Path loss models

S-72.333 Physical layer methods in wireless communication systems

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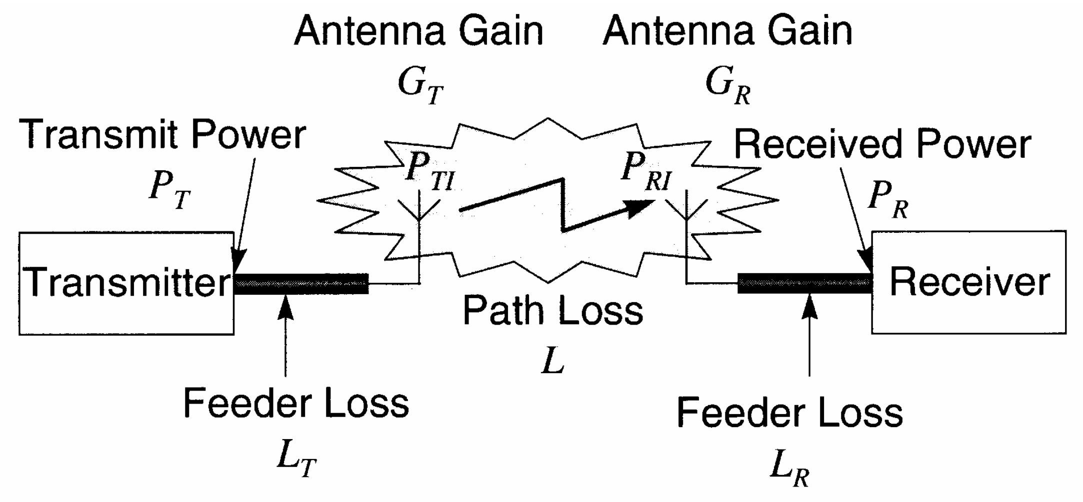
Line out

Definition of path loss :

The path loss is the difference (in dB) between the transmitted power and the received power

↳ Represents signal level attenuation caused by free space propagation, reflection, diffraction and scattering

➡ Necessary to calculate **link budget**



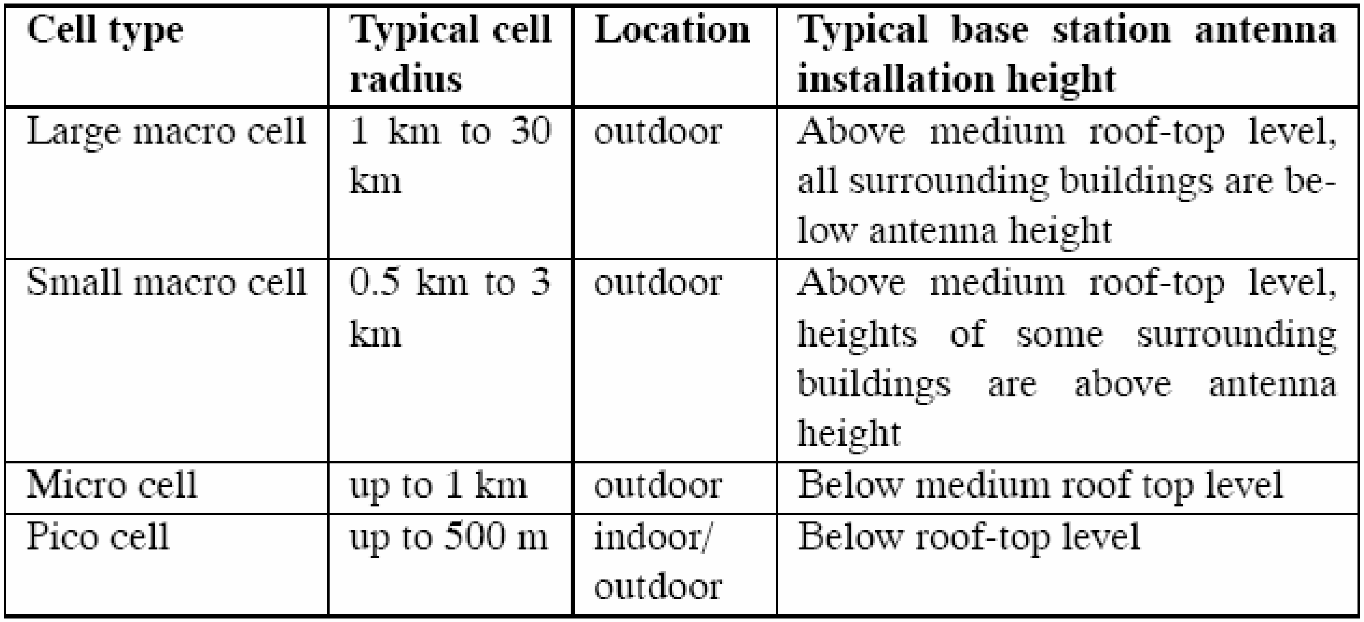
Three kinds of models

- **Empirical models**
- **Semi-deterministic models**
- **Deterministic models**

- **Empirical models :** based on measurement data, simple (few parameters), use statistical properties, not very accurate
- **Semi-deterministic models :** based on empirical models + deterministic aspects
- **Deterministic models :** site-specific, require enormous number of geometry information about the cite, very important computational effort, accurate

Different types of cells :

- each model is define for a specific environement



Cell type	**Typical cell radius**	**Location**	**Typical base station antenna installation height**
Large macro cell	1 km to 30 km	outdoor	Above medium roof-top level, all surrounding buildings are below antenna height
Small macro cell	0.5 km to 3 km	outdoor	Above medium roof-top level, heights of some surrounding buildings are above antenna height
Micro cell	up to 1 km	outdoor	Below medium roof top level
Pico cell	up to 500 m	indoor/ outdoor	Below roof-top level

2. Macrocell path loss models

2.1 Empirical models

Why empirical models, so called “simplified models” ?

↳ Purely theoretical treatment of urban and suburban propagation is very complicated

- ➡ Not all required geometric descriptions of coverage area are available (e.g. description of all trees, buildings etc…)
- ➡ Excessive computational effort

Important parameter for cells designer : overall area covered

NOT the specific field strength at particular locations

Example

To remove effect of fast fading :

➡ each measurement = average of set of samples : *local mean*

(small area around 10-50 m)

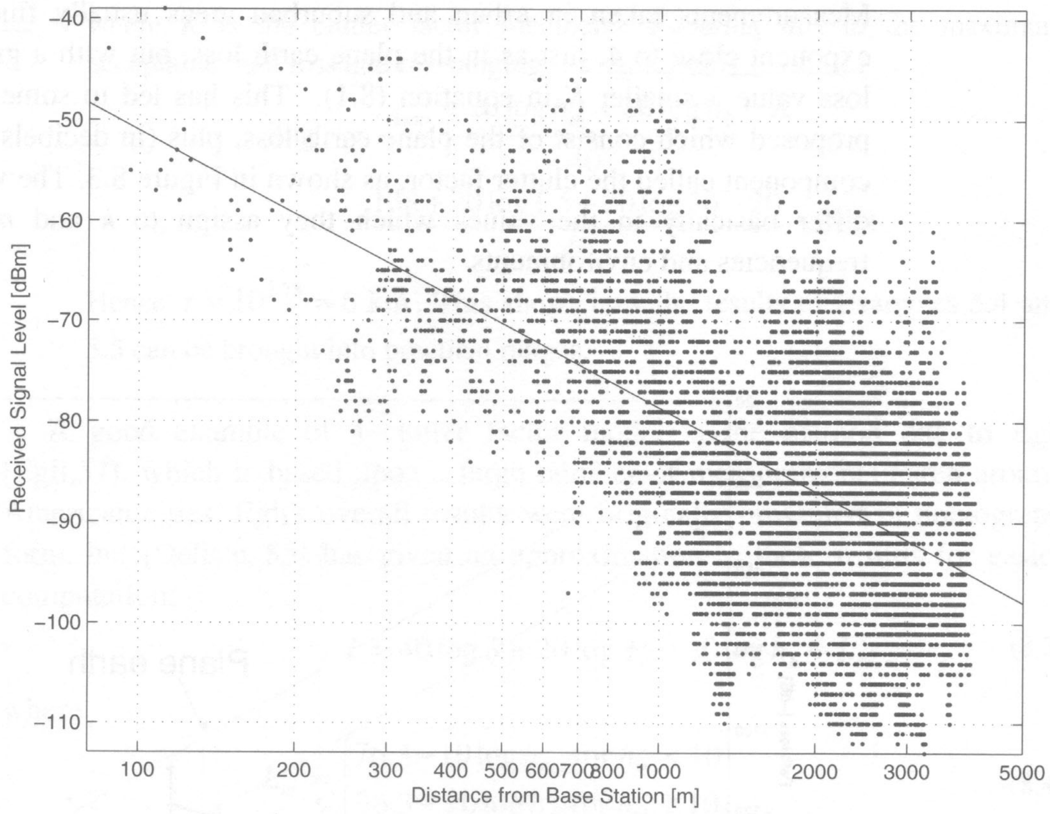


Figure 8.2: Empirical model of macrocell propagation: the dots are measurements taken in a suburban area and the line represents a best-fit empirical model

Okumura-Hata model [1]

Most popular model

Based on measurements made in and around Tokyo in 1968

↳ between 150 MHz and 1500 MHz

- Predictions from series of graphs ➡ approximate in a set of formulae (Hata)
- Output parameter : mean path loss (median path loss) L_{dB}
- Validity range of the model :
  - Frequency f between 150 MHz and 1500 Mhz
  - T_X height h_b between 30 and 200 m
  - R_X height h_m between 1 and 10 m
  - T_X - R_X distance r between 1 and 10 km

Okumura-Hata model cont.

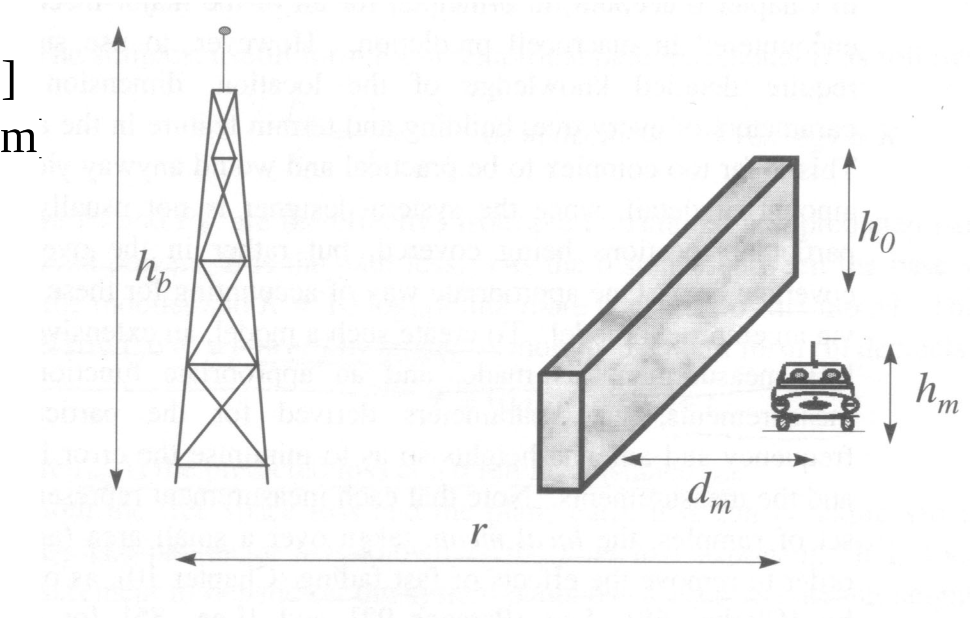
3 types of prediction area :

- Open area : open space, no tall trees or building in path
- Suburban area : Village Highway scattered with trees and house
  Some obstacles near the mobile but not very congested
- Urban area : Built up city or large town with large building and houses
  Village with close houses and tall

Okumura-Hata model cont.

Definition of parameters :

h_m	mobile station antenna height above local terrain height [m]
d_m	distance between the mobile and the building
h_0	typically height of a building above local terrain height [m]
h_b	base station antenna height above local terrain height [m]
r	great circle distance between base station and mobile [m]
$R=r \times 10^{-3}$	great circle distance between base station and mobile [km]
f	carrier frequency [Hz]
$f_c=f \times 10^{-6}$	carrier frequency [MHz]
λ	free space wavelength [m



Okumura-Hata model cont.

- Okumura takes urban areas as a reference and applies correction factors

Urban areas : $L_{dB} = A + B \log_{10} R - E$

Suburban areas : $L_{dB} = A + B \log_{10} R - C$

Open areas : $L_{dB} = A + B \log_{10} R - D$

$A = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} \mathrm{hb}$

$B = 44.9 - 6.55 \log_{10} h_b$

$C = 2 (\log_{10} (f_c / 28))^2 + 5.4$

$D = 4.78 (\log_{10} f_c)^2 + 18.33 \log_{10} f_c + 40.94$

$E = 3.2 (\log_{10} (11.7554\, h_m))^2 - 4.97$ for large cities, $f_c \geq 300\text{MHz}$

$E = 8.29 (\log_{10} (1.54\, h_m))^2 - 1.1$ for large cities, $f_c < 300\text{MHz}$

$E = (1.1 \log_{10} f_c - 0.7)\, h_m - (1.56 \log_{10} f_c - 0.8)$ for medium to small cities

COST 231-Hata model [1][5]

Okumura-Hata model for medium to small cities has been extended to cover 1500 MHz to 2000 MHz (1999)

$$L_{dB} = F + B\,log_{10}\,R - E + G$$

$$F = 46.3 + 33.9\,\log_{10} f_c - 13.82\,\log_{10} h_b$$

E designed for medium to small cities

$$G = \begin{cases} 0 \text{ dB medium sized cities and suburban areas} \\ 3 \text{ dB metropolitan areas} \end{cases}$$

COST 231-Hata model cont.

Accuracy

Extensive measurement in Lithuania [8] at 160, 450, 900 and 1800MHz :
- Standard deviation of the error = 5 to 7 dB in urban and suburban environment
- Best precision at 900 MHz in urban environment
- In rural environment : standard deviation increases up to 15 dB and more

Measurements in Brazil at 800 / 900 MHz :
- mean absolute error = 4.42 dB in urban environment
- standard deviation of the error = 2.63 dB

➡ path loss prediction could be more accurate
➡ but models are not complex and fast calculations are possible
➡ precision greatly depends on the city structure

2.2 Semi-empirical models

COST 231-Walfisch-Ikegami [2][5]

Cost 231-WI takes the characteristics of the city structure into account :

- Heights of buildings h_{Roof}
- Widths of roads w
- Building separation b
- Road orientation with respect to the direct radio path Φ

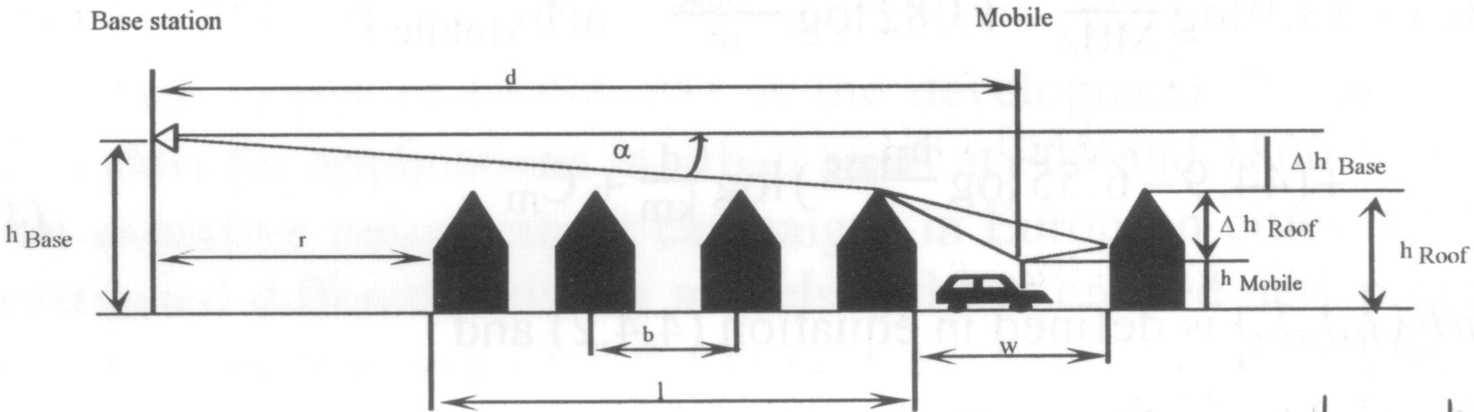
↳ increases accuracy of the propagation estimation

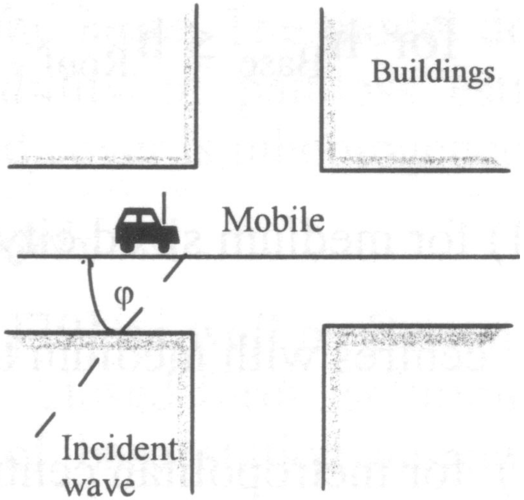
➡ more complex

N.B. allows estimation **from 20 m** (instead of **1 km** for Okumura-Hata model)

Output parameter : mean path loss

COST 231-Walfisch-Ikegami cont.





Restrictions :

- Frequency f between 800 MHz and 2000 Mhz
- T_X height h_{Base} between 4 and 50 m
- R_X height h_{Mobile} between 1 and 3 m
- T_X - R_X distance d between 0.02 and 5 km

COST 231-Walfisch-Ikegami cont.

2 cases : LOS and NLOS

LOS :

$L_{LOS}\,[\text{dB}] = 42.6 + 26 \log_{10} d[\text{km}] + 20 \log_{10} f\,[\text{MHz}]$

NLOS :

$L_{NLOS}\,[\text{dB}] = L_{FS} + L_{rts}\,(w_r, f, \Delta h_{Mobile}, \Phi) + L_{MSD}\,(\Delta h_{Base}, h_{Base}, d, f, b_S)$

L_{FS} = free space path loss = $32.4 + 20 \log_{10} \text{d[km]} + 20 \log_{10} f\,[\text{MHz}]$

L_{rts}= roof-to-street loss

L_{MSD}= multi-diffraction loss

COST 231-Walfisch-Ikegami cont.

$$L_{rts} = -8.8 + 10\log_{10}(f\,[\mathrm{MHz}]) + 20\log_{10}(\Delta h_{Mobile}[\mathrm{m}]) - 10\log_{10}(w\,[\mathrm{m}]) + L_{ori}$$

L_{ori} = street orientation function

$$L_{ORI} = \begin{cases} -10 + 0.35\,\Phi & 0 \leq \Phi < 35^\circ \\ 2.5 + 0.075\,(\Phi - 35) & 35^\circ \leq \Phi < 55^\circ \\ 4.0 - 0.114\,(\Phi - 55) & 55^\circ \leq \Phi < 90^\circ \end{cases}$$

$$L_{MSD} = L_{bsh} + k_a + k_d \log_{10}(d\,[\mathrm{km}]) + k_f \log_{10}(f\,[\mathrm{MHz}]) - 9\log_{10}(b)$$

$$\text{Where } L_{bsh} = \begin{cases} -18\log_{10}(1 + \Delta h_{Base}) & h_{Base} > h_{Roof} \\ 0 & h_{Base} \leq h_{Roof} \end{cases}$$

COST 231-Walfisch-Ikegami cont.

$$k_a = \begin{cases} 54 & h_{Base} > h_{Roof} \\ 54 - 0.8\,\Delta h_{Base} & d \geq 0.5\text{ km},\ h_{Base} \leq h_{Roof} \\ 54 - 0.8\,\Delta h_{Base}\, d\,[\text{km}] / 0.5 & d < 0.5\text{ km},\ h_{Base} \leq h_{Roof} \end{cases}$$

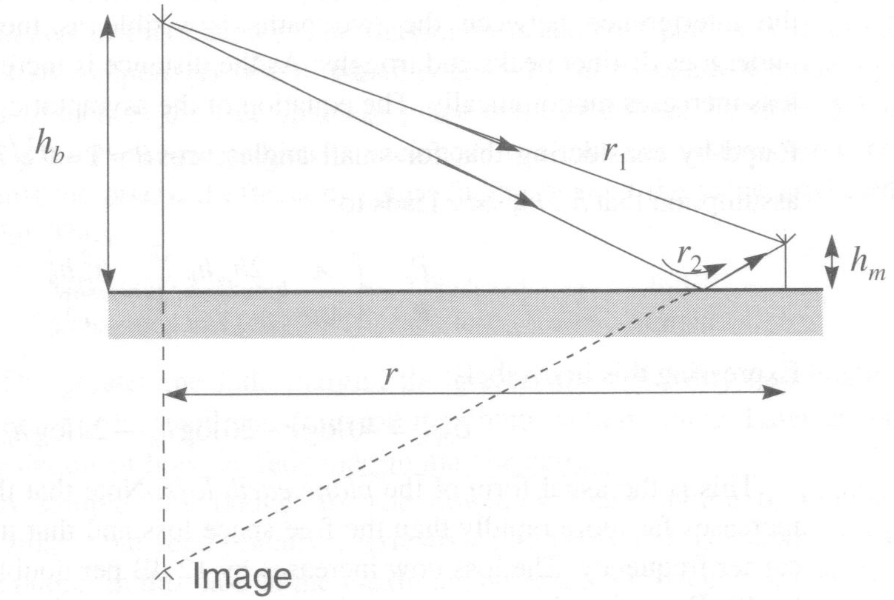
$$k_d = \begin{cases} 18 & h_{Base} > h_{Roof} \\ 18 - 15\,\Delta h_{Base} / h_{Roof} & h_{Base} \leq h_{Roof} \end{cases}$$

$$k_f = -4 + \begin{cases} 0.7\,(f / 925 - 1) & \text{medium sized city} \\ 1.5\,(f / 925 - 1) & \text{metropolitan center} \end{cases}$$

Clutter Factor model - Plane earth model [1]

Plane earth model : deterministic model

Propagation : direct path + reflection from ground



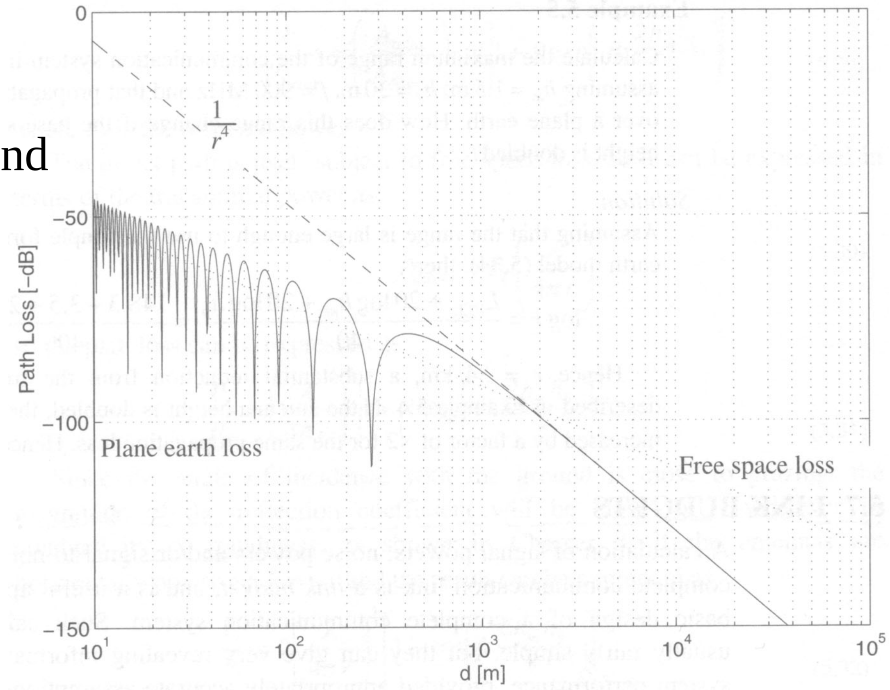


Figure 5.6: Plane earth loss (–), free space loss (…), approximate plane earth loss (– –) from (5.34). Here $h_m = 1.5$ m, $h_b = 30$ m, $f = 900$ MHz

Plane earth loss : $L_{\text{PEL}} = 40 \log_{10} r - 20 \log_{10} h_m - 20 \log_{10} h_b$ $\qquad h_m,\ h_b << r$

➡ Not accurate when taken in isolation

Clutter Factor model [1]

Measurements in urban and suburban areas :

path loss exponent close to 4 (like in plane earth model)

➡ model : based on plane earth loss + clutter factor

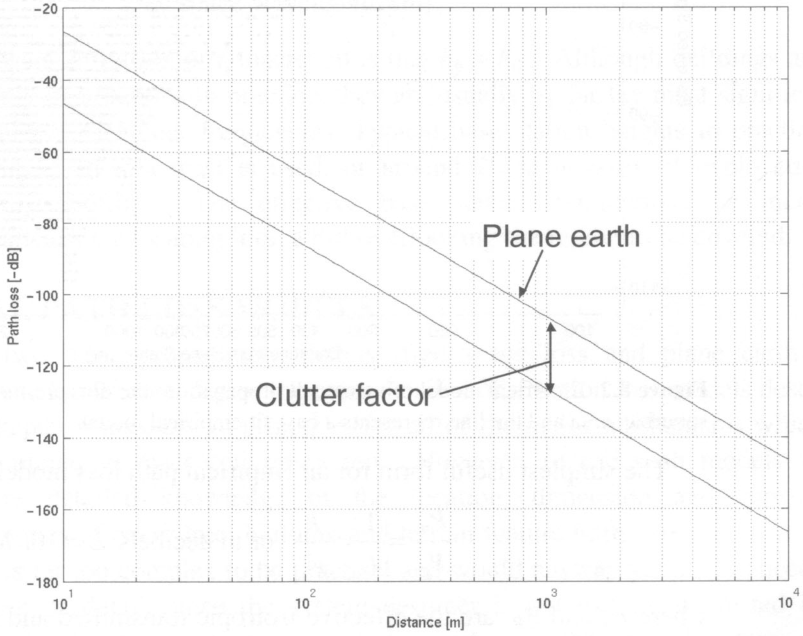


Figure 8.3: Clutter factor model. Note that the *y*-axis in this figure and in several to follow is the negative of the propagation loss in decibels. This serves to make clear the way in which the received power diminishes with distance

2.3 Deterministic models

➡ Based on theory (propagation mechanisms)

Deterministic models estimate propagation of radio wave **analytically**

- two different approaches : solving electromagnetic formulas and ray tracing

➡ solving electromagnetic formulas : extremely complicated

⤷ ray tracing : most widely used (requires a lot of computing power)

Ray tracing [6][7]

➡ based on geometrical optics (GO)

↳ used to modelling reflection and refraction of optical rays.

if *f* < 10 GHz : diffraction has to be taken into account

↳ different diffraction models are added to GO as extensions

➡ Two methods for ray tracing : **ray imaging** and **ray launching**

Ikegami model [1]

➡ entirely deterministic prediction of field strengths at specified points

- Using detail map of building heights, shapes and positions ➡ trace ray paths

  Restriction : only single reflection from wall accounted for

- Diffraction calculated using single edge approximation

- Wall reflection are assumed to be fixed at constant value

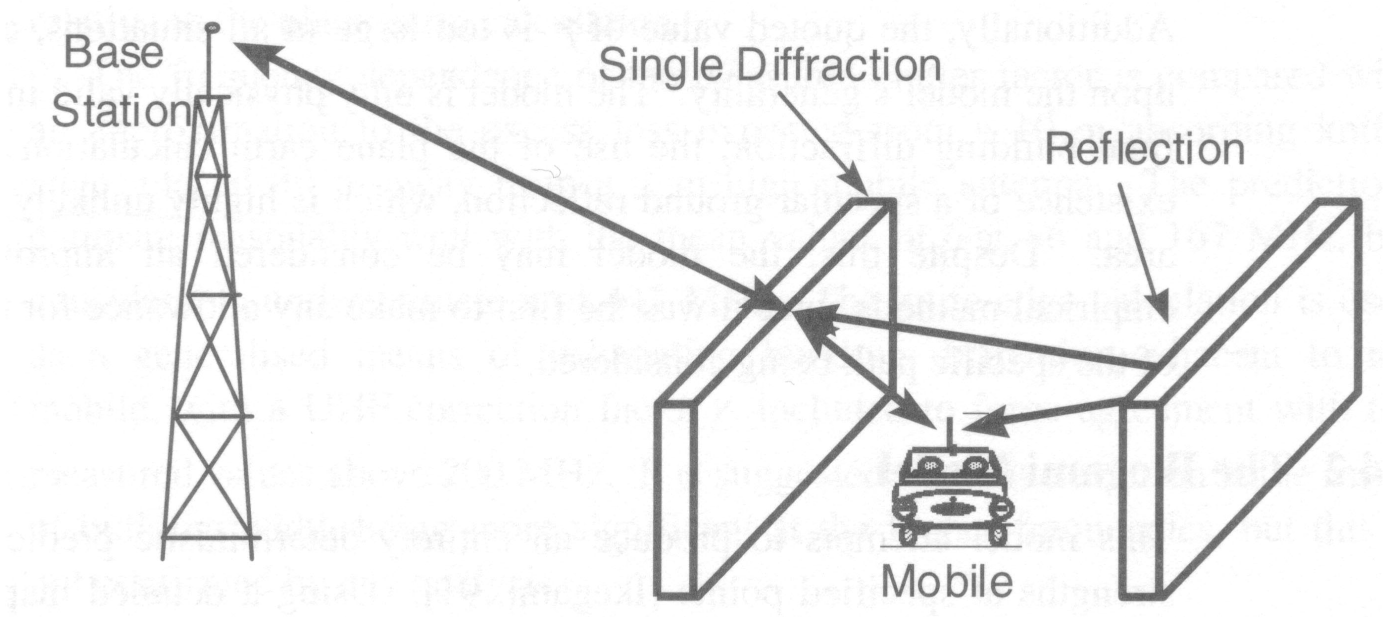
➡ two ray (reflected, diffracted) are power summed :

$$L_E = 10\log_{10} f_c + 10\log_{10}(\sin\phi) + 20\log_{10}(h_0 - h_m) - 10\log_{10} w - 10\log_{10}\left(1 + \frac{3}{L_r^2}\right) - 5.8$$

Φ= angle between the street and the direct line from base to mobile

L_r = reflection loss = 0.25

Ikegami model cont.



- model tends to underestimate loss at large distance
- Variation of frequency is underestimated compared with measurement

3. Microcell path loss models

3.1 Empirical model

Dual slope empirical model [1]

Motivation : simple power law path loss model not accurate enough

➡ Dual slop model

↳ Two separate path loss exponents are used to characterize the propagation

↳ breakpoint distance of a few hundred meters

$$\text{Path loss : } L = \begin{cases} 10n_1 \log_{10} r + L_1 & \text{for } r \leq r_b \\ 10n_2 \log_{10} (r / r_b) + 10n_1 \log_{10} r_b + L_1 & \text{for } r > r_b \end{cases}$$

L_1 = reference path loss at r =1 m
r_b = breakpoint distance
n_1 = path loss exponent for $r \leq r_b$
n_2 = path loss exponent for $r > r_b$

Dual slope empirical model cont.

To avoid sharp transition between the two region :

↳ $L = L_1 + 10n_1 \log_{10} r + 10\,(n_2 - n_1)\log_{10} (1 + r / r_b)$

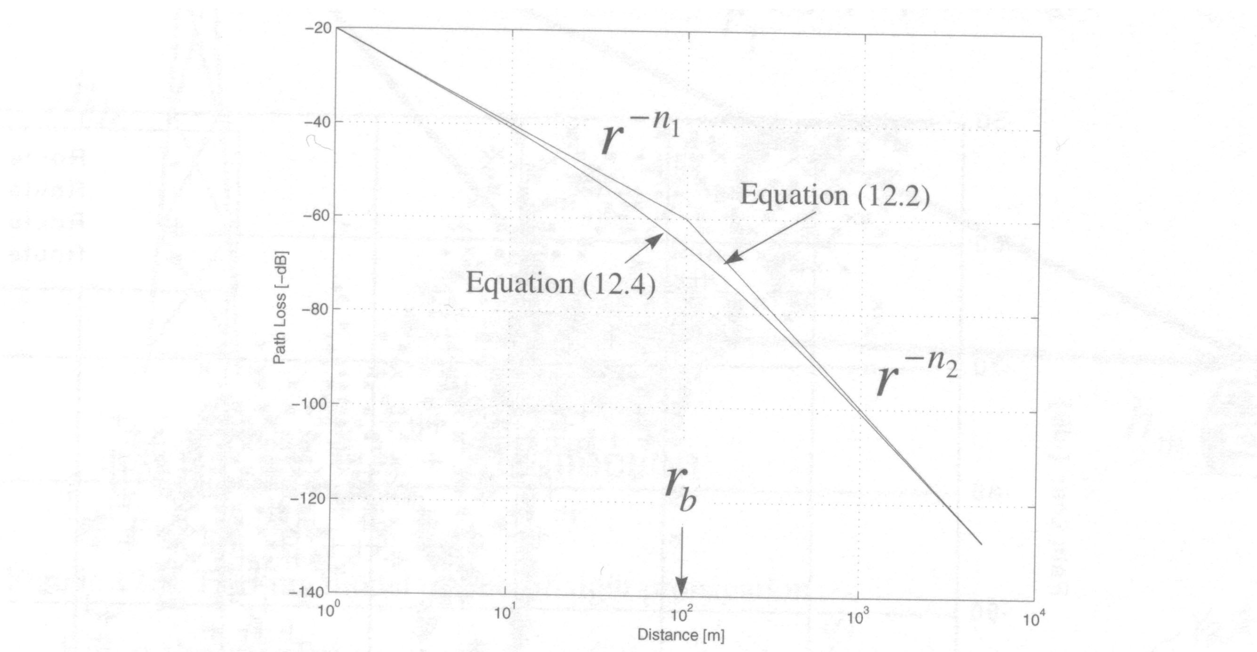


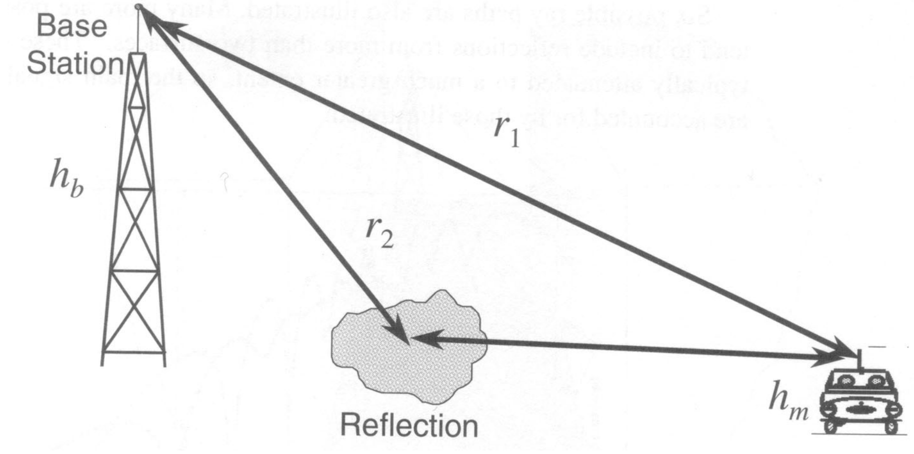
Figure 12.2: Dual-slope empirical loss models. $n_1 = 2$, $n_2 = 4$, $r_b = 100$ m and $L_1 = 20$ dB

Usually $n_1 = 2$ and $n_2 = 4$ but can vary greatly depending on environment

3.2 deterministic model

Two-ray model [1]

- valid for line of sight
  - at least 1 direct ray and 1 reflected ray



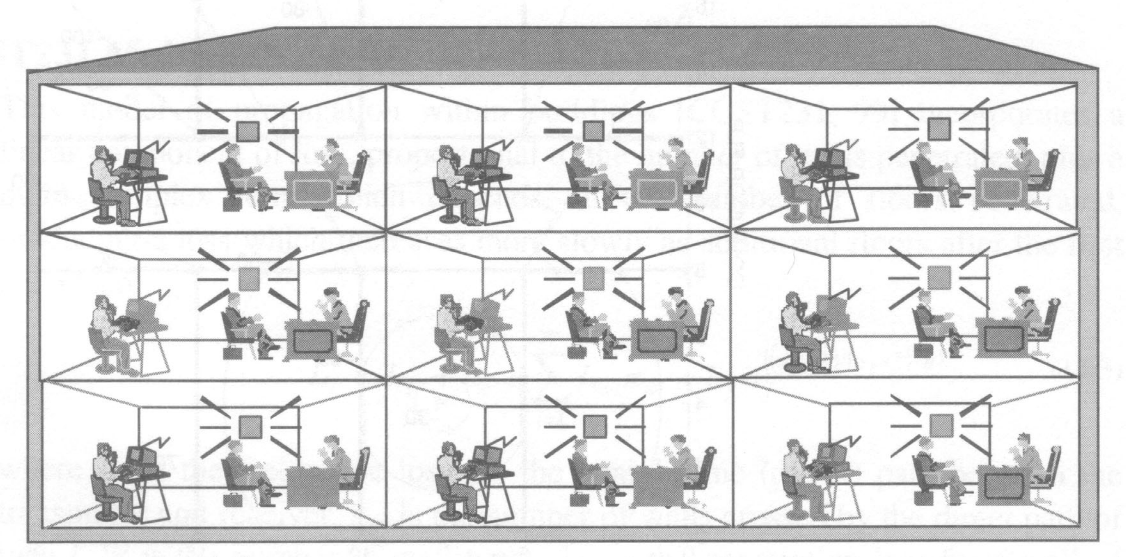
Similar approach as plane earth loss but two path lengths not necessarily equal

$$\frac{1}{L} = \left(\frac{\lambda}{4\pi}\right)^2 \left|\frac{e^{-jkr_1}}{r_1} + R\,\frac{e^{-jkr_2}}{r_2}\right|^2$$

R = Fresnel reflection coefficient

4. Picocell path loss models

➡ Base station antenna located inside building



4.1 Empirical model

<u>Propagation within buildings</u>

Wall and floor factor models [1]

Characterize indoor path loss by :

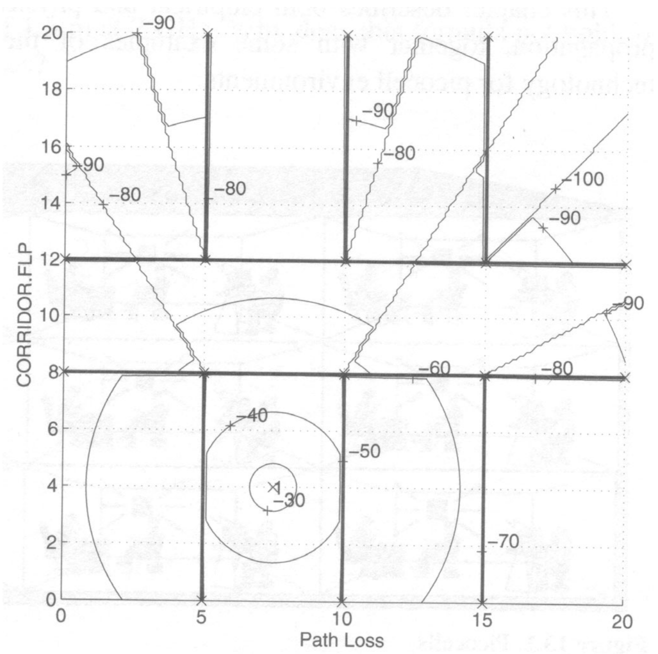
a fixed exponent of 2 (as in free space) + additional loss factors relating to number of floors n_f and walls n_w intersected by the straight-line distance r between terminals

$L= L_1 + 20\log r + n_f\ a_f + n_w\ a_w$

a_f = attenuation factor per floor

a_w = attenuation factor per wall

L_1 = reference path loss at r =1 m



Wall and floor factor models - ITU-R models. [1]

➡ Similar approach except :

- only floor loss is accounted explicitly
- loss between points on same floor included implicitly by changing path loss exponent

$$L_T = 20\log_{10} f_c[\text{MHz}] + 10n \log_{10} r\ [\text{m}] + L_f(\ n_f\ ) - 28$$

Wall and floor factor models - ITU-R models cont.

- $L_T = 20\log_{10} f_c[\text{MHz}] + 10n \log_{10} r\,[\text{m}] + L_f(n_f) - 28$

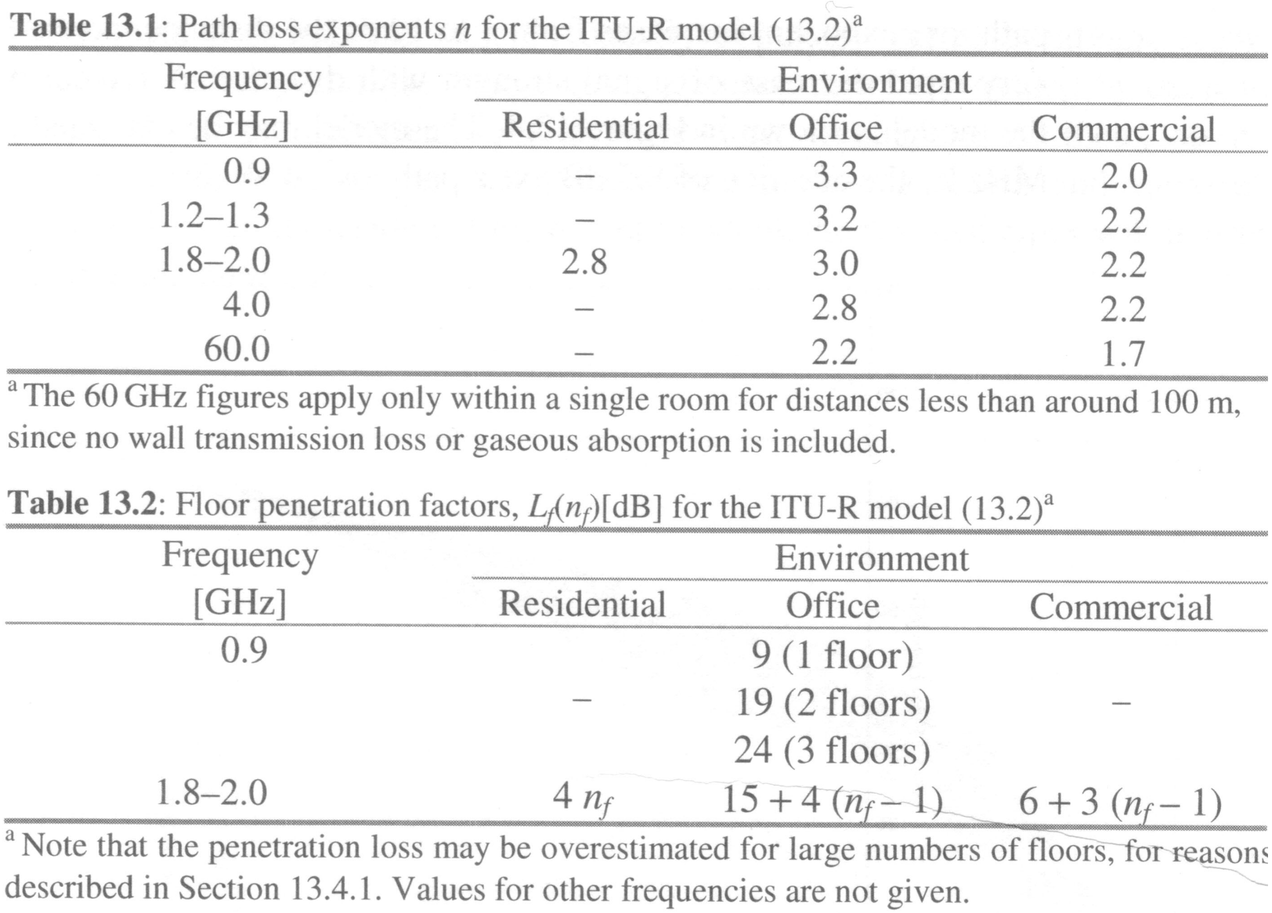


Table 13.1: Path loss exponents n for the ITU-R model (13.2)[a]

Frequency [GHz]	Environment		
	Residential	Office	Commercial
0.9	–	3.3	2.0
1.2–1.3	–	3.2	2.2
1.8–2.0	2.8	3.0	2.2
4.0	–	2.8	2.2
60.0	–	2.2	1.7

[a] The 60 GHz figures apply only within a single room for distances less than around 100 m, since no wall transmission loss or gaseous absorption is included.

Table 13.2: Floor penetration factors, $L_f(n_f)$[dB] for the ITU-R model (13.2)[a]

Frequency [GHz]	Environment		
	Residential	Office	Commercial
0.9	–	9 (1 floor) 19 (2 floors) 24 (3 floors)	–
1.8–2.0	$4\,n_f$	$15 + 4\,(n_f - 1)$	$6 + 3\,(n_f - 1)$

[a] Note that the penetration loss may be overestimated for large numbers of floors, for reasons described in Section 13.4.1. Values for other frequencies are not given.

4.2 Semi-empirical model

<u>Propagation into buildings</u>

COST231 line-of-sight model [1]

Total path loss : $L_T = L_F + L_e + L_g\,(1\text{-}\cos\theta)^2 + \max(L_1\,, L_2)$

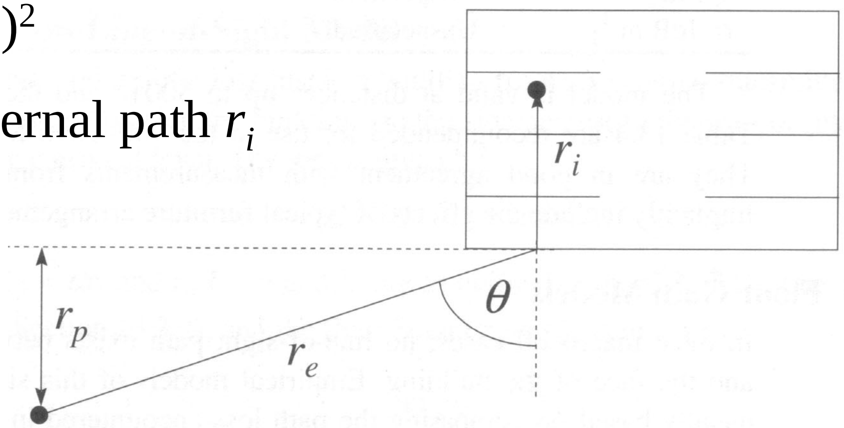
L_F = free space loss for total path length ($r_i + r_e$)
L_e = path loss through external wall at normal incidence ($\theta = 0°$)
L_g = additional external wall loss incurred at grazing incidence ($\theta = 90°$)

$L_1 = n_w L_i$ *and* $L_2 = \alpha\,(r_i - 2)(1\text{-}\cos\theta)^2$

N_w = number of wall crossed by the internal path r_i

L_i = loss per internal wall

α= specific attenuation which applies for unobstructed internal path



COST231 line-of-sight model cont.

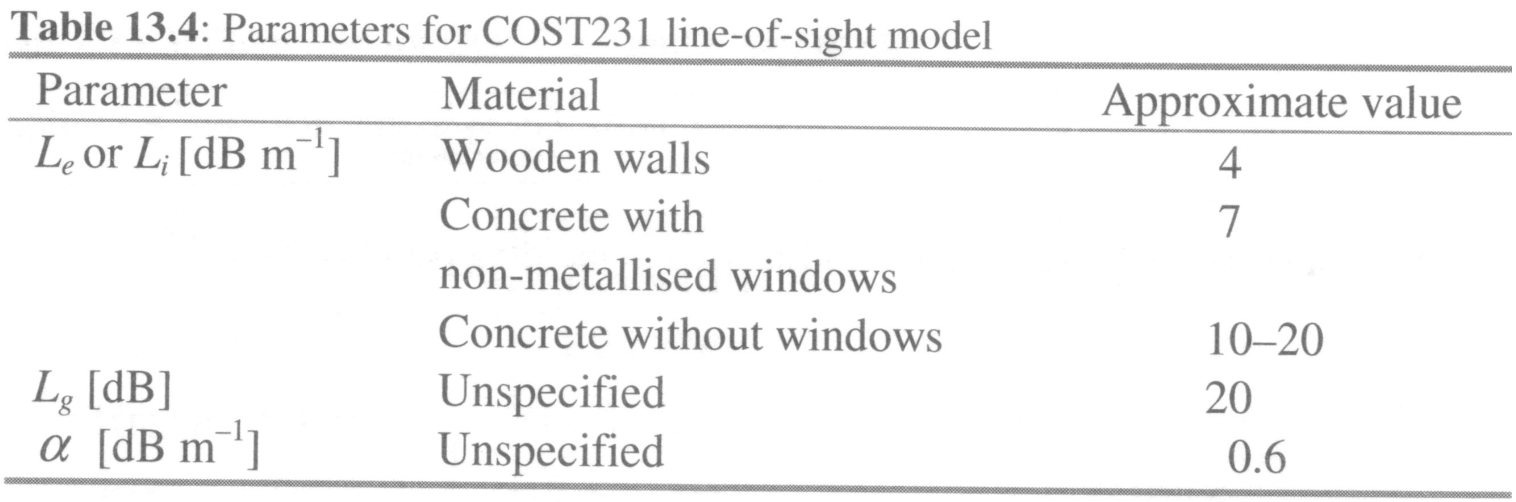


Table 13.4: Parameters for COST231 line-of-sight model

Parameter	Material	Approximate value
L_e or L_i [dB m^{-1}]	Wooden walls	4
	Concrete with non-metallised windows	7
	Concrete without windows	10–20
L_g [dB]	Unspecified	20
α [dB m^{-1}]	Unspecified	0.6

5. Conclusion

Empirical models :

- not always accurate enough
- can be used only over parameter ranges included in the original measurement set

Deterministic models :

- require an enormous amount of data to describe fully the cover area
- very important computational effort

➡ **Compromise**

References :

[1] S. Saunders, *Antennas and Propagation for Wireless Communication Systems*, Wiley, 2000, 409 p.

[2] R. Vaughan, J. Bach Andersen, *Channels, Propagation and Antennas for Mobile Communications*, IEE, 2003, 753 p.

[3] H. Bertoni, *Radio Propagation for Modern Wireless Systems*, Prentice Hall, 2000, 258 p.

[4] K. Siwiak, *Radiowave Propagation and Antennas for Personal Communications*, Artech House, 1998, 418 p.

[5] COST231, final report, 1999.

[6] W. Backman, *Error Correction on Predicted Signal levels in Mobile Communications*, master thesis, 2003.

[7] J. Rissanen, *Dynamic resource reallocation in cellular networks,* master thesis, 2003.

[8] A. Medeisis, A.Kajackas, *On the Use of the Universal Okumura-Hata Propagation Prediction Model in Rural Areas*, IEEE Vehicular Technology Conference Proceeding, Vol. 3, May 2000, pp. 450-453.

Homework :

1) What are the advantages and defaults of empirical models, what is the most widely used empirical model ?

2) Using the ITU-R model, calculate the path loss at 0.9 GHz in an office environment, where the distance between Tx and Rx is 10 m, and they are separated by 1 floor.