7.6.1 Appendix 7.A: The Okumura–Hata model

Two forms of the Okumura–Hata model are available. In the first form, the pathloss (in dB) is written as:

$$PL = PL_{\text{freespace}} + A_{\text{exc}} - H_{\text{cb}} - H_{\text{cm}} \tag{7.13}$$

where $PL_{\text{freespace}}$ is the free space pathloss, A_{exc} is the excess pathloss (as a function of distance and frequency) for a BS height $h_{\text{bs}} = 200\,\text{m}$, and an MS height $h_{\text{ms}} = 3\,\text{m}$; it is shown in Fig. 7.12. The correction factors H_{cb} and H_{cm} are shown in Figs. 7.13 and 7.14, respectively.

The more common form is a curve fitting of Okumura's original results.[5] In this implementation, the pathloss is written as:

$$PL = A + B\log(d) + C$$

where A, B, and C are factors that depend on frequency and antenna height:

$$A = 69.55 + 26.16\log(f_{\text{c}}) - 13.82\log(h_{\text{b}}) - a(h_{\text{m}}) \tag{7.14}$$

$$B = 44.9 - 6.55\log(h_{\text{b}}) \tag{7.15}$$

where f_{c} is given in MHz and d in km.

The function $a(h_{\text{m}})$ and the factor C depend on the environment:

- small and medium-size cities:

$$a(h_{\text{m}}) = (1.1\log(f_{\text{c}}) - 0.7)h_{\text{m}} - (1.56\log(f_{\text{c}}) - 0.8) \tag{7.16}$$

$$C = 0 \tag{7.17}$$

- metropolitan areas:

$$a(h_{\text{m}}) = \begin{cases} 8.29(\log(1.54h_{\text{m}})^2 - 1.1 & \text{for } f \le 200\text{MHz} \\ 3.2(\log(11.75h_{\text{m}})^2 - 4.97 & \text{for } f \ge 400\text{MHz} \end{cases} \tag{7.18}$$

$$C = 0 \tag{7.19}$$

- suburban environments:

$$C = -2[\log(f_{\text{c}}/28)]^2 - 5.4 \tag{7.20}$$

- rural area:

$$C = -4.78[\log(f_{\text{c}})]^2 + 18.33\log(f_{\text{c}}) - 40.98 \tag{7.21}$$

  The function $a(h_{\text{m}})$ in suburban and rural areas is the same as for urban (small and medium-sized cities) areas.

Table 7.1 gives the parameter range in which the model is valid. It is noteworthy that the parameter range does not encompass the 1,800-MHz frequency range most commonly used for second- and third-generation cellular systems. This problem was solved by the COST 231–Hata model, which extends the validity region to the 1,500–2,000-MHz range by defining:

$$\left.\begin{aligned} A &= 46.3 + 33.9\log(f_{\text{c}}) - 13.82\log(h_{\text{b}}) - a(h_{\text{m}}) \\ B &= 44.9 - 6.55\log(h_{\text{b}}) \end{aligned}\right\} \tag{7.22}$$

where $a(h_m)$ is defined in Eq. (7.16). C is 0 in small and medium-sized cities, and 3 in metropolitan areas.

[5] Note that the results from curve fitting can be slightly different from the results of Eq. (7.13).

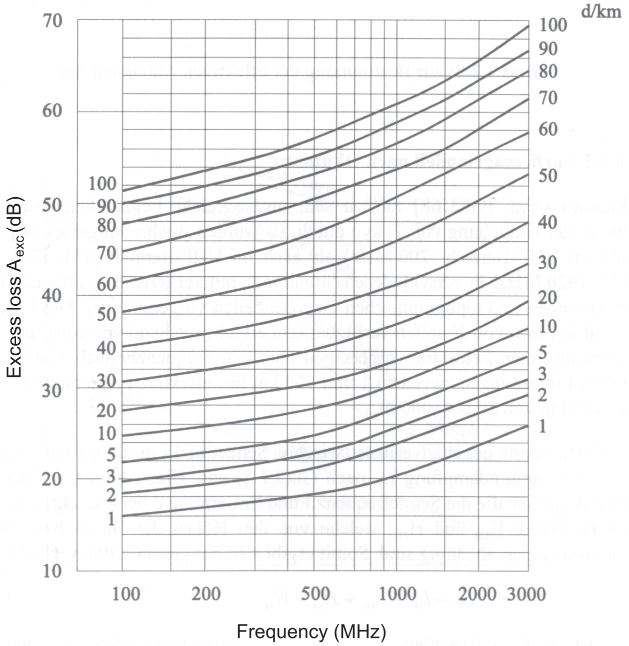

Figure 7.12 Pathloss according to the Okumura–Hata model. Excess loss is the difference between Okumura–Hata pathloss (at the reference points $h_b = 200$ m, $h_m = 3$ m), and free space loss.

Reproduced from Okumura et al. [1968].

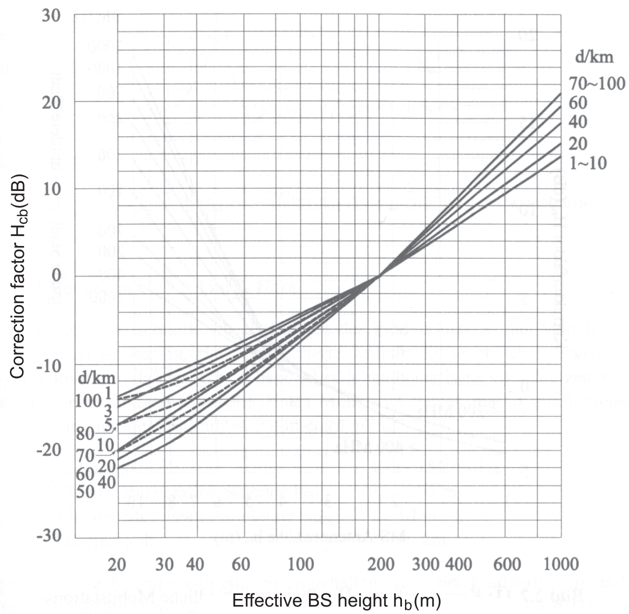

Figure 7.13 Correction factor for base station height.

Reproduced from Okumura et al. [1968].

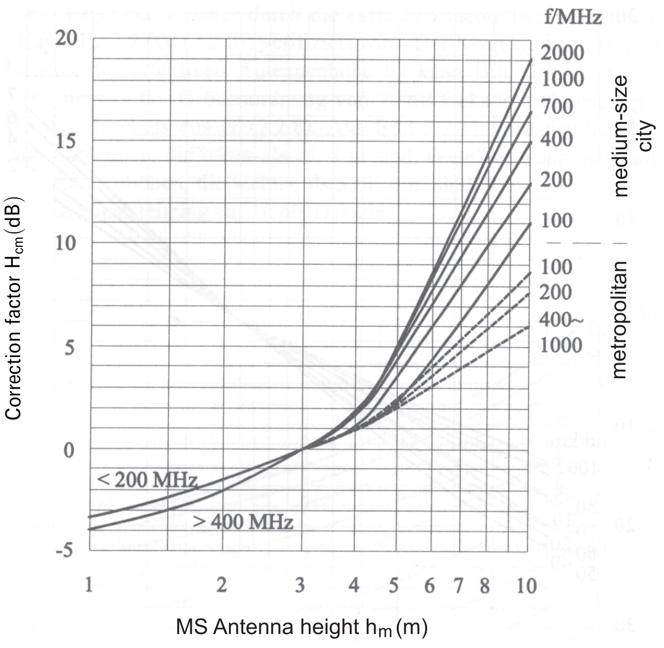

Figure 7.14 Correction factor for mobile station height.

Reproduced from Okumura et al. [1968].

Table 7.1 Range of validity for the Okumura–Hata model.

Carrier frequency	f_c	150–1,500 MHz
Effective BS antenna height	h_b	30–200 m
Effective MS antenna height	h_m	1–10 m
Distance	d	1–20 m

The Okumura–Hata model also assumes that there are no dominant obstacles between the BS and the MS, and that the terrain profile changes only slowly. Badsberg et al. [1995] and Isidoro et al. [1995] suggested correction factors that are intended to avoid these restrictions; however, they did not find the widespread acceptance of COST 231 correction factors.

7.6.2 Appendix 7.B: The COST 231–Walfish–Ikegami model

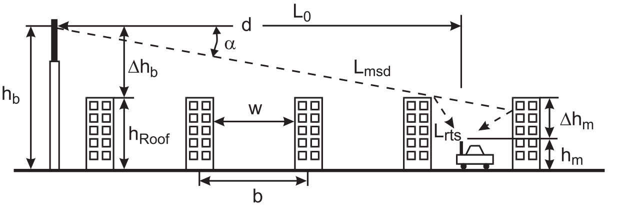

Figure 7.15 Parameters in the COST 231–Walfish–Ikegami model.
Reproduced with permission from Damosso and Correia [1999] © European Union.

The COST 231 model is a pathloss model when small distances exist between the MS and BS, and/or the MS has a small height. The total pathloss for the LOS case is given by:

$$PL = 42.6 + 26\log(d) + 20\log(f_c) \tag{7.23}$$

for $d \geq 20$ m, where again d is in units of kilometers, and f_c is in units of MHz.

For the non-LOS case, pathloss consists in the free space pathloss L_0, the *multiscreen loss* L_{msd} along the propagation path, and attenuation from the last roof edge to the MS, L_{rts} (*rooftop-to-street diffraction and scatter loss*):

$$PL = \begin{cases} PL_0 + L_{rts} + L_{msd} & \text{for} \quad L_{rts} + L_{msd} > 0 \\ PL_0 & \text{for} \quad L_{rts} + L_{msd} \leq 0 \end{cases} \tag{7.24}$$

The free space pathloss is:

$$L_0 = 32.4 + 20\log d + 20\log f_c \tag{7.25}$$

Ikegami derived the diffraction loss L_{rts} as:

$$L_{rts} = -16.9 - 10\log w + 10\log f_c + 20\log\Delta h_m + L_{ori} \tag{7.26}$$

where w is the width of the street in meters, and

$$\Delta h_m = h_{Roof} - h_m \tag{7.27}$$

is the difference between the building height h_{Roof} and the height of the MS h_m (see Fig. 7.15). Orientation of the street is taken into account by an empirical correction factor L_{ori}:

$$L_{ori} = \begin{cases} -10 + 0.354\varphi & \text{for } 0^\circ \leq \varphi \leq 35^\circ \\ 2.5 + 0.075(\varphi - 35) & \text{for } 35^\circ \leq \varphi \leq 55^\circ \\ 4.0 - 0.114(\varphi - 55) & \text{for } 55^\circ \leq \varphi \leq 90^\circ \end{cases} \tag{7.28}$$

where φ is the angle between the street orientation and the direction of incidence in degrees.

For the computation of the multiscreen loss L_{msd}, building edges are modeled as screens. The multiscreen loss is then given as [Walfish and Bertoni 1988]:

$$L_{msd} = L_{bsh} + k_a + k_d\log d + k_f\log f_c - 9\log b \tag{7.29}$$

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where b is the distance between two buildings (in meters). Furthermore:

$$L_{\mathrm{bsh}} = \begin{cases} -18\log(1+\Delta h_{\mathrm{b}}) & \text{for } h_{\mathrm{b}} > h_{\mathrm{Roof}} \\ 0 & \text{for } h_{\mathrm{b}} \le h_{\mathrm{Roof}} \end{cases} \tag{7.30}$$

$$k_{\mathrm{a}} = \begin{cases} 54 & \text{for } h_{\mathrm{b}} > h_{\mathrm{Roof}} \\ 54 - 0.8\Delta h_{\mathrm{b}} & \text{for } d \ge 0.5\,\text{km and } h_{\mathrm{b}} \le h_{\mathrm{Roof}} \\ 54 - 0.8\Delta h_{\mathrm{b}} d/0.5 & \text{for } d < 0.5\,\text{km and } h_{\mathrm{b}} \le h_{\mathrm{Roof}} \end{cases} \tag{7.31}$$

where

$$\Delta h_{\mathrm{b}} = h_{\mathrm{b}} - h_{\mathrm{Roof}} \tag{7.32}$$

and h_{b} is the height of the BS. The dependence of pathloss on frequency and distance is given via the parameters k_{d} and k_{f} in Eq. (7.29):

$$k_{\mathrm{d}} = \begin{cases} 18 & \text{for } h_{\mathrm{b}} > h_{\mathrm{Roof}} \\ 18 - 15\Delta h_{\mathrm{b}}/h_{\mathrm{Roof}} & \text{for } h_{\mathrm{b}} \le h_{\mathrm{Roof}} \end{cases} \tag{7.33}$$

$$k_{\mathrm{f}} = -4 + \begin{cases} 0.7\left(\dfrac{f_{\mathrm{c}}}{925} - 1\right) & \begin{array}{l}\text{for medium-size cities} \\ \text{suburban areas with average vegetation density}\end{array} \\ 1.5\left(\dfrac{f_c}{925} - 1\right) & \text{for metropolitan areas} \end{cases} \tag{7.34}$$

Table 7.2 gives the validity range for this model.

Table 7.2 Range of validity for the COST 231–Walfish–Ikegami model.

Carrier frequency	f_{c}	800–2,000 MHz
Height of BS antenna	h_{b}	4–50 m
Height of MS antenna	h_{m}	1–3 m
Distance	d	0.02–5 km

7.6.3 Appendix 7.C: The COST 207 GSM model

The COST 207 model [Failii 1989] gives normalized scattering functions, as well as amplitude statistics, for four classes of environments: Rural Area, Typical Urban, Bad Urban, and Hilly Terrain. The following PDPs are used:

- Rural Area (RA)

$$P_h(\tau) = \begin{cases} \exp\left(-9.2\frac{\tau}{\mu s}\right) & \text{for } 0 < \tau < 0.7\,\mu s \\ 0 & \text{elsewhere} \end{cases} \tag{7.35}$$

- Typical Urban area (TU)

$$P_h(\tau) = \begin{cases} \exp\left(-\frac{\tau}{\mu s}\right) & \text{for } 0 < \tau < 7\,\mu s \\ 0 & \text{elsewhere} \end{cases} \tag{7.36}$$

- Bad Urban area (BU)

$$P_h(\tau) = \begin{cases} \exp\left(-\frac{\tau}{\mu s}\right) & \text{for } 0 < \tau < 5\,\mu s \\ 0.5\exp\left(5-\frac{\tau}{\mu s}\right) & \text{for } 5 < \tau < 10\,\mu s \\ 0 & \text{elsewhere} \end{cases} \tag{7.37}$$

- Hilly Terrain (HT)

$$P_h(\tau) = \begin{cases} \exp\left(-3.5\frac{\tau}{\mu s}\right) & \text{for } 0<\tau<2\,\mu s \\ 0.1\exp\left(15-\frac{\tau}{\mu s}\right) & \text{for } 15<\tau<20\,\mu s \\ 0 & \text{elsewhere} \end{cases} \tag{7.38}$$

In a tapped delay line realization, each channel has a Doppler spectrum $P_s(\nu, \tau_i)$, where i is the index of the tap. The following four types of Doppler spectra are defined in the COST 207 model, where $\nu_{\max}$ represents the maximum Doppler shift and $G(A, \nu_1, \nu_2)$ is the Gaussian function:

$$G(A, \nu_1, \nu_2) = A\exp\left(-\frac{(\nu-\nu_1)^2}{2\nu_2^2}\right) \tag{7.39}$$

and A is a normalization constant chosen so that $\int P_s(\nu, \tau_i)d\nu = 1$.

a. *CLASS* is the classical (Jakes) Doppler spectrum and is used for paths with delays not in excess of 500 ns ($\tau_i \leq 0.5\,\mu s$):

$$P_s(\nu, \tau_i) = \frac{A}{\sqrt{1-(\nu/\nu_{\max})^2}} \tag{7.40}$$

for $\nu \in [-\nu_{\max}, \nu_{\max}]$.

b. *GAUS1* is the sum of two Gaussian functions and is used for excess delay times in the range of 500 ns to 2 μs ($0.5\,\mu s \leq \tau_i \leq 2\,\mu s$):

$$P_s(\nu, \tau_i) = G(A, -0.8\nu_{\max}, 0.05\nu_{\max}) + G(A_1, 0.4\nu_{\max}, 0.1\nu_{\max}) \tag{7.41}$$

where A_1 is 10 dB smaller than A.

c. *GAUS2* is also the sum of two Gaussian functions and is used for paths with delays in excess of 2 μs ($\tau_i \geq 2\,\mu s$):

$$P_s(\nu, \tau_i) = G(B, 0.7\nu_{\max}, 0.1\nu_{\max}) + G(B_1, -0.4\nu_{\max}, 0.15\nu_{\max}) \tag{7.42}$$

where B_1 is 15 dB smaller than B.

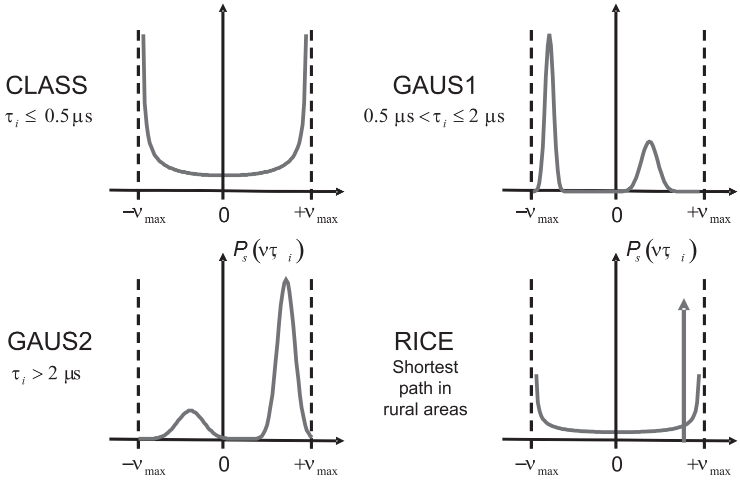

Figure 7.16 Doppler spectra used in GSM channel models.

d. *RICE* is the sum of a classical Doppler spectrum and one direct path. This spectrum is used for the shortest path of the model for propagation in rural areas:

$$P_s(\nu, \tau_i) = \frac{0.41}{2\pi\nu_{\max}\sqrt{1 - \left(\frac{\nu}{\nu_{\max}}\right)^2}} + 0.91\delta(\nu - 0.7\nu_{\max}) \tag{7.43}$$

for $\nu \in [-\nu_{\max}, \nu_{\max}]$.

Tapped delay line implementations for the four propagation environments suggested by COST 207 are shown in Tables 7.3–7.6.

Table 7.3 Parameters for rural (non-hilly) area (RA).

Tap#	Delay [μs]	Power [dB]	Doppler category
1	0	0	RICE
2	0.2	−2	CLASS
3	0.4	−10	CLASS
4	0.6	−20	CLASS

Table 7.4 Parameters for typical urban area (TU).

Tap#	Delay [μs]	Power [dB]	Doppler category
1	0	−3	CLASS
2	0.2	0	CLASS
3	0.6	−2	GAUS1
4	1.6	−6	GAUS1
5	2.4	−8	GAUS2
6	5.0	−10	GAUS2

Table 7.5 Parameters for bad urban area (BU).

Tap#	Delay [μs]	Power [dB]	Doppler category
1	0	−3	CLASS
2	0.4	0	CLASS
3	1.0	−3	GAUS1
4	1.6	−5	GAUS1
5	5.0	−2	GAUS2
6	6.6	−4	GAUS2

Table 7.6 Parameters for hilly terrain (HT).

Tap#	Delay [μs]	Power [dB]	Doppler category
1	0	0	CLASS
2	0.2	−2	CLASS
3	0.4	−4	CLASS
4	0.6	−7	CLASS
5	15	−6	GAUS2
6	17.2	−12	GAUS2

7.6.4 Appendix 7.D: The ITU-R models

For the selection of the air interface of third-generation cellular systems, the *International Telecommunications Union* (ITU) developed another set of models that is available only as a tapped-delay-line implementation [ITU 1997]. It specifies three environments: indoor, pedestrian (including outdoor to indoor), and vehicular (with high BS antennas). For each of these environments, two channels are defined: channel A (low-delay-spread case) and channel B (high-delay-spread case). The occurrence rate of these two models is also specified; all these parameters are given in Table 7.7. The amplitudes follow a Rayleigh distribution; the Doppler spectrum is uniform between $-\nu_{max}$ and ν_{max} for the indoor case and is a classical Jakes spectrum for pedestrian and vehicular environments.

In contrast to the COST 207 model, the ITU model also specifies the pathloss (in dB) depending on distance d:

- *Indoor*:
$$PL = 37 + 30\log_{10} d + 18.3 \cdot N_{\text{floor}}^{\left(\frac{N_{\text{floor}}+2}{N_{\text{floor}}+1}-0.46\right)} \tag{7.44}$$
- *Pedestrian*:
$$PL = 40\log_{10} d + 30\log_{10} f_{\text{c}} + 49 \tag{7.45}$$
where again d is in km and f_{c} is in MHz. For the outdoor-to-indoor case, an additional building penetration loss (in dB) is modeled as a normal variable with 12 dB mean and 8 dB standard deviation.
- *Vehicular*:
$$PL = 40(1 - 4 \cdot 10^{-3}\Delta h_{\text{b}})\log_{10} d - 18\log_{10}\Delta h_{\text{b}} + 21\log_{10} f_{\text{c}} + 80 \tag{7.46}$$

Table 7.7 Tapped-delay-line implementation of ITU-R models.

Tap#	Delay [ns]	Power [dB]	Delay [ns]	Power [dB]
Indoor	*Channel A* (50%)		*Channel B* (45%)	
1	0	0	0	0
2	50	−3	100	−3.6
3	110	−10	200	−7.2
4	170	−18	300	−10.8
5	290	−26	500	−18.0
6	310	−32	700	−25.2
Pedestrian	*Channel A* (40%)		*Channel B* (55%)	
1	0	0	0	0
2	110	−9.7	200	−0.9
3	190	−19.2	800	−4.9
4	410	−22.8	1,200	−8.0
5			2,300	−7.8
6			3,700	−23.9
Vehicular	*Channel A* (40%)		*Channel B* (55%)	
1	0	0	0	−2.5
2	310	−1	300	0
3	710	−9	8,900	−12.8
4	1,090	−10	12,900	−10.0
5	1,730	−15	17,100	−25.2
6	2,510	−20	20,000	−16.0

where Δh_{b} is the BS height measured from the rooftop level; the model is valid for $0 < \Delta h_b < 50\,\mathrm{m}$.

In all three cases, lognormal shadowing is imposed. The standard deviation is 12 dB for the indoor case, and 10 dB in the vehicular and outdoor pedestrian case. The autocorrelation function of shadowing is assumed to be exponential, $ACF(\Delta x) = \exp(-\ln(2)|\Delta x|/d_{\mathrm{corr}})$ where the correlation length d_{corr} is 20 m in vehicular environments, but not specified for other environments.

The ITU models have been widely used, because they were accepted by international standards organizations. However, they are not very satisfactory from a scientific point of view. It is difficult to motivate differences in the power delay profile of pedestrian and vehicular channels, while neglecting the differences between suburban and metropolitan areas. Also, some of the channels have regularly spaced taps, which leads to a periodicity in frequency of the transfer function; this can lead to problems when evaluting the correlation between duplex frequencies (see Chapter 17). Finally, the number of taps is too low for realistic modeling of 5-MHz-wide systerms.