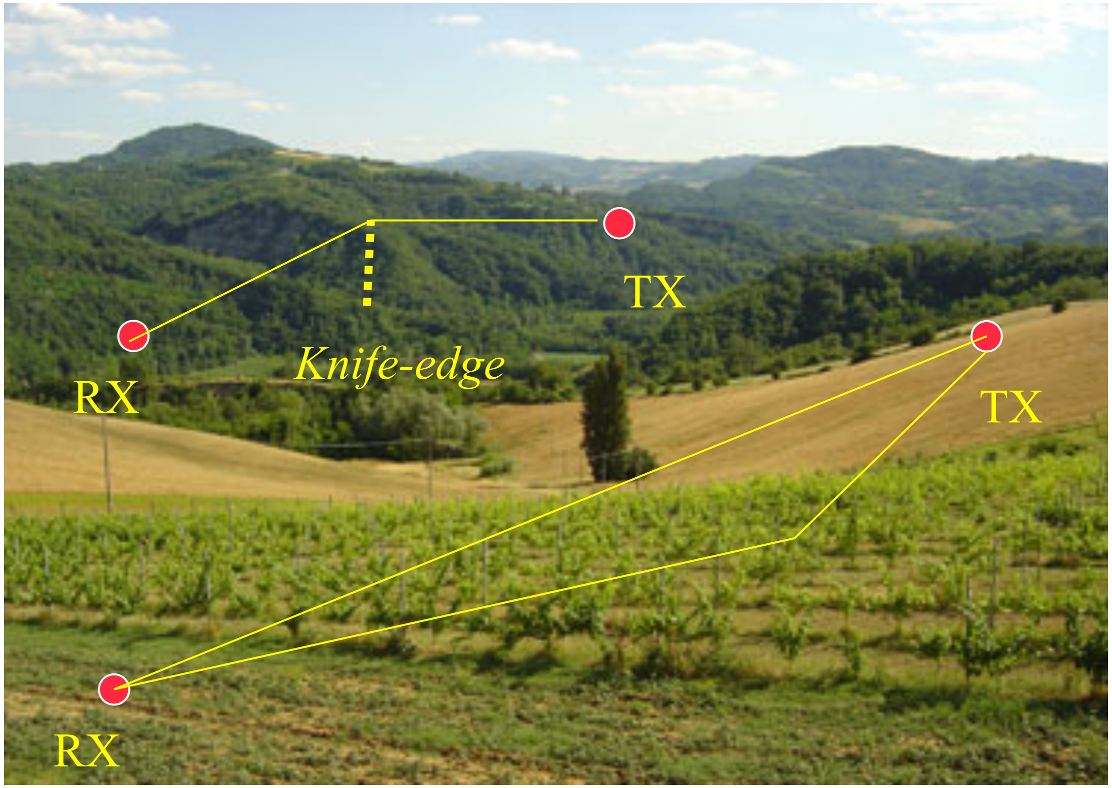
B – MODELLI DI PROPAGAZIONE

- Modelli empirico statistici per la previsione della copertura (intensità di campo) radio
  - Ambienti e meccanismi di propagazione: propagazione laterale e verticale. Classificazione dei modelli.
  - Approccio statistico principali componenti dell’attenuazione e le loro origini. Fast-fading e Shadowing.
  - Modelli generici
  - Modelli per ambiente urbano semplifcati e ibridi
- Modelli deterministici per la propagazione multicammino
  - Problematiche di input output.
  - Ray Launching e Ray Tracing
  - Modelli a raggi semplificati
  - Ray tracing in dettaglio - esempi

Propagation environments: Rural environment

- Free-space Propagation
- Ground reflection
- Knife-edge diffraction
- Other effects (atmospheric, radio horizon, etc.)



- With one or more obstacles: diffraction attenuation with one or more knife-edges (see hereinafter)

Rural environment (II)

Without obstacles:

ex: <u>Dual-slope model</u>

For mean attenuation

$$L(R) = L(R_o)\left(\frac{R}{R_o}\right)^2 \qquad \text{for } R_o \le R \le R_{BP}$$

NB: terrain profile required

$$L(R) = L(R_{BP})\left(\frac{R}{R_{BP}}\right)^\alpha \quad \text{(es: } \alpha\text{=4)} \quad \text{for } R > R_{BP}$$

$in\ dB:$

$$L_{dB}(R) = L_{dB}(R_{BP}) - 10\alpha\log(R_{BP}) + 10\alpha\log(R)$$

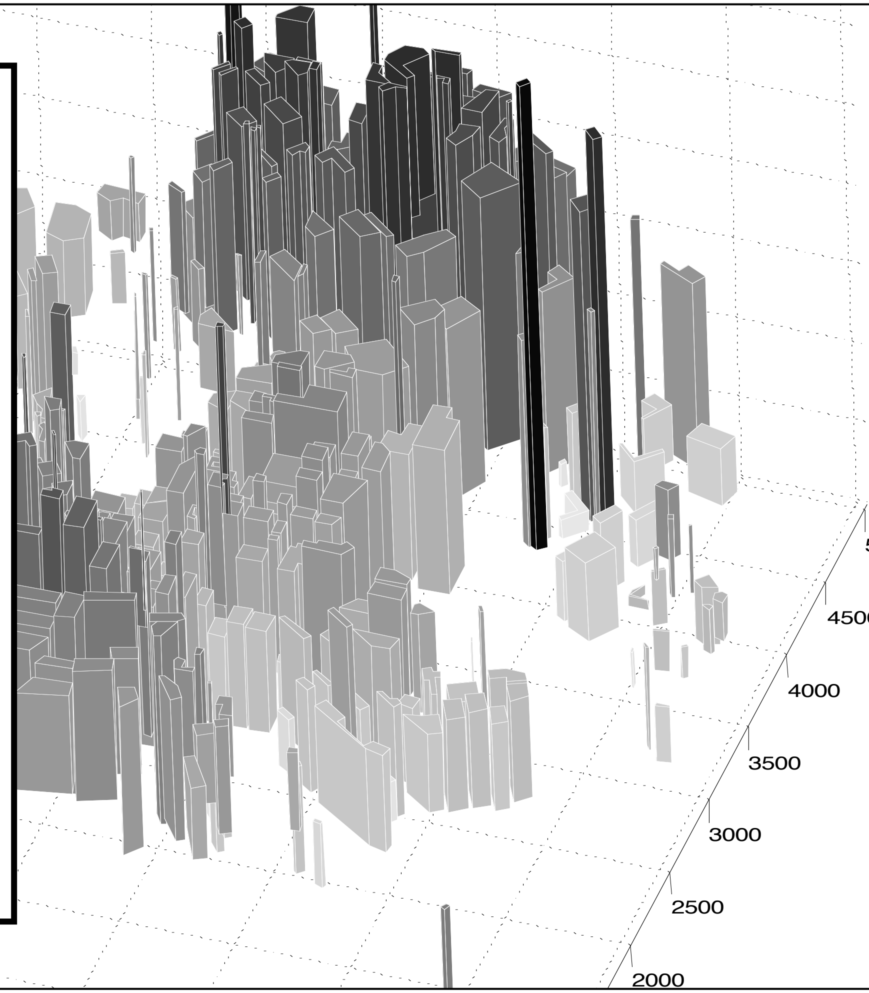
Urban environment

Buildings can be represented as truncated prysms with polygonal base

Radio propagation “over” them is called ***Over-Roof-Top*** or ***Vertical Propagation***

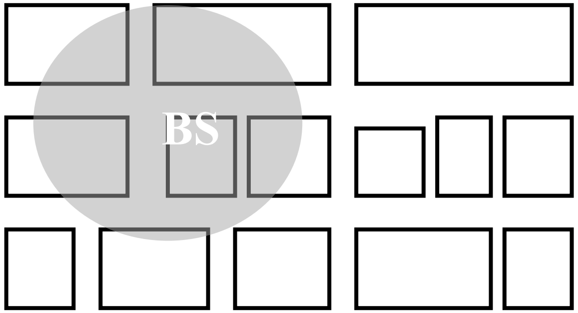
Radio propagation “around” them is called ***Lateral Propagation***

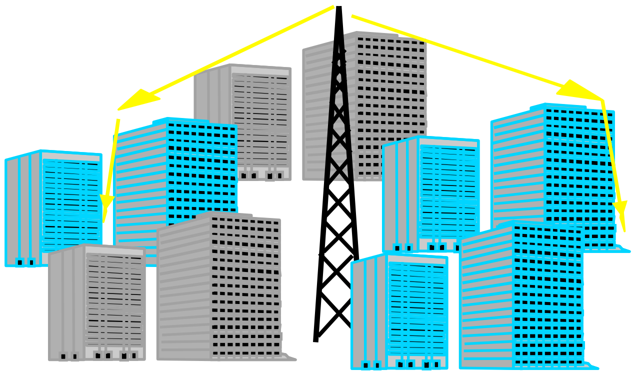
Radio propagation “inside” them is called ***Indoor Propagation***



Over-Roof-Top (ORT) propagation

"Macrocell" (R > 1km)





When the BS is above the surrounding buildings, then most propagation takes place in free space. Link distance can be of many km's.

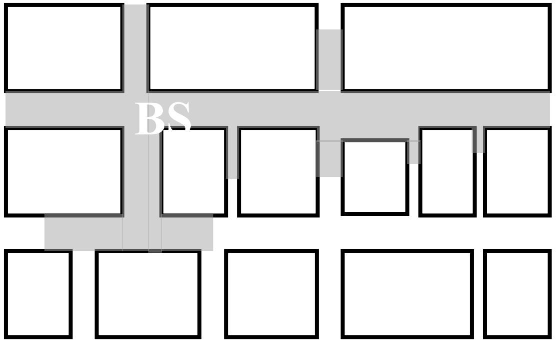
Interaction with buildings is limited to the last part of the path. ***Spatial granularity*** of the environment can be disregarded, and mean path loss considered (+fading).

Simple ***statistical models*** with $2<\alpha<4$ can be used (Hata-like models):

$$\boxed{L^{dB}(R) = L^{dB}(R_o) - 10\alpha \log R_o + 10\alpha \log R}$$

Lateral Propagation (LP)

"Microcell?" (R < 1km)



When the BS is below the surrounding building rooftops, then propagation takes. Place "around" the buildings, interacts with them.

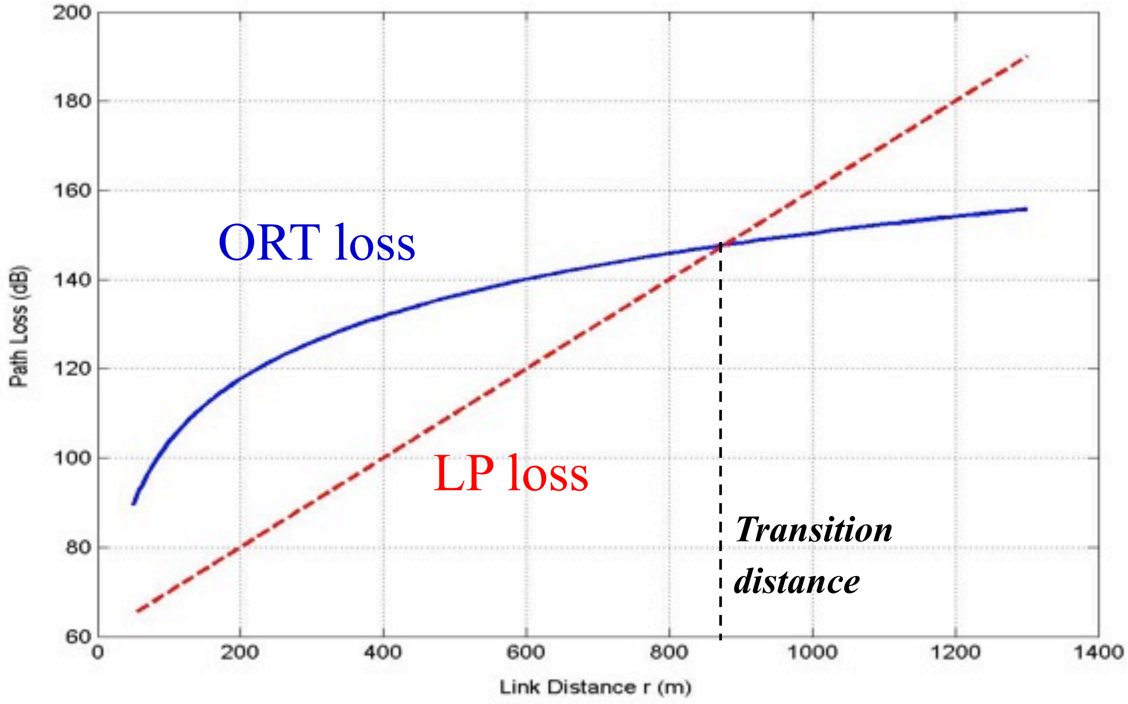
Simple statistical models cannot be used anymore, propagation models should take into account the urban structure, must be ***deterministic***, and take into account interactions like ***reflection***, ***diffraction*** and ***diffuse scattering***. Transmission is usually disregarded in outdoors. In this case fading is 'included' in the model.

$$\boxed{\cancel{L^{dB}(R) = L^{dB}(R_o) - 10\alpha \log R_o + 10\alpha \log R}}$$

...

LP vs. ORT propagation

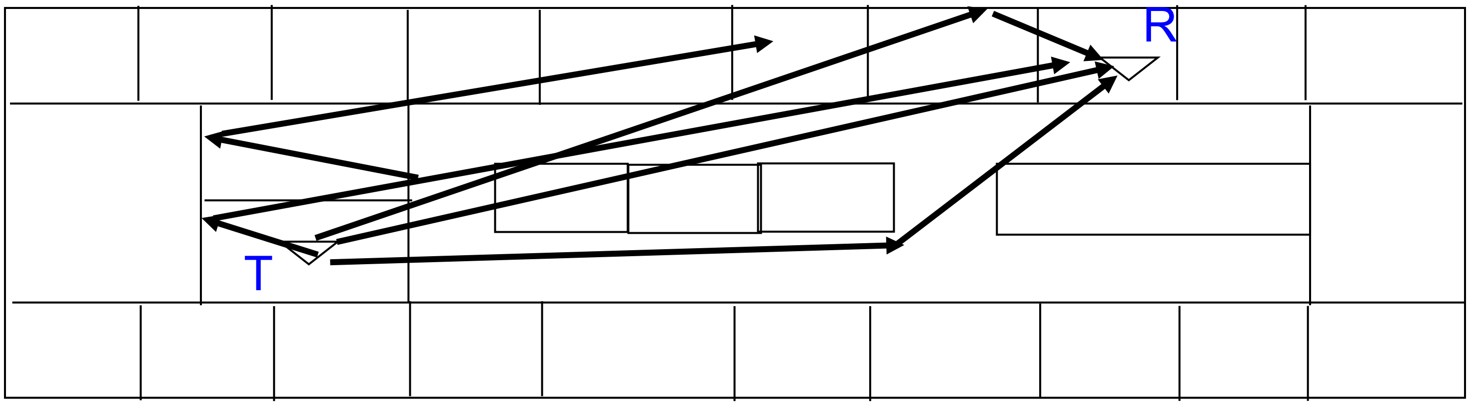
After a certain distance (***transition distance***) lateral propagation (LP) attenuates more rapidly than ORT propagation [*].
LP is dominant before the *transition distance*, while ORT is dominant after it.



[*] Barbiroli, M.; Carciofi, C.; Falciasecca, G.; Frullone, M.; Grazioso, P. "A measurement-based methodology for the determination of validity domains of prediction models in urban environment," IEEE Transactions on Vehicular Technology, Volume 49, Issue 5, Page(s):1508 – 1515, Sept. 2000

Indoor propagation

"Picocell? Femtocell?" (R < 100m)



When the terminals are within buildings then propagation strongly interacts with the internal structure of them.

Surprisingly, since internal walls are easily penetrable (L ~4-5 dB), indoor propagation is more similar to free space propagation than lateral propagation.

Appropriate models however should be ***deterministic***, and take into account inter-actions like reflection, diffraction, diffuse scattering and ***transmission*** through walls

Propagation models (1/3)

- Only ray models (ray tracing) attempt to model multipath propagation. The other models are generally much more simplified, either for speed or usability reasons or because they focus on particular environments where a few, major propagation mechanisms are present

- Models are defined ***heuristic*** or ***empirical***, if they need measurements to be either validated or derived, respectively. On the opposite models are defined ***physical*** if they are based on a sound physical theory

- Models are defined ***statistical*** if only statistics of the main propagation parameter are provided on the base of a generic environment description. On the opposite models are defined ***deterministic*** if the actual values of such parameters are provided for a specific environment configuration

- When a solid theoretical interpretation of measurements is lacking then often only statistics can be derived, therefore empirical models are often also statistical, and thus defined ***empirical-statistical*** models.

Propagation models (2/3)

- Generally, emipirical/statistical models are simpler and faster than physical/deterministic models, while the latter are more accurate and flexible.

- The latter are usually more expensive to use since require expensive env. databases

- The former are generally used in the ***design phase*** while the latter in the ***deployment phase*** of a radio transmission system.

- However, the insight provided by some deterministic models is often necessary also for a correct design.

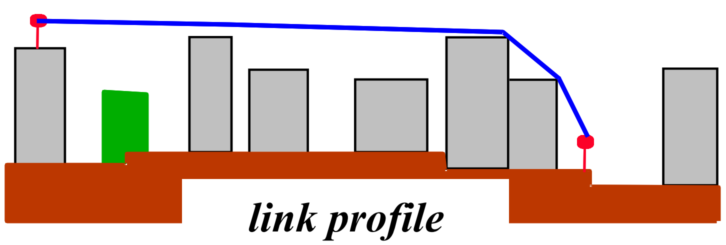
- This classification defines reference "poles". Actual propagation models often lay in the middle between two or more "poles". Therefore 3D ray tracing has some statistics in it, and Hata-like models have some deterministic parameters or aspects.

- Every environment/context has appropriate models.

Propagation models (3/3)

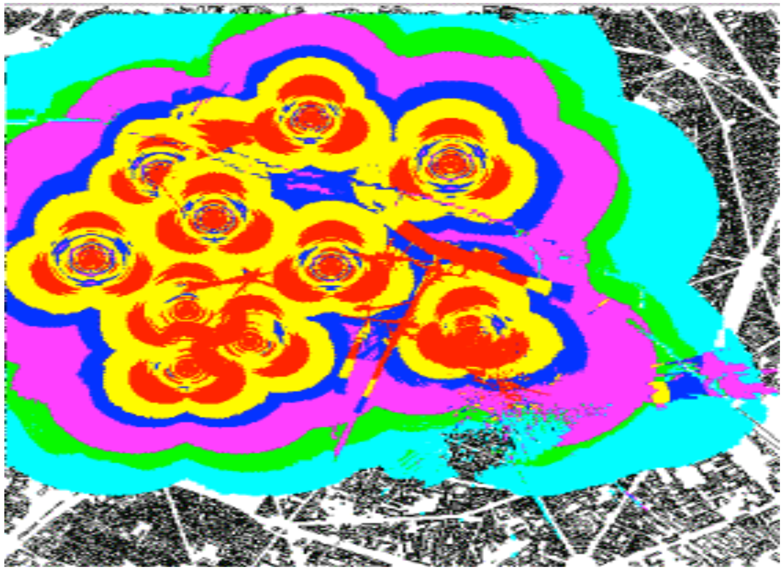
- Generally, **Empirical Statistical** (ES) and **Over-Roof-Top** (ORT) models describe overall propagation along the **radial** Tx-Rx
- LP is accurately described only by Ray tracing and deterministic propagation models, however some ES and hybrid methods attempt a partial description of LP

The main difference between ES methods and ORT models is that the latter are more deterministic since they need in input a simplified ***radio link profile.*** Therefore ORT models can be defined hybrid

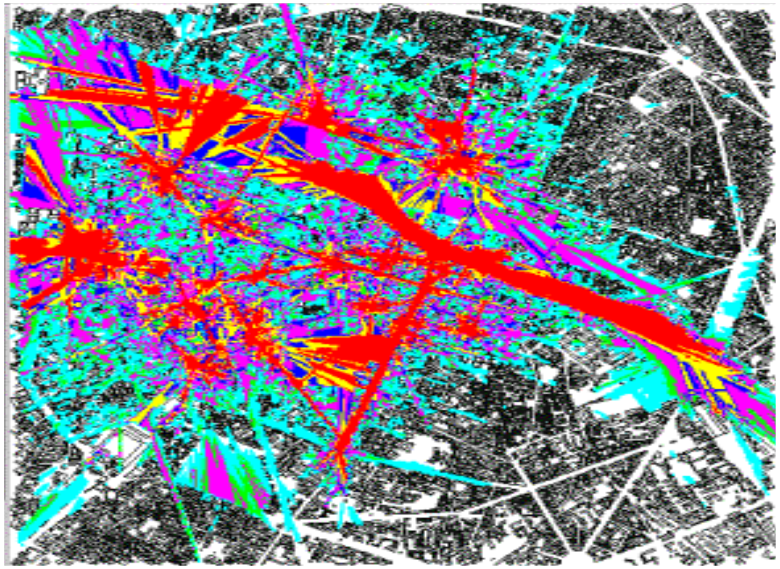


Example with the same environment:

Hata-like model:
Granularity disregarded



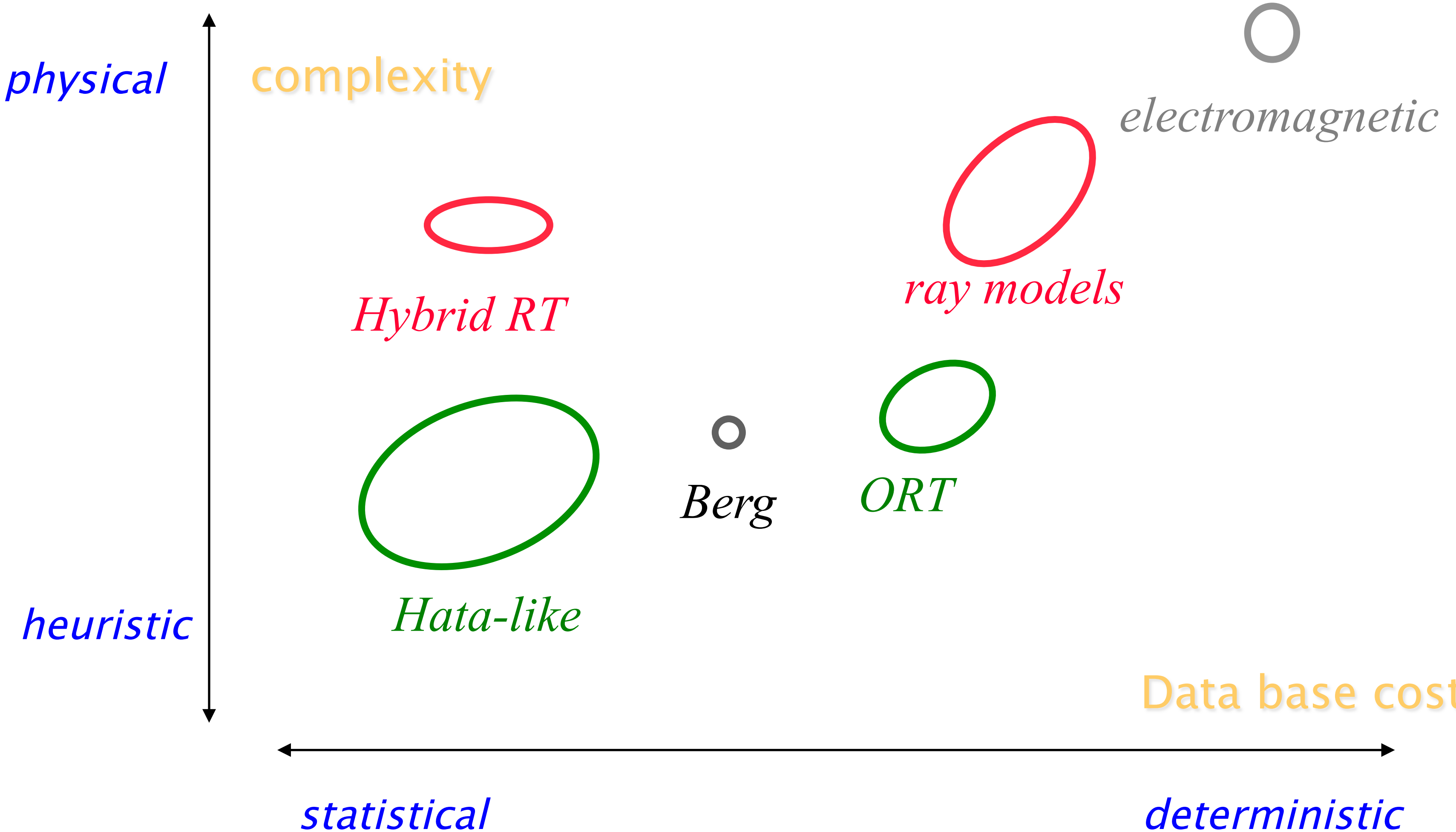
Ray Tracing model:
Granularity considered



(source: WAVECALL BV, Amsterdam)

Granular environment: non-homogeneous, non-isotropic lossy mean
Non-granular environment : homogeneous, isotropic lossy mean

A visual classification



Empirical-statistical and ORT models

• **ES/ORT models are generally incoherent, <u>only provide mean path-loss or path-gain as a function of radial distance R</u> (link distance)**

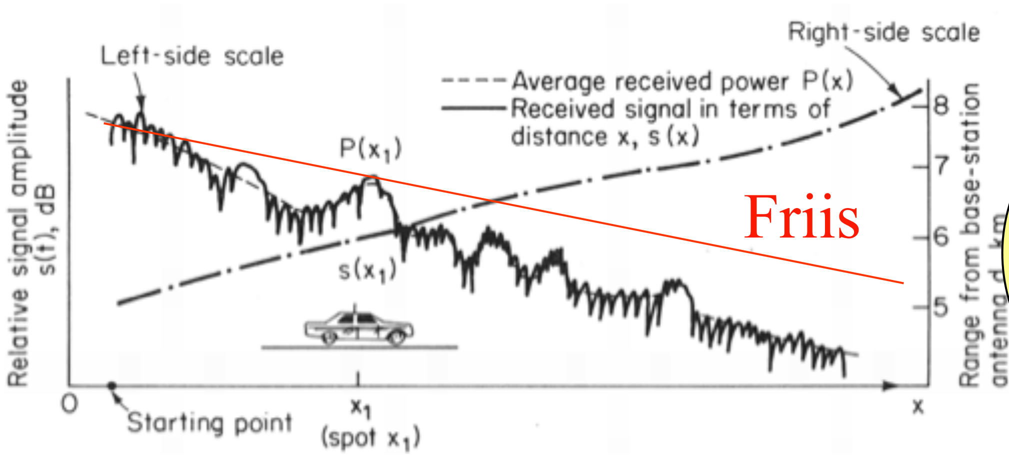
• Since ES/ORT model only give mean path loss, deviations from this value are called **<u>fading</u>** and can only be described in a statistical way

• Fading is an ergodic random process of space, however due to mobility also becomes an ergodic random process of time

• According to this "empirical-statistical" approach it is necessary to define different **<u>path-loss components</u>**

Componenti dell' attenuazione/ (1/7)

- E' noto che, in ambiente reale, l'andamento della potenza ricevuta con la distanza si discosta da quello previsto dalla formula di Friis:



Il termine dominante è una funzione monotona della distanza. Gli altri termini corrispondono a "oscillazioni"

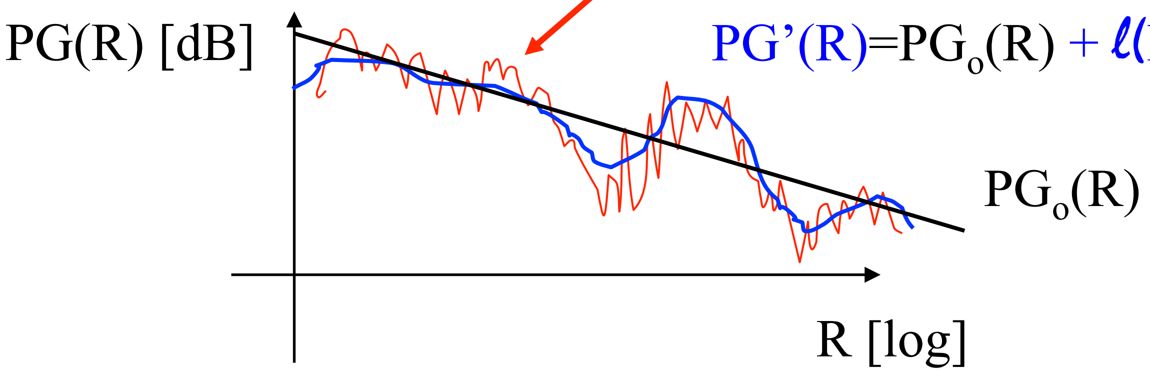
✓ In ambiente reale si possono individuare 3 componenti principali dell'attenuazione o del path gain :

1. ***Termine dominante deterministico***;
2. ***Oscillazioni lente (slow fading o shadowing);***
3. ***Oscillazioni rapide (fast fading).***

Componenti dell'attenuazione/ (2/7)

E' un processo aleatorio ergodico dello spazio (tempo). E' utile fare una <u>fattorizzazione</u> del Path Gain (o dell'attenuazione), che in dB diventa una separazione in termini additivi:

$PG(R)=PG_o(R)\cdot \ell(R)\cdot r(R)$, in dB: $PG(R)=PG_o(R) + \ell(R) + r(R)$



$PG(R)[dB]=PG_o(R) + \ell(R) + r(R)$

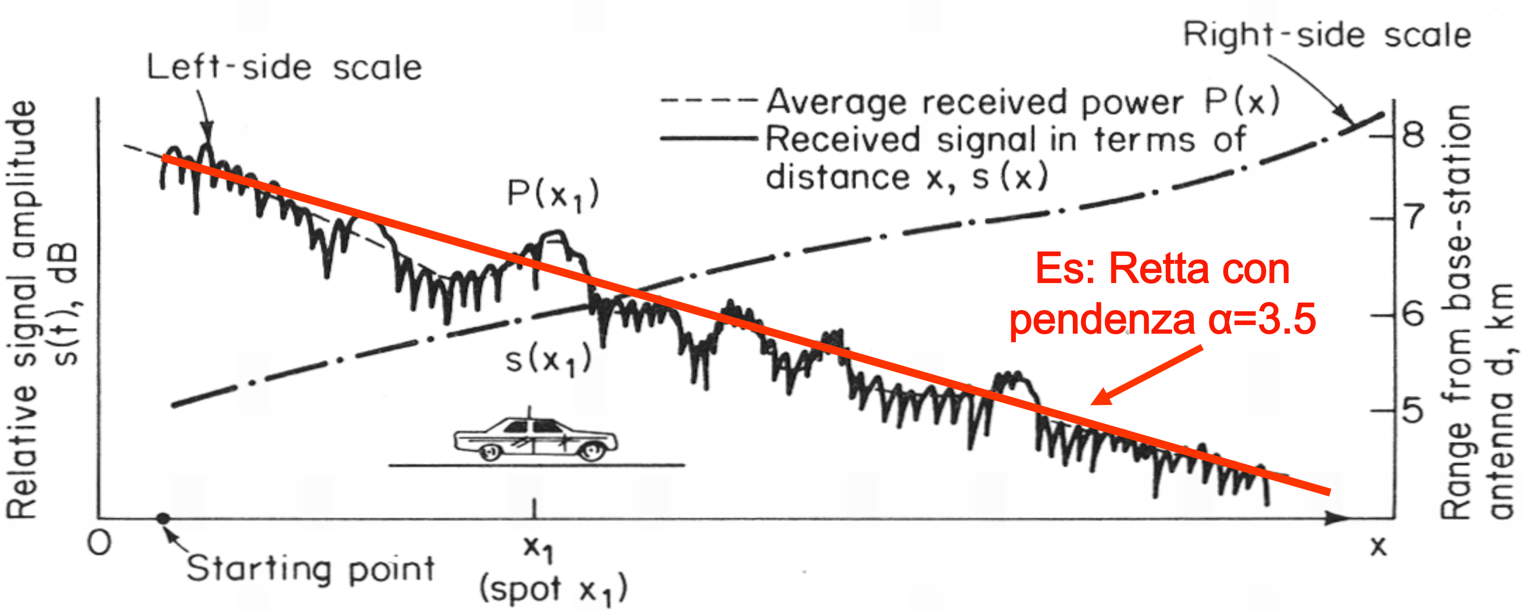
Termine dominante deterministico

Oscillazioni lente (slow fading o shadowing)

Oscillazioni rapide (fast fading).

Componenti dell' attenuazione (3/7)

1. Termine dominante funzione della distanza



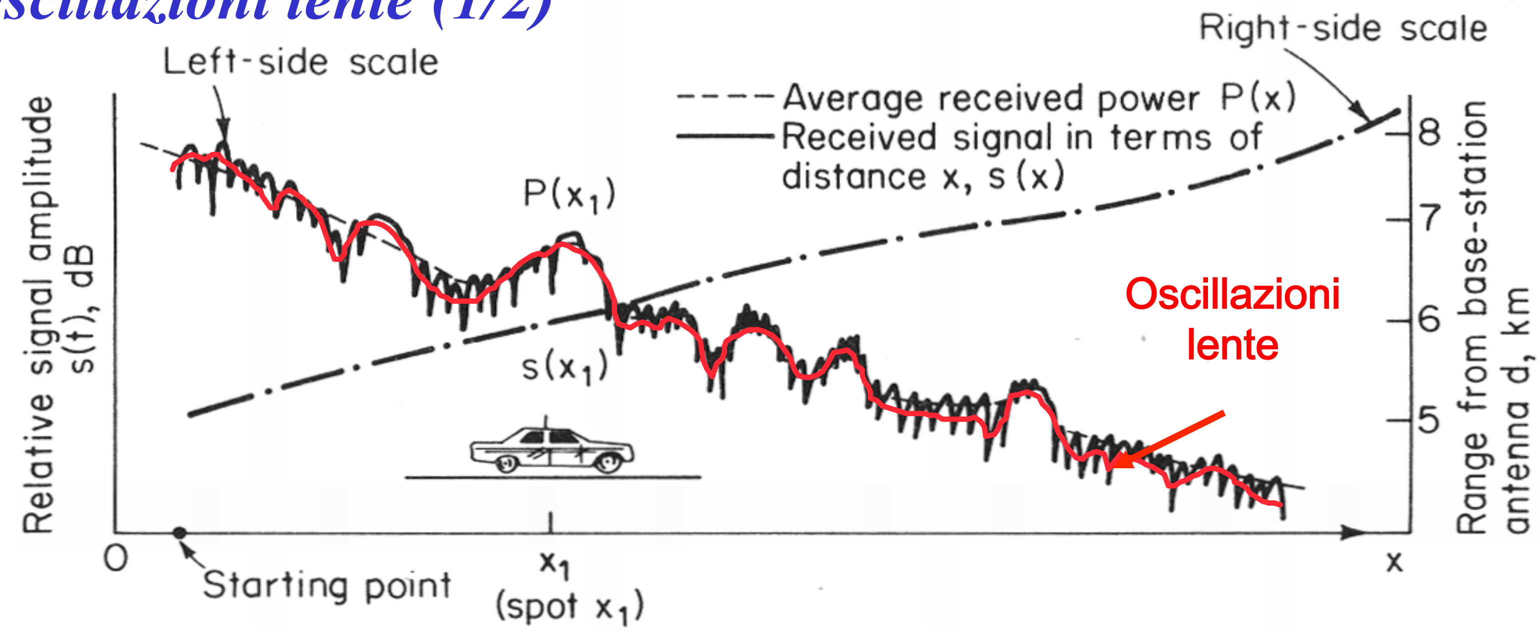
Il Path Gain si può rappresentare in funzione della distanza con un andamento del tipo:

$$PG_0 = PG(R_0)\left(\frac{R_0}{R}\right)^{\alpha} \qquad \text{con } 2 \le \alpha \le 4 \text{ (o più)}$$

α esponente/fattore di attenuazione

Componenti dell’attenuazione (4/7)

2. Oscillazioni lente (1/2)



Le oscillazioni lente ($\Delta P \sim 0$ su distanze dell’ordine di λ) possono essere descritte per mezzo di una distribuzione (p.d.f.) log-normale.

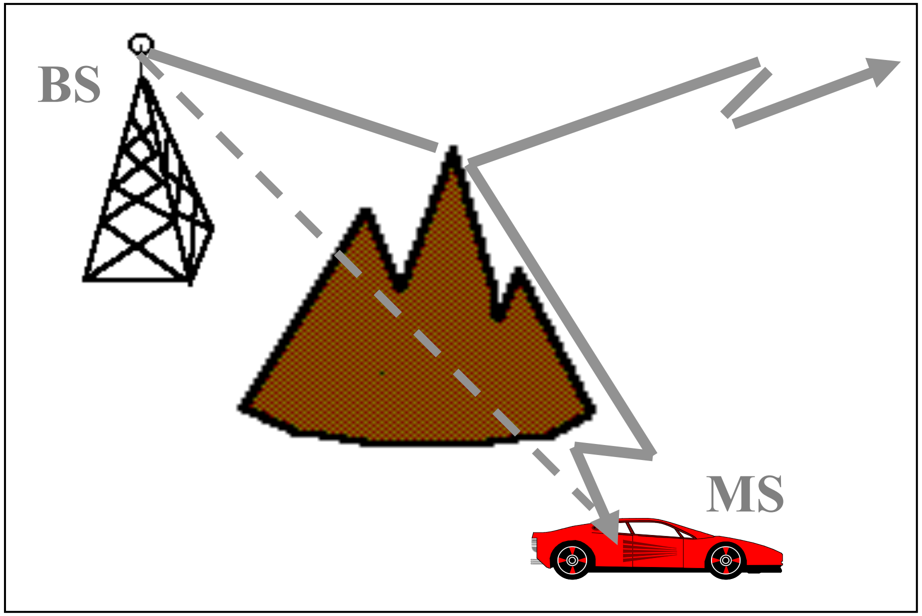
$$f_L(\ell) = \frac{1}{\sqrt{2\pi}\,\sigma\,\ell} \cdot e^{-\frac{(\ln \ell)^2}{2\sigma^2}}$$

In dB la distribuzione è Gaussiana a valor medio nullo (Normale)

Componenti dell' attenuazione (5/7)

2. Oscillazioni lente (2/2)

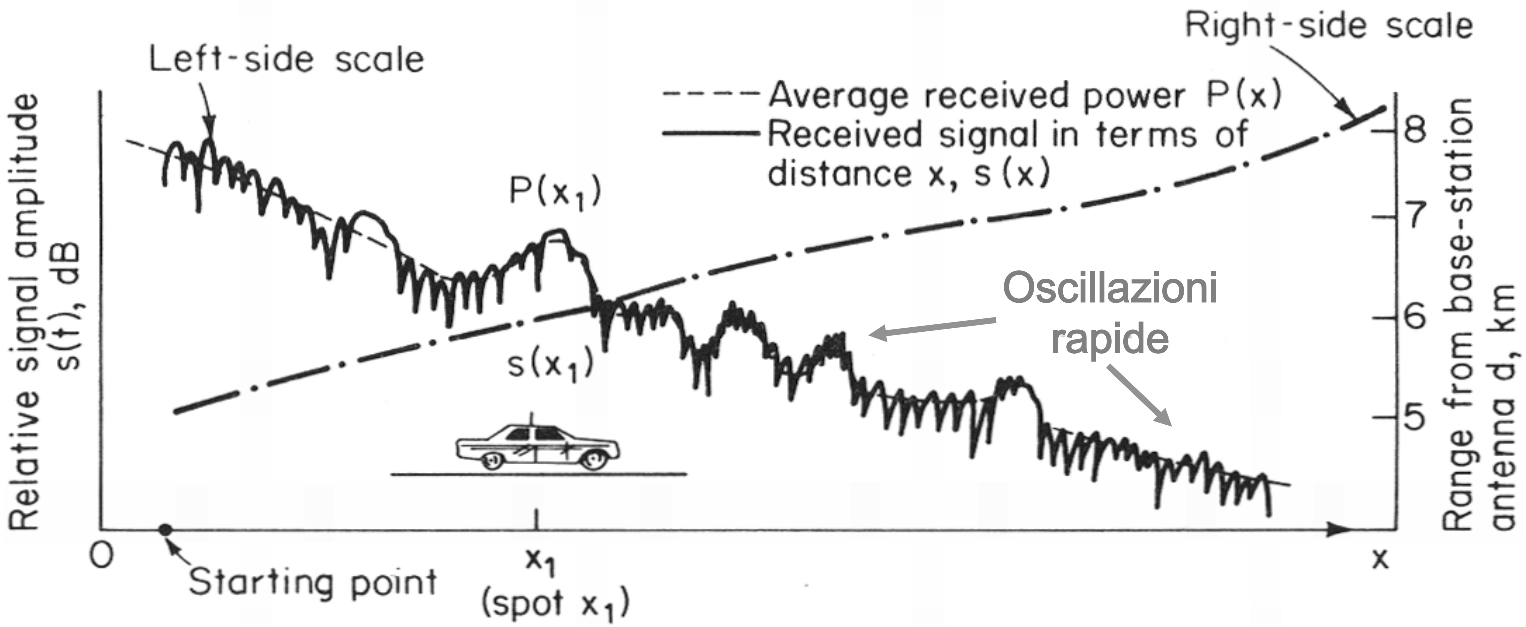
Un collegamento radiomobile è soggetto a forti ostruzioni variabili da posizione a posizione



Gli ostacoli presenti sul cammino di propagazione causano attenuazioni per ostruzione del cammino principale che sono all'origine dello ***shadowing lognormale***

Componenti dell' attenuazione (6/7)

3. Oscillazioni rapide (1/2)



Le oscillazioni rapide ($\Delta P \neq 0$ su distanze dell'ordine di λ) possono essere descritte da una distribuzione (p.d.f.) di Rayleigh (o più in generale, Rice)

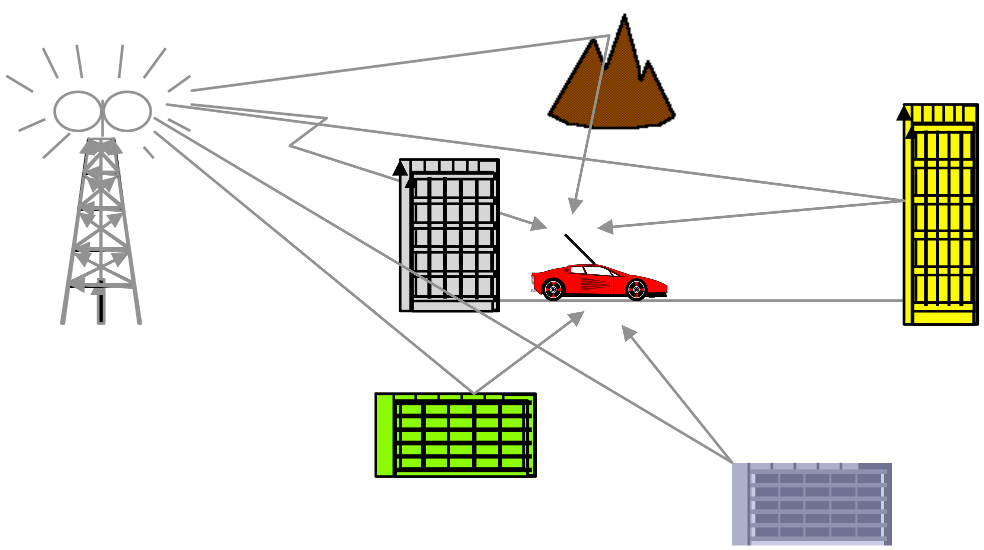
$$f_r(r) = \frac{r}{\alpha^2} \exp\left(-\frac{r^2}{2\alpha^2}\right) \qquad \text{Con} \quad E\{r\} = \alpha\sqrt{\frac{\pi}{2}}$$

Per noi dovrà essere: $E\{r\} = 1 \rightarrow \alpha = \sqrt{\frac{2}{\pi}}$

Componenti dell' attenuazione (7/7)

3. Oscillazioni rapide (2/2)

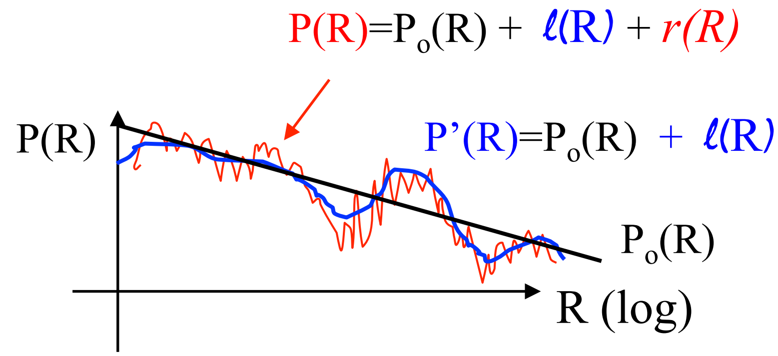
A causa dei cammini multipli ***(multipath)*** il segnale ricevuto è dato dall'*interferenza* di molti contributi che giungono al ricevitore dopo aver percorso cammini differenti e si osserva un'oscillazione per la somma fase/ controfase dei segnali, simile a quanto si osserva con la riflessione del suolo



Gli oggetti dello scenario causano *riflessione*, *trasmissione diffrazione* e *scattering* delle onde elettromagnetiche dando origine al multicammino e quindi al ***fast fading***

How to extract fading statistics from measurements?

The random process is ergodic and defined over space and therefore statistical averages can be replaced by spatial averages



Measured power over a route P(R)

↓ Sliding window $\Delta R \approx 10\lambda$

Dominant component + shadowing: P'(R)

↓ Sliding window ΔR>obstacles (regression line)

Dominant component $P_0(R)$

Sliding window filter

$$P'(R) = \frac{1}{\Delta R} \int_{R-\Delta R/2}^{R+\Delta R/2} P(\xi)\, d\xi$$

Power budget with fading: Fading margin (I)

Let' assume:

- mean attenuation (dominant component E{L}) and its statistics (cumulative distribution F(L))

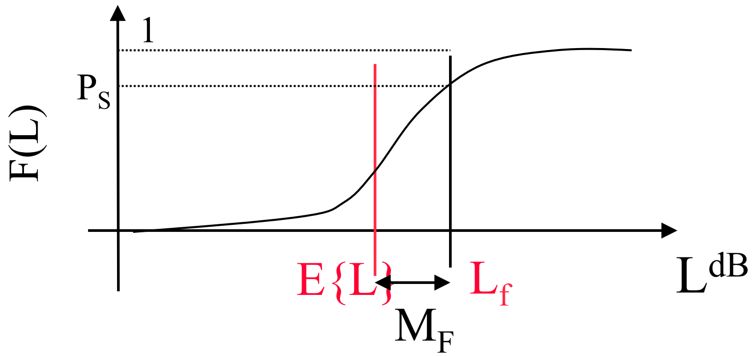
- a given <u>service probability</u> Ps (or coverage probability P_c), i.e. a given <u>outage probability</u> Pout=1-Ps

→ then the Ps–th percentile of the fading CDF must be computed, L_F

$$\boxed{L_F \ so \ that : F\left(L_F\right) = P_S}$$

An overestimated attenuation L_F must be considered when designing the radio system in presence of fading. This fictitious attenuation increase is called <u>fading margin M_F</u>

$$\boxed{M_F = L_F - E\left\{L\right\}}$$



Power budget with fading: Fading margin (II)

Moreover for coverage evaluations it is necessary to take cable/connection losses L_c into account and average antenna gains.
Therefore we get the power budget equation

$$\boxed{\begin{aligned} P_R &= P_T + G_T + G_R - L_{TOT} \\ L_{TOT} &= L(\text{model})^* + M_F + L_C \end{aligned}}$$

original formula: $P_R = P_T + G_T + G_R - L_0$

$$L_0 = 20\log\left(\frac{4\pi R}{\lambda}\right)$$

Usually only slow fading statistics is considered to compute M_F because fast fading is partly filtered out by the finite size of the Rx antenna and by other methods. Usually, an additional fixed fast-fadin margin is added in the L_{TOT} expression.

*NOTE: here and in the following slides L is used instead of E{L}

"Hata-like" models

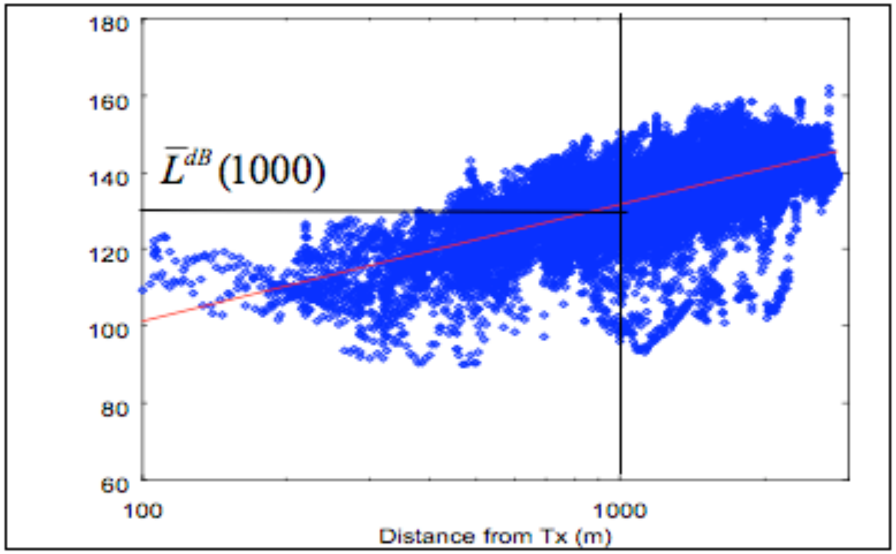
Mean path loss L as a function of distance

$$L = L(R_0)\left(\frac{R}{R_0}\right)^{\alpha} = KR^{\alpha} \quad (f.s: \alpha = 2)$$

$$in\, dB:$$

$$L^{dB}\left(R\right) = L^{dB}(R_o) - 10\alpha \log R_o + 10\alpha \log R =$$

$$= K(f,\alpha) + 10\alpha \log R$$



Es: h_{Tx} = 48 m
α = 3.05

<u>Limitations</u>

- *only mean L*
- *macrocells R >1 km*
- *low accuracy*
- *tuning needed in new environments*
- *Statistical description of fading needed*

The original Okumura-Hata model

- Its original formulation was derived by Hata in 1980 on the base of measurements performed by Okumura in Tokio in 1968

$$\boxed{L = 69.55 + 26.16 \log f - 13.82 \log h_{BS} - a\left(h_{MS}\right) + \left(44.9 - 6.55 \log \cdot h_{BS}\right) \log R^{n}}$$

f: frequency [MHz]
h_{BS}: equivalent height of the BS (if terrain is hilly)
$a(h_{MS})$: parameter related to the height of the MS (usually negligible)
R: link distance [km]

$$n = \begin{cases} 1 & \text{for } R \le 20 \text{ km} \\ 1 + \left(0.14 + 1.87 \cdot 10^{-4} * f + 1.07 \cdot 10^{-3} * h_{BS}\right) * \left(\log R / 20\right)^{0.8} & \text{otherwise} \end{cases}$$

- Applicability range: $R \ge 1\ km;\ h_{BS} \ge 30\ m$

Derived Hata-like models

- The original formulation has been specified and simplified for mobile radio systems by CCIR. The ETSI derived formulas for GSM and UMTS.

- Ex. GSM 1800:

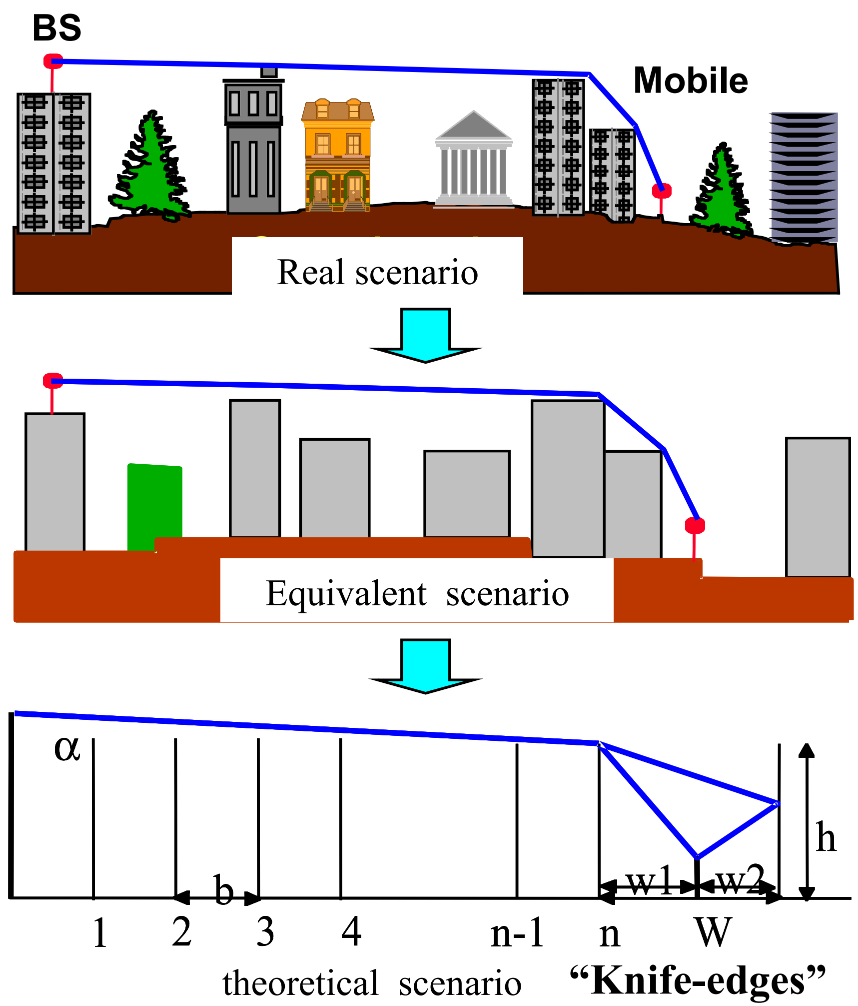
GSM 1800	Rural	Urban
Base station height (m)	60	50
Mobile stat. height (m)	1.5	1.5
Loss (Hata) (R in Km)	100.1 + 33.3 log (R)	133.2 + 33.8 log (R)
Outdoor-to indoor loss (dB)	10	15

Over-Roof-Top models

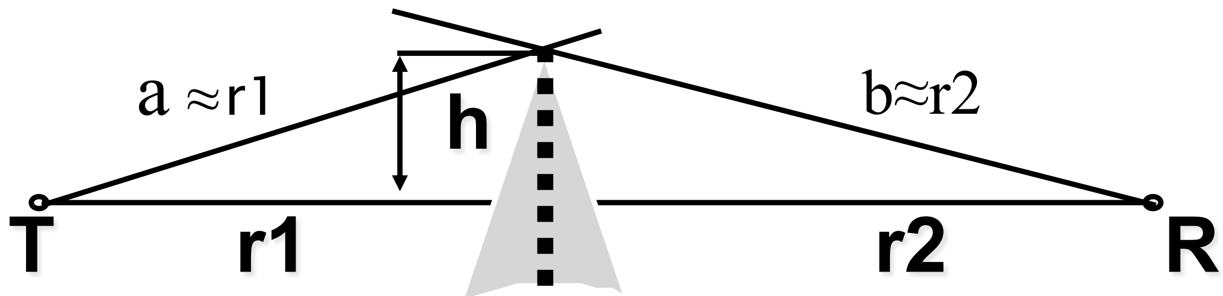
- **Epstein–Peterson**
- **Deygout**
- **Walfish-Ikegami**
- **COST 259**
- **Saunders-Bonar**

ORT models are "hybrid" because they need some deterministic info on The environment (link profile)

All refer to a representation of The radio link profile with ***Knife-edges***



Single "knife-edge" diffraction



a , b, r1, r2 >> h

Fresnel's parameter

$$v_0 = h\sqrt{\frac{2}{\lambda}\frac{a+b}{ab}}\left(=\frac{h}{\rho_1}\sqrt{2}\right)$$

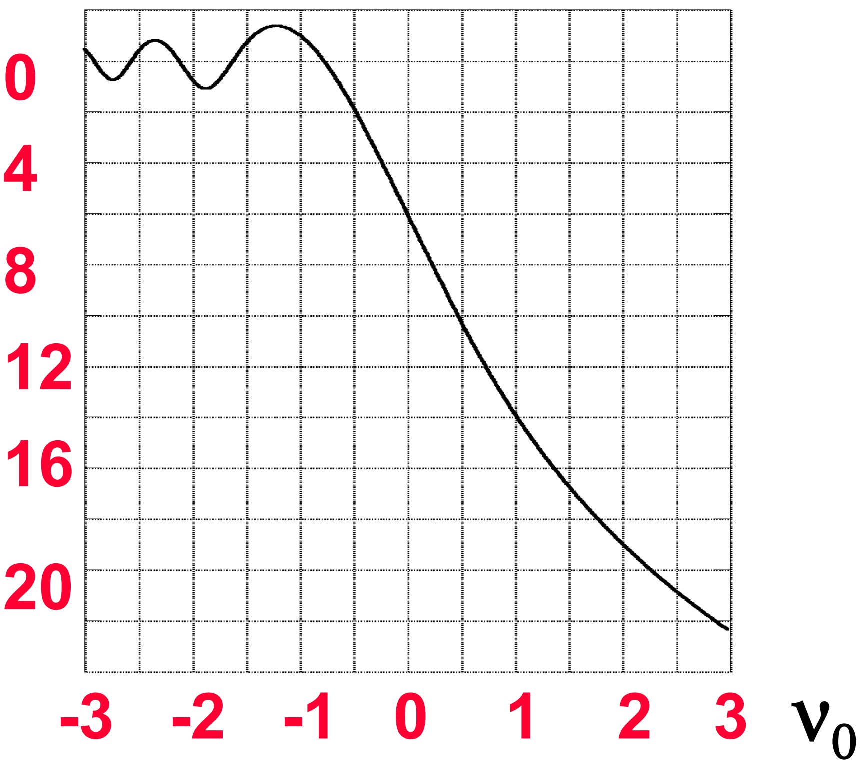
Approximate excess PG
(Kirchhoff scalar theory [*])

$$\sqrt{PG} = \frac{E}{E_o} = \frac{1+j}{2}\int_{v_0}^{\infty} e^{-j(\pi/2)x^2}\, dx$$

[*]W. C. Y. Lee, *Mobile Communications Engineering*, Mc Graw Hill, New York 1982

Kirckhhoff Path loss graph

Excess Path loss $L_S(\nu_0)$ (dB)



$$L_S(\nu_0)(dB) = -20\log\left|\frac{E}{E_o}\right|$$

$$= -20\log\left|\frac{1+j}{2}\int_{\nu_0}^{\infty} e^{-j(\pi/2)x^2}\,dx\right|$$

Lee's simplified attenuation formulas [*]

$$L_S(v_0)=\begin{cases} -20\log\left(0.5-0.62v_0\right) & \text{-0.8}<v_0<0 \\ -20\log\left[0.5\exp\left(-0.95v_0\right)\right] & 0<v_0<1 \\ -20\log\left[0.4-\left\{0.1184-\left(0.38-0.1v_0\right)^2\right\}^{1/2}\right] & \\ \quad 1<v_0<2.4 & \\ -20\log\left[\dfrac{0.225}{v_0}\right] & v_0>2.4 \end{cases}$$

[*]W. C. Y. Lee, *Mobile Communications Engineering*, Mc Graw Hill, New York 1982

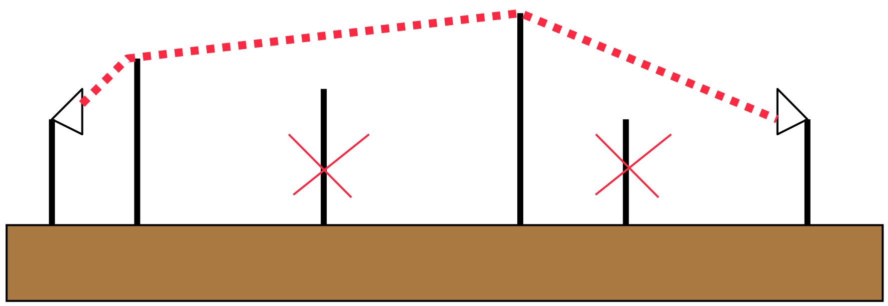
Multiple "knife-edge" diffraction

- While a closed-form expression for single knife edge diffraction is available, it is not so for multiple knife edge diffraction. There are solutions for two knife edges (Millington) but only iterative solutions are available for a higher number of k.e.'s.

- Therefore ***heuristic*** methods have been developed which consist of arbitrary geometric constructions conceived so as to resort to multiple computations of single-knife-edge diffraction losses

The Tight rope/Epstein-Peterson method

- The *tight rope method* is a profile-simplification method:
  - ***An ideal elastic rope is stretched over the link profile. Only those knife-edges which are touched by the rope are selected, the others are dropped***

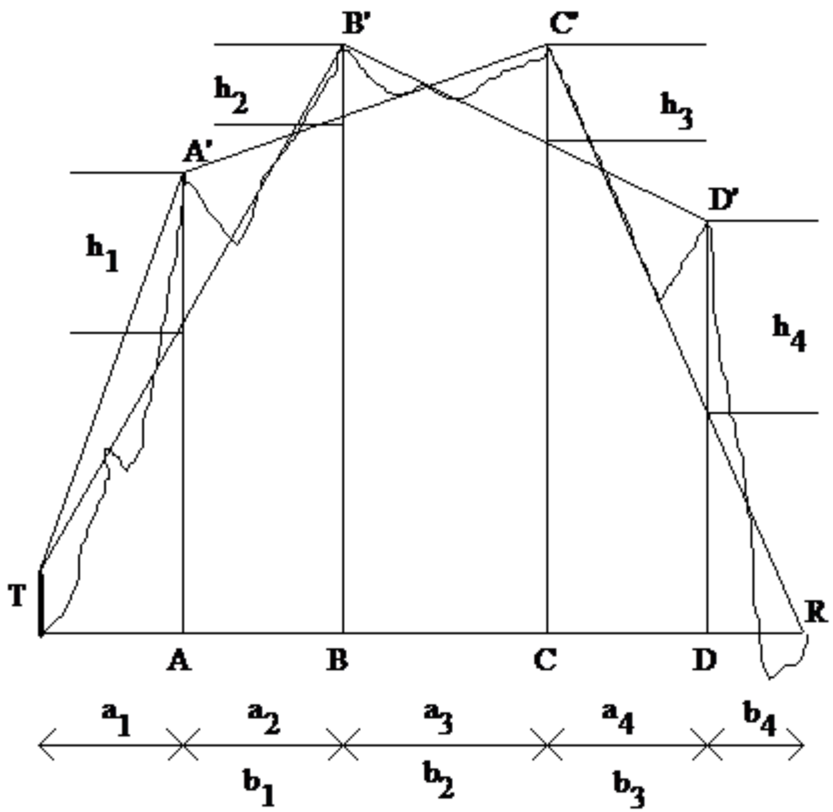


- The E.P method is based on a decomposition of the path in sub-paths each one experiencing only one knife-edge diffraction

- The excess loss is computed as a product of each single sub-path loss. The E.P method is not very accurate for a number of obstacles > 4-5

The Epstein-Peterson method (II)

A partial path is associated to each obstacle which spans from the preceding to the following obstacles (virtual Tx and Rx, respectively)



$$\sqrt{L_{S\_TOT}} = \prod_{i=1}^{n_o} \left| \frac{1}{\frac{1+j}{2} \int_{\nu_{0i}}^{+\infty} e^{-j\frac{\pi}{2}\nu^2} d\nu} \right|$$

ν_{0i} is the Fresnel's parameter for the i-th obstacle

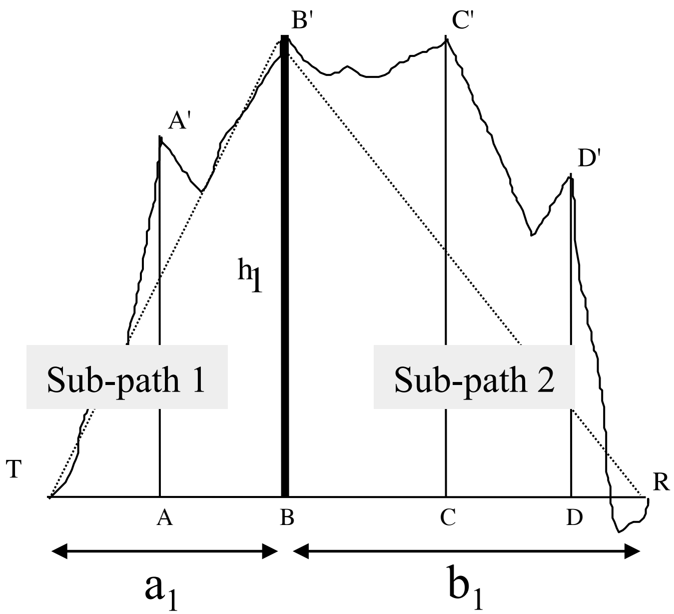
$$\nu_{0i} = h_i \sqrt{\frac{2}{\lambda} \frac{a_i + b_i}{a_i b_i}} \quad i = 1,...N$$

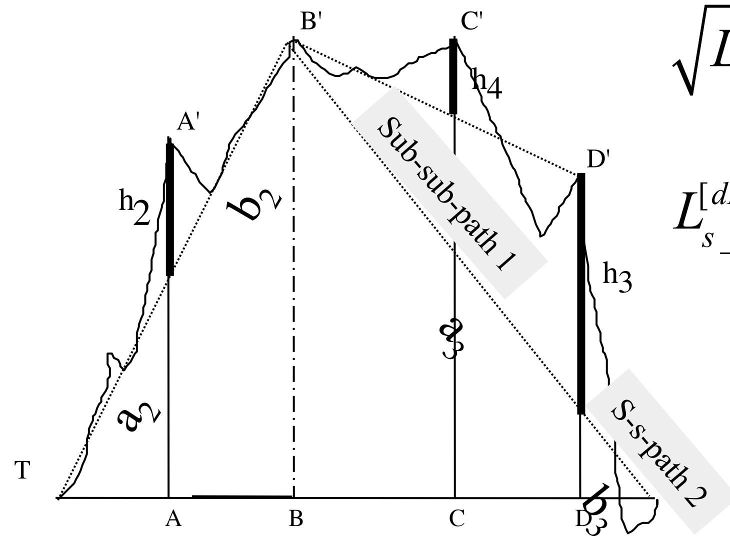
h_i a_i b_i are shown in the figure. Notice that the h_i values are measured *from* the Tx-Rx line of sight

The Deygout method

Differs from the EP method only in the geometrical construction of each single sub-path. The first sub-path is the actual path with only the “main” knife-edge as obstacle. Then the main k.e. defines 2 sub-paths on his lef and right…

At the i-th iteration the main knige-edge is the one with the greatest Fresnel’s parameter





$$\sqrt{L_{s\_tot}} = \prod_{i=1}^{N} \sqrt{L_{s\_i}}$$

$$L_{s\_tot}^{[dB]} = \sum_{i=1}^{N} L_{s\_i}^{[dB]}$$

The advantage over the EP method is that accuracy is good even without prior application of tight-rope method.

The Saunders and Bonar method (outline)

It's the combination of two different methods
Flat edge method: computes the loss due to a uniform series of knife-edges
Voegler's method[*] : allows the computation of the loss due to an arbitrary series of knife-edges (limited number of k.e.'s for CPU time reasons) using a recursive algorithm

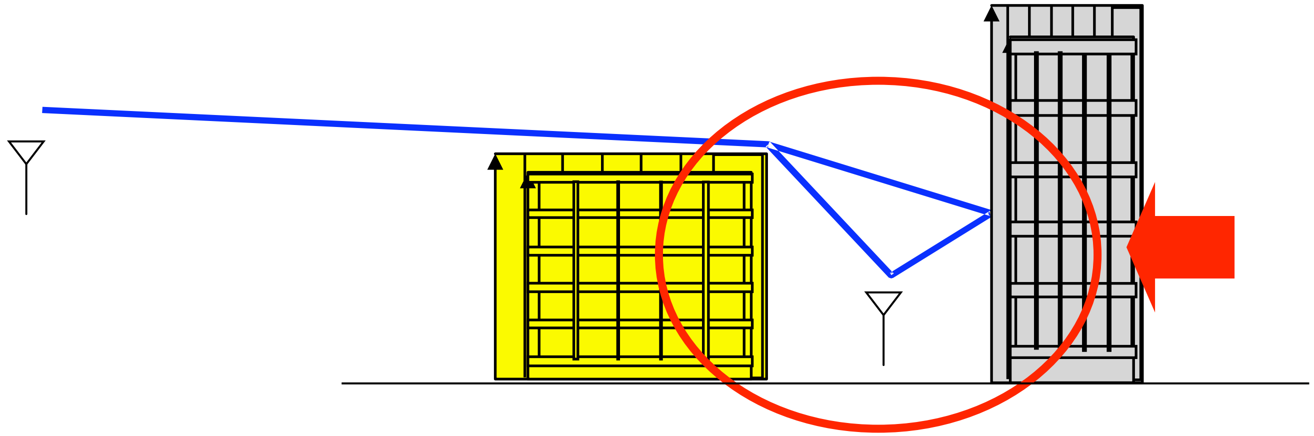
At first the loss L_1 due to a mean, uniformized profile is computed with the Flat Edge method. Then the original profile is simplified (e.g. with the tight rope method) reducing it to a low number of knife edges. Thus the loss L_2 is computed and the final excess loss is obtained as a combination of L_1 and L_2

The Saunders and Bonar method, although quite complex is the most accurate heuristic ORT method.

[*] L. E. Voegler, "An attenuation function for multiple knife-edges diffraction," Radio Sci., Vol. 17, No. 6, pp. 1541-1546, 1982

Additional notes on ORT methods

- ***ORT*** models only predict multiple diffraction loss along the radial
- ***Roof-to-street*** propagation, including reflections etc. is not included
- Specific ray models for roof-to-street propagation have been developed



Il Modello Nazionale Italiano GSM

E' stato sviluppato negli anni 90' per certificare la copertura degli operatori mobili GSM allora operanti in Italia

$$L_{tot} = L_{base} + L_{diff} - F_{amb}$$

Okumura Hata

E.P corretto

Tiene conto dei diversi ambienti

Ambiente	Percentuale di edificato	Famb
Area urbana densa	**> 35%**	**-6 dB**
Area urbana media	**da 15% a <35%**	**2 dB**
Area urbana a bassa densità	**da 8% a 15%**	**10dB**
Area suburbana	**da 3% a 8%**	**15 dB**
Area aperta con vegetazione	**< 3%**	**24 dB**
Area aperta	**< 3%**	**29 dB**
Acqua	**-**	**32 dB**

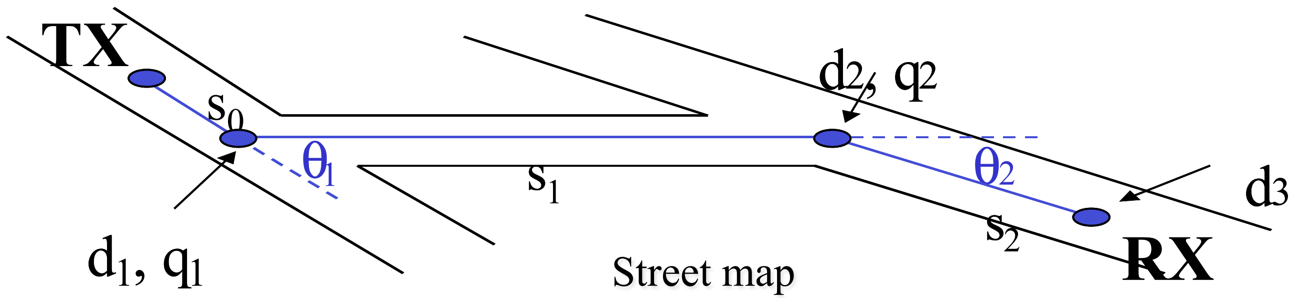
Simplified, hybrid models

- A simplified model is any kind of model which takes spatial granularity and LP into account in a “simplified way”

- Simplified models need some kind of deterministic information on environment topology, not only on link profile. Therefore can also be defined hybrid models.

- Tuning with measurements is often necessary

Berg's model [*] (1/2)



A street path (polygonal line) connecting the terminal is considered
Street corners are replaced by nodes with concentrated street-corner losses

s_j: j-th physical distance
d_j: j-th effective distance
q_j: j-th loss factor [m^{-1}]

Total attenuation at the *n-th* node:

$$L_{dB}^{(n)} = 20\log\left(\frac{4\pi d_n}{\lambda}\right)$$

$$\begin{cases} k_j = k_{j-1} + d_{j-1} \cdot q_{j-1} \\ d_j = k_j \cdot s_{j-1} + d_{j-1} \end{cases} \qquad k_1 = 1,\ d_0 = 0$$

Limitations
- *only L*
- *only LP*
- *microcells, small distance*
- *tuning needed*

[*] Berg, J.-E, "A recursive method for street microcell path loss calculations," PIMRC'95, 27-29 Sept, 1995.

Berg's model (2/2)

q_j values are model parameters, which need to be tuned.
q_j must increase with θ_j. If $\theta=0$ then $q=0$, there is no corner loss; if $\theta=90°$ appropriate values for q are 0.3-1

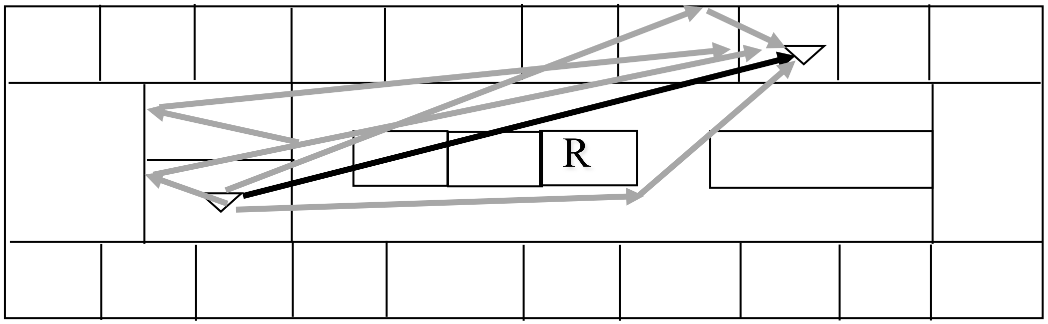
A simple heuristic formula for example is:

$$q_j(\theta_j) = \left(\theta_j \cdot \frac{q_{90}}{90}\right)^{\nu}$$

with $q_{90}=0.5$ and $\nu=1.5$

An improved version of the model to account for dual-slope power attenuation with distance (terrain reflection) is also available.

Multi-Wall indoor Model [*] (1/2)



The MWM is based on the fact that there is always a multi-transmitted dominant path. Therefore, total loss L_{dB} along this path is computed by summing multiple transmission losses to free space attenuation

Limitations

- *indoor env.*
- *small distances*
- *tuning needed*
- *building map needed*

$$L_{dB} = 20\log\left(\frac{4\pi R}{\lambda}\right) + L_c + \sum_{i=1}^{N_{type}} N_{wi} L_{wi} + N_f L_f$$

Where:

L_c=constant loss

N_{wi}=n. of penetrated walls of type i

L_{wi}= loss of walls of type i

N_f=n. of penetrated floors

L_f=floor loss

N_{type}=n. of wall types

[*] COST Action 231 "Digital mobile radio towards future generation systems" Final Report, 1999

Multi-Wall indoor Model (2/2)

Since floor penetration loss empirically appears to be non-linear with the number of penetrated floors, then an improved version of the MWM model has been proposed

$$L_{dB} = 20\log\left(\frac{4\pi R}{\lambda}\right) + L_c + \sum_{i=1}^{N_{type}} N_{wi} L_{wi} + N_f^{\left(\frac{N_f+2}{N_f+1}-b\right)} L_f$$

Where:
b=empirical parameter

Typical parameter values are:
L_c= 0 dB
L_w= 3-5 dB
L_f=15-20dB
b=0.46

Linear attenuation indoor model [*]

It is based on the following loss expression

$$L_{dB} = 20\log\left(\frac{4\pi R}{\lambda}\right) + \alpha_S R$$

or, with a reference distance:

$$L_{dB} = L[R_o] + 20\log\left(\frac{R}{R_o}\right) + \alpha_S\left(R - R_o\right)$$

If α_S is the additional "***specific attenuation***" [dB/m] it is clear that the linear attenuation model and the simpler version of the MWM model are very similar, especially if wall spacing is uniform.
The former however neglects spatial granularity while the latter doesn't.

[*] COST Action 231 "Digital mobile radio towards future generation systems" Final Report, 1999