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

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

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

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

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

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**, **σ** (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 σ are computed from measured data, using linear regression such that the difference between the measured and estimated path losses **is minimized in a mean square error sense** 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.

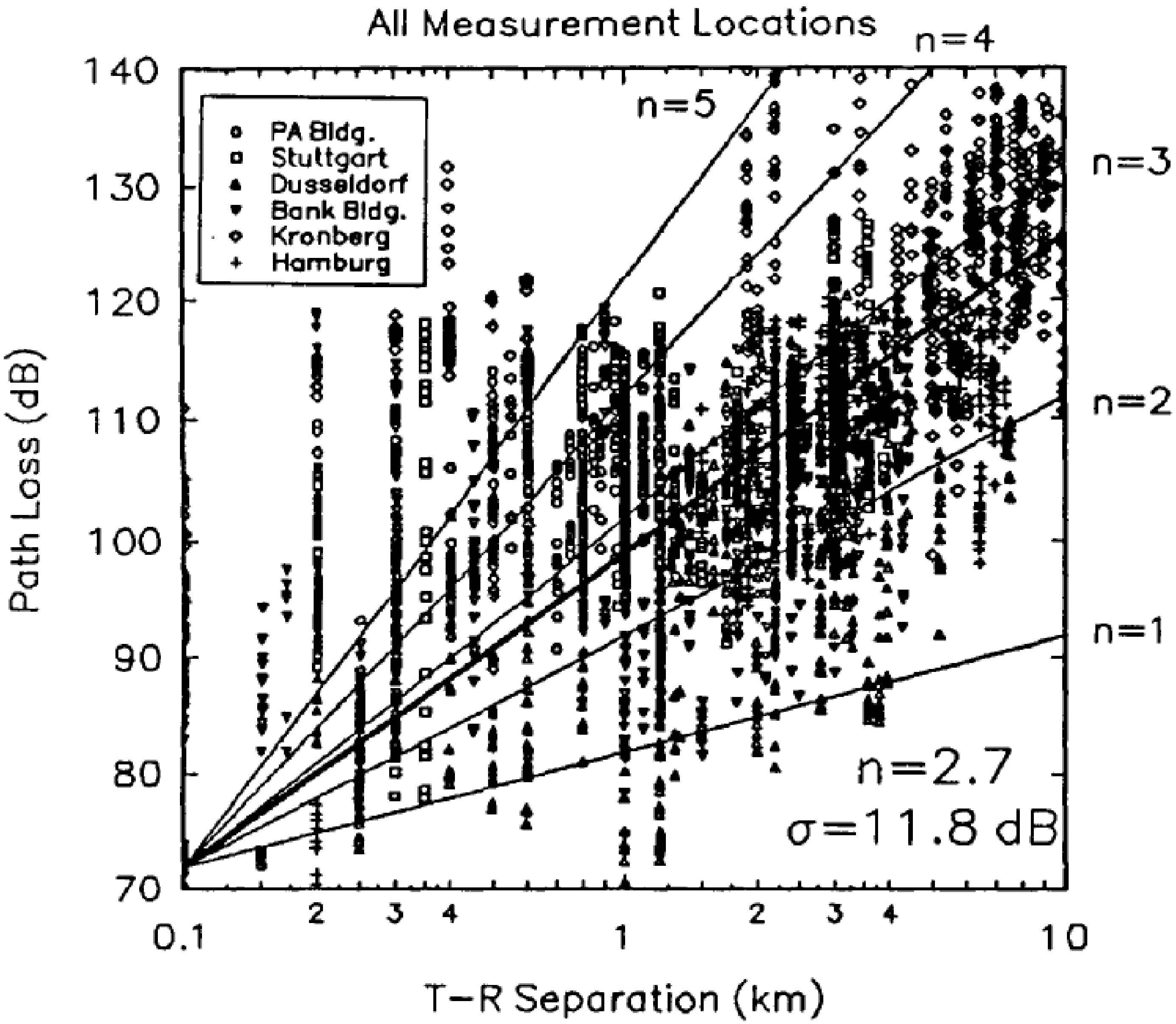

Figure 3.17
Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [From [Sei91] © IEEE].

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.