EEENG473 Mobile Communications
Module 3 : Week # (11)

Mobile Radio Propagation:
Large-Scale Path Loss

Practical Link Budget Design using Path Loss Models

• Most radio propagation models are derived using a **combination of analytical** (from a set of measured data) **and empirical methods.** (based on fitting curves)

• **all propagation factors** through actual field measurements **are included**.

•some classical propagation models are now used to predict large-scale coverage for mobile communication systems design.

•Practical path loss estimation techniques are presented next.

Free Space Propagation Model n=2

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$

$$P_r(d) \text{ dBm} = 10\log\left[\frac{P_r(d_0)}{0.001\text{ W}}\right] + 20\log\left(\frac{d_0}{d}\right) \qquad d \geq d_0 \geq d_f$$

Next model is generalized model for any value of n
Log-distance Path Loss Model

1 Log-distance Path Loss Model

average received signal power decreases logarithmically with distance, (theoretical and measurments), whether in outdoor or indoor radio channels.

The average large-scale path loss for an arbitrary T-R separation is expressed as a function of distance (d) by using a path loss exponent, (n).

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$$

$$\overline{PL}(\mathrm{dB}) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

where :**n** is the path loss exponent, **d_0 is the close-in reference distance** (determined from measurements close to the transmitter), **d** is the **T-R separation distance**.

•Bars denote **the ensemble average** of all possible path loss values for a given ***d***.

• On a **log-log scale plot**, **the modeled path loss is a straight line** with a slope equal to ***10n*** dB per decade.

Path loss at a close-in reference distance

• **(d0)** :**free space reference distance** that is appropriate for the propagation environment. In large coverage cellular systems, **1 km reference distances are commonly used** whereas in microcellular systems, much smaller distances **(such as 100 m or 1 m)** are used.

• The reference distance **should always be in the far field** of the antenna so that near-field effects do not alter the reference path loss.

• The reference path loss is calculated using the free space path loss formula given by **friis free space equation** or through field measurements at distance **d0**.

$$PL\,(\mathrm{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

Table 3.2 lists typical path loss exponents obtained in various mobile radio environments.

Table 3.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

n **:** depends on the specific propagation environment.
For example, **in free space, n is equal to 2,** and when obstructions are present, n will have a larger value.

2. Log-normal Shadowing

The log distance path loss model does not consider the fact that the surrounding environmental clutter may be vastly different at two different locations having the same T-R separation.

Measurements have shown that at any value of **d**, the path loss **PL(d)** at a particular location **is random and distributed log-normally (normal in dB) about the mean distance dependent value That is**

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \quad (3.69.a)$$

and

$$P_r(d)[dBm] = P_t[dBm] - PL(d)[dB] \text{ (antenna gains included in } PL(d)\text{)} \quad (3.69.b)$$

where X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB).

log-normal shadowing. Simply implies that measured signal levels at a specific T-R separation have a Gaussian (normal) distribution about the distance-dependent mean of (3.68),

$$\overline{PL}(\text{dB}) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

- **d_0**, **n**, **¥** (the standard deviation),

statistically describe the path loss model for an arbitrary location having a specific T-R separation.

- This model may be used in computer simulation to provide received power levels for random locations in communication system design and analysis.

- In practice, the values of n and [illegible] are computed from measured data, using linear regression such that the difference between the measured and estimated path losses **<u>is minimized in a mean square error sense</u>** over a wide range of measurement locations and T-R separations.

- **PL(d0)** is obtained from measurements or free space assumption (friis) from the transmitter to d0.

An example of how the path loss exponent is determined from measured data follows.

Figure 3.17 illustrates actual measured data in several cellular radio systems and demonstrates the random variations about the mean path loss (in dB) due to shadowing at specific T-R separations.

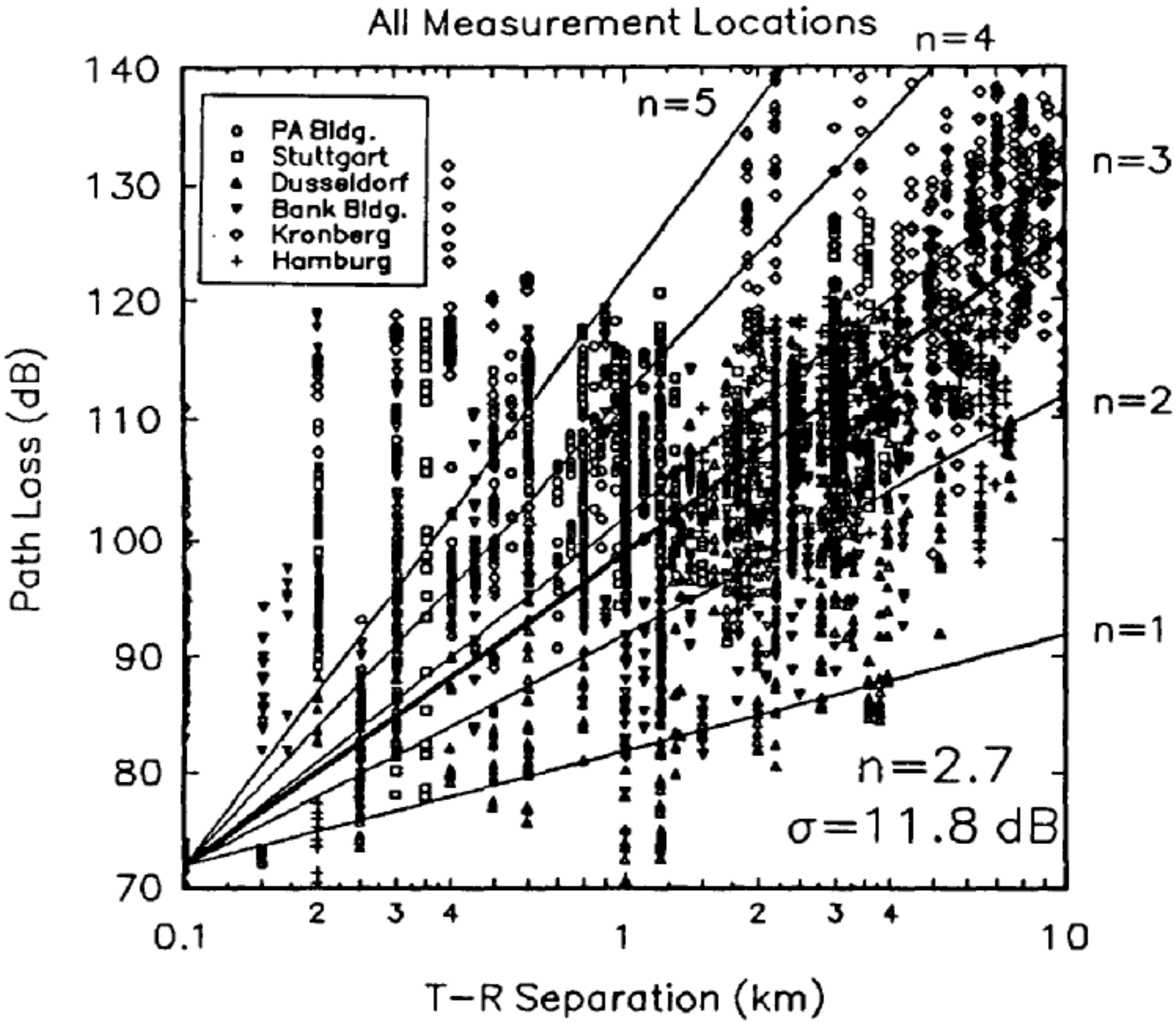

Figure 3.17
Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [From [Sei91] © IEEE].

Example 3.9

Four received power measurements were taken at distances of 100 m, 200 m, 1 km, and 3 km from a transmitter. These measured values are given in the following table. It is assumed that the path loss for these measurements follows the model in equation (3.69.a), where $d_0 = 100$ m: (a) find the minimum mean square error (MMSE) estimate for the path loss exponent, n ; (b) calculate the standard deviation about the mean value; (c) estimate the received power at $d = 2$ km using the resulting model;

Distance from Transmitter	Received Power
100 m	0 dBm
200 m	-20 dBm
1000 m	-35 dBm
3000 m	-70 dBm

Solution to Example 3.9

The MMSE estimate may be found using the following method. Let p_i be the received power at a distance d_i and let $\hat{p}_i$ be the estimate for p_i using the $(d/d_0)^n$ path loss model of equation (3.67). The sum of squared errors between the measured and estimated values is given by

$$J(n) = \sum_{i=1}^{k} (p_i - \hat{p}_i)^2$$

The value of n which minimizes the mean square error can be obtained by equating the derivative of $J(n)$ to zero, and then solving for n.

(a) Using equation (3.68), we find $\hat{p}_i = p_i(d_0) - 10n\log(d_i/100\text{ m})$. Recognizing that $P(d_0) = 0$ dBm, we find the following estimates for $\hat{p}_i$ in dBm:

$$\hat{p}_1 = 0,\ \hat{p}_2 = -3n,\ \hat{p}_3 = -10n,\ \hat{p}_4 = -14.77n.$$

The sum of squared errors is then given by

$$J(n) = (0-0)^2 + (-20-(-3n))^2 + (-35-(-10n))^2 + (-70-(-14.77n))^2$$
$$= 6525 - 2887.8n + 327.153n^2$$

$$\frac{dJ(n)}{dn} = 654.306n - 2887.8.$$

Setting this equal to zero, the value of n is obtained as $n = 4.4$.

(b) The sample variance $\sigma^2 = J(n)/4$ at $n = 4.4$ can be obtained as follows.

$$J(n) = (0+0) + (-20+13.2)^2 + (-35+44)^2 + (-70+64.988)^2$$
$$= 152.36.$$

$$\sigma^2 = 152.36/4 = 38.09$$

therefore

$\sigma = 6.17$ dB, which is a biased estimate. In general, a greater number of measurements are needed to reduce σ^2.

(c) The estimate of the received power at $d = 2$ km is given by

$$\hat{p}(d = 2\text{ km}) = 0 - 10(4.4)\log(2000/100) = -57.24\text{ dBm}.$$

A Gaussian random variable having zero mean and $\sigma = 6.17$ could be added to this value to simulate random shadowing effects at $d = 2$ km.

Measurement-Based Propagation Models

Outdoor Propagation Models

- Radio transmission in a mobile communications system often takes place over irregular terrain (landscape).

- The terrain profile of a particular area needs to be taken into account for estimating the path loss. The terrain profile may vary from a simple curved earth profile to a highly mountainous profile.

- The presence of trees, buildings, and other obstacles also must be taken into account. A number of propagation models are available to predict path loss over irregular terrain.

- While all these models aim to predict signal strength at a particular receiving point or in a specific local area (called a sector), the methods vary widely in their approach, complexity, and accuracy.

- Most of these models are based on a systematic interpretation of measurement data obtained in the service area. **Some of the commonly used outdoor propagation models are now discussed**.

Here are number of standard models for computing the mean received signal level. These are well-treated in the literature.

Models are typically developed to approximate system behavior over a given area. Models are developed for different types of areas using extensive measured data. Curve-fitting techniques are used to fit equations to the experimental data. Models are usually developed for the following classifications of areas:

- urban area (built up area such as city centers)
- suburban area (one and two story homes with open spaces)
- open areas (pastures, farms, etc.)

Other models are often included. Examples are

- geographical data bases (USGS data base for the US)
- atmospheric models for scattering

Parameters of interest often include the following:

- transmission frequency
- antenna heights
- surface reflectivity
- path length
- ground dielectric and conductivity constants
- polarization
- terrain effects (ground cover, etc.)

Many different models are possible and most have both strong and weak points to recommend their use.

Okumura Model

The Okumura model is widely used. It is simple to apply and often gives reasonable results. Based a set of curves obtained by curve fitting to measurement results. Typical parameters:

- Frequency range: 150MHz to 2 or 3 GHz
- Distances: 1 km to 100 km
- Base station antenna heights: 30 m to 1000 m

$$L_{50} = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}, \quad \text{dB}$$

where

$$L_F = \text{free space path loss} = -10\log_{10}\left[\left(\frac{\lambda}{4\pi d}\right)^2\right]$$

$A_{mu}(f,d)$ = medium attenuation relative to free space (in graph)

G_{AREA} = terrain correction (in graphs)

$G(h_{re})$ = receiving antenna factor

$G(h_{te})$ = transmitting antenna factor

L_{50} is the 50th percentile (i.e., median) value of propagation path loss,

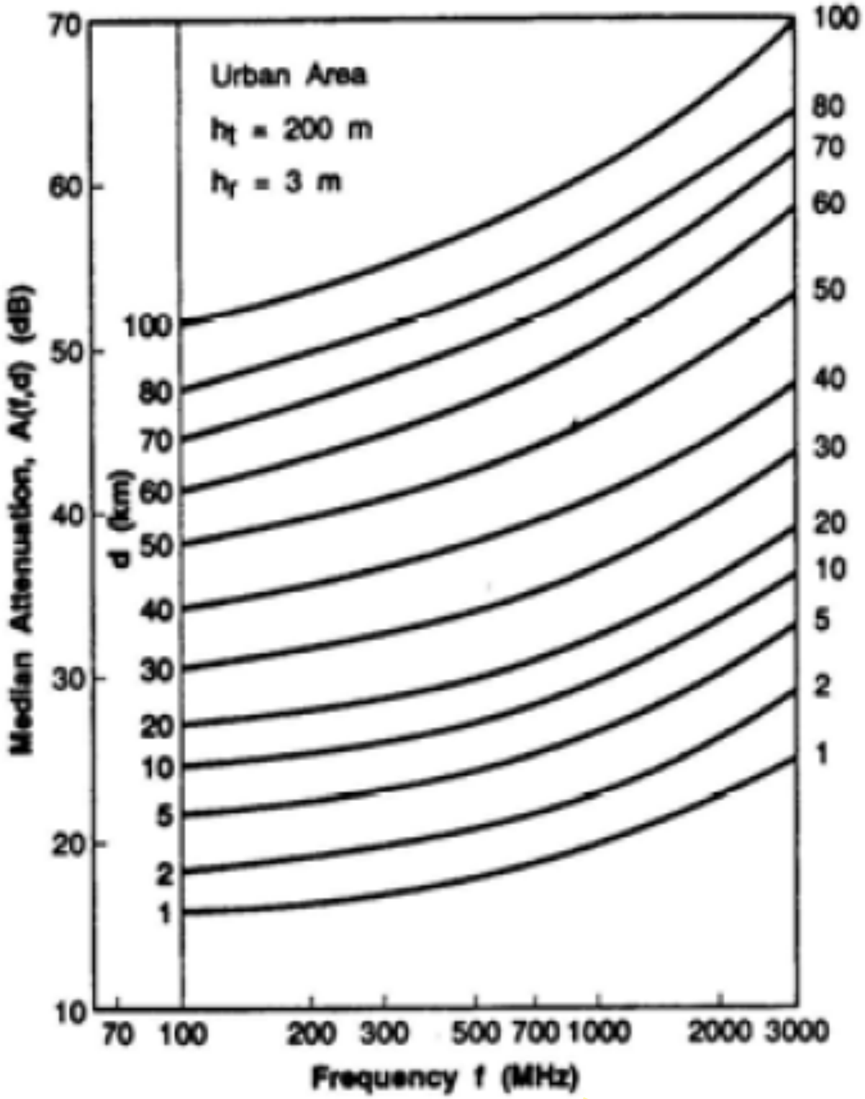

Figure 4.23 Median attenuation relative to free space ($A_{mu}(f,d)$), over a quasi-smooth terrain [from [Oku68] © IEEE].

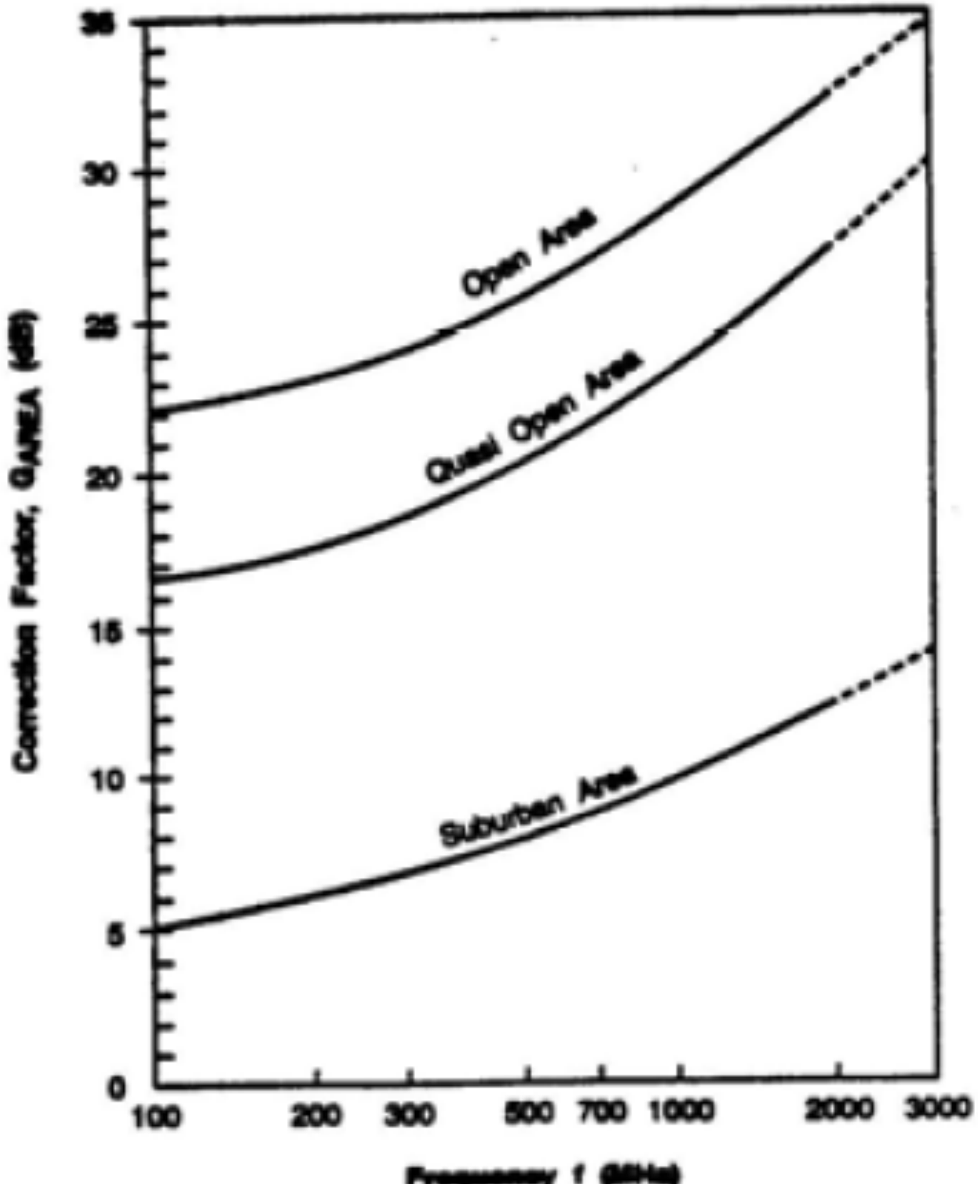

Figure 4.24 Correction factor, G_{AREA}, for different types of terrain [from [Oku68] © IEEE].

Okumura Model

Antenna height correction factors:

$$G(h_{te}) = 20\log_{10}(h_{te}/200), \quad 30 \text{ m} < h_{te} < 1000 \text{ m}$$

$$G(h_{re}) = 10\log_{10}(h_{re}/3), \quad h_{re} < 3\text{m}$$

$$G(h_{re}) = 20\log_{10}(h_{re}/3), \quad 3 \text{ m} < h_{re} < 10 \text{ m}$$

Example 3.10

Find the median path loss using Okumura's model for $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m in a suburban environment. If the base station transmitter radiates an EIRP of 1 kW at a carrier frequency of 900 MHz, find the power at the receiver (assume a unity gain receiving antenna).

Solution to Example 3.10

The free space path loss L_F can be calculated using equation (3.6) as

$$L_F = 10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] = 10\log\left[\frac{(3\times 10^8/900\times 10^6)^2}{(4\pi)^2\times(50\times 10^3)^2}\right] = 125.5\ \text{dB}.$$

From the Okumura curves

$$A_{mu}(900\ \text{MHz}(50\ \text{km})) = 43\ \text{dB}$$

and

$$G_{AREA} = 9\ \text{dB}.$$

Using equation (3.81.a) and (3.81.c) we have

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) = 20\log\left(\frac{100}{200}\right) = -6\ \text{dB}.$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) = 20\log\left(\frac{10}{3}\right) = 10.46\ \text{dB}.$$

Using equation (3.80) the total mean path loss is

$$\begin{aligned} L_{50}(\text{dB}) &= L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \\ &= 125.5\ \text{dB} + 43\ \text{dB} - (-6)\ \text{dB} - 10.46\ \text{dB} - 9\ \text{dB} \\ &= 155.04\ \text{dB}. \end{aligned}$$

Therefore, the median received power is

$$\begin{aligned} P_r(d) &= EIRP(\text{dBm}) - L_{50}(\text{dB}) + G_r(\text{dB}) \\ &= 60\ \text{dBm} - 155.04\ \text{dB} + 0\ \text{dB} = -95.04\ \text{dBm}. \end{aligned}$$

Hata Model

An easy to use model that is quite popular is the Hata/Okumura model defined using by following assumptions:

Base station height: between 30 and 200 meters
Carrier frequency: between 150 and 1,500 MHz
Mobile station antenna height: between 1 and 10 meters
Distance from BS to MS: between 1 and 20 meters

For these assumptions, the model on the following page applies. Note that the model is used to calculate path loss. The path is converted to a dB scale and subtracted from the transmitted power expressed in dB.

Hata Model

The path loss (in dB) for urban areas is given in the Hata model as

$$L_{50}(urban) = 69.55 + 26.16\log_{10} f_c - 13.82\log_{10} h_{te} - a(h_{re}) + (44.9 - 6.55\log_{10} h_{te})\log_{10} d$$

For various environments we apply a correction factor for the mobile antenna height. For a small to medium size city

$$a(h_{re}) = (1.1\log_{10} f_c - 0,7)h_{re} - (1.56\log_{10} f_c - 0.8)$$

For a large city the correction factors take the form

$$a(h_{re}) = 8.29(\log_{10} 1.54 h_{re})^2 - 1.1, \qquad f_c < 300 \text{ MHz}$$
$$a(h_{re}) = 3.2(\log_{10} 11.75 h_{re})^2 - 4.97, \qquad f_c > 300 \text{ MHz}$$

Hata Model

For a suburban area the original expression is modified as

$$L_{50}(suburban) = L_{50}(urban) - 2\left[\log(f_c/28)\right]^2 - 5.4$$

Finally for open rural areas we have

$$L_{50}(suburban) = L_{50}(urban) - 4.78\left[\log(f_c)\right]^2 + 18.33\log_{10}(f_c) - 40.94$$

Note that the Hata model is a formula and does not have the path specific graphical corrections available in the Okumura model.

Model Accuracy

As previously illustrated, a random variable may be added to account for random fluctuations due to shadowing.

Keep in mind that these models are not very precise and provide only very rough approximations. The approximations are useful however.

Empirical Path Loss: Okamura, Hata, COST231

- Empirical models include effects of path loss, shadowing and multipath.
  - Multipath effects are averaged over several wavelengths: local mean attenuation (LMA)
  - Empirical path loss for a given environment is the average of LMA at a distance d over all measurements
- **Okamura**: based upon Tokyo measurements. 1-100 lm, 150-1500MHz, base station heights (30-100m), median attenuation over free-space-loss, 10-14dB standard deviation.

$$P_L(d) \text{ dB} = L(f_c, d) + A_{mu}(f_c, d) - G(h_t) - G(h_r) - G_{AREA}$$

- **Hata**: closed form version of Okamura

$$P_{L,urban}(d) \text{ dB} = 69.55 + 26.16 \log_{10}(f_c) - 13.82 \log_{10}(h_t) - a(h_r) + (44.9 - 6.55 \log_{10}(h_t)) \log_{10}(d). \quad (2.31)$$

- **COST 231:** Extensions to 2 GHz

$$P_{L,urban}(d)\text{dB} = 46.3 + 33.9 \log_{10}(f_c) - 13.82 \log_{10}(h_t) - a(h_r) + (44.9 - 6.55 \log_{10}(h_t)) \log_{10}(d) + C_M, \quad (2.34)$$