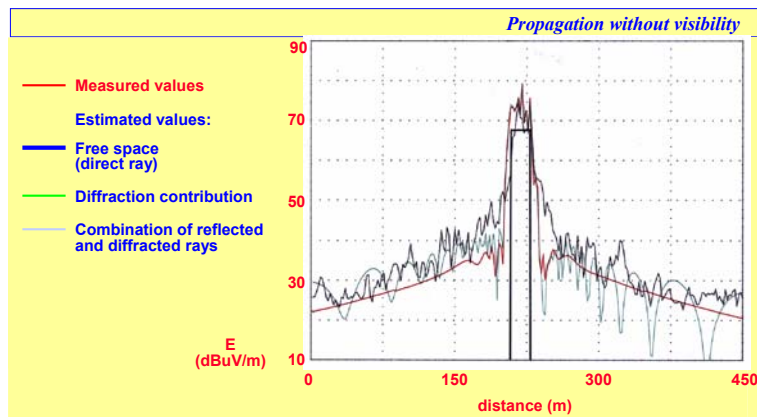


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The results derived from 2D models compared with the measures. The comparison is done for different accuracies of the model.

The conditions are *line-of-sight* (Tx and Rx on the same road).

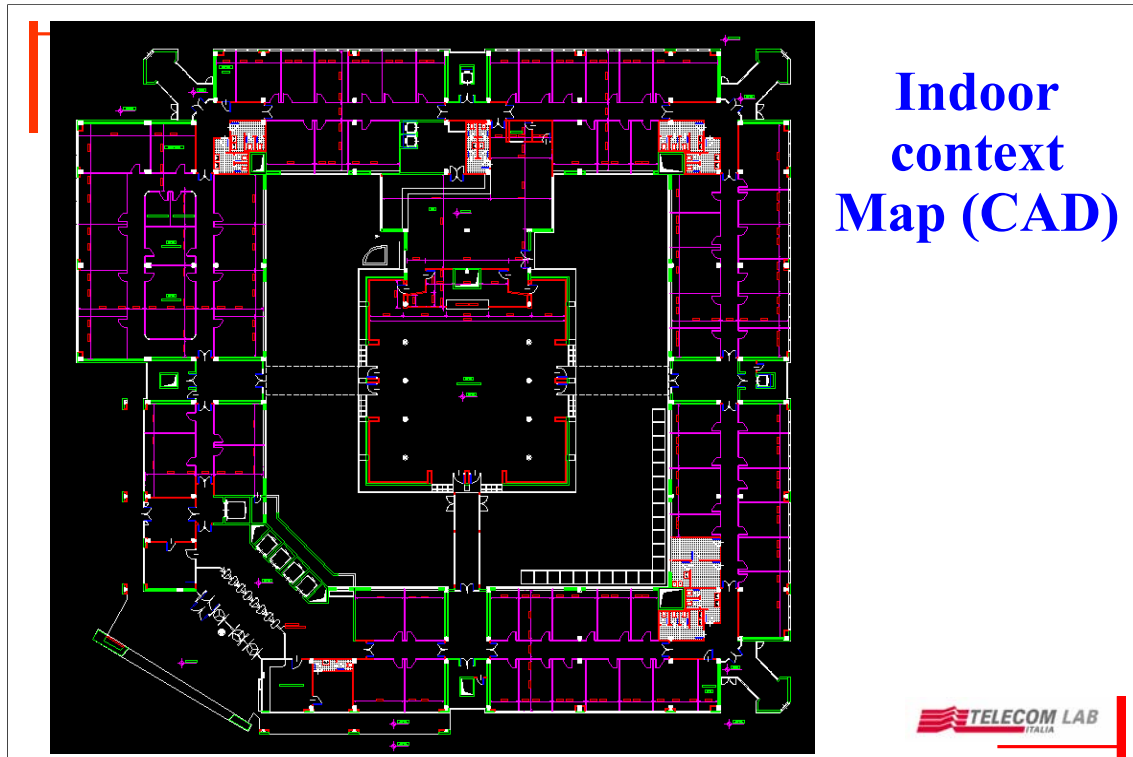
Comparison with measured data



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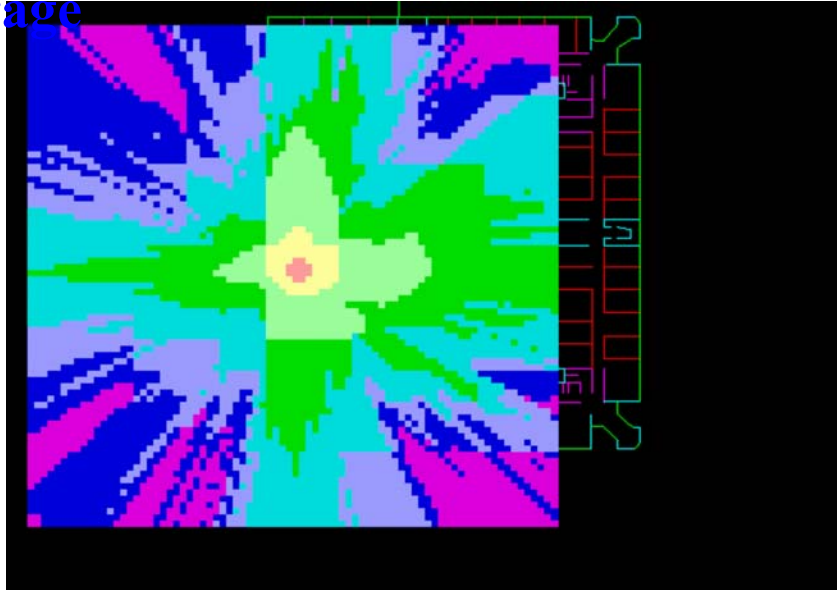
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As in the previous case but in *non-line-of-sight conditions*. Tx and Rx are on orthogonal streets.



An indoor map (10 cm accuracy).

Field strength calculation for indoor coverage



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Indoor coverage calculated for the previous map. It is obtained through a 2D *ray-tracing* approach. This approach can still be used due to the small dimensions of the environment.

Simplified indoor propagation models (empirical)

Simple models are used, offering the overall attenuation in an indoor context

Two models are mostly used:

- *one-slope model*

$$L = L_0 + 10n \cdot \log(d) + L'$$

- *multi-wall model*

$$L = L_c + \sum_{i=1}^I k_{wi} \cdot L_{wi} + k_f \cdot L_f$$

One-Slope model (ETSI)

Distance-tied attenuation

$$L = 30 + 3.5 * 10 \log(d) + L'$$

Floor attenuation

$$L' = 15 - 18 \text{ dB}$$

Shadowing

Random variable uniformly distributed between -10 e 10 dB

Adopted in many simulation models (ETR 42)
Deriving from measures (Philips)

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Multi-Wall model (Motley-Keenan)

Distance-tied attenuation

$$L = 37 + 2 * 10 \log(d)$$

Wall attenuation

$$L_w = k_w * L_{wi}$$

Material	Lw (dB)
Brick	2.5
Plasterboard	1.3
Concrete	10.8
Light wall	2.31
Thick wall	15.62

Floor attenuation

$$K_f * L_f = \text{number of floors} * \text{1-floor attenuation} (\sim 15 \text{ dB})$$

Shadowing

Log-normal random variable with σ ranging from 2.7 to 5.3 dB