Table 2.1: Typical partition losses

Partition type	Partition loss (dB)
Cloth partition	1.4
Double plasterboard wall	3.4
Foil insulation	3.9
Concrete wall	13
Aluminum siding	20.4
All metal	26

where FAF_i represents the floor attenuation factor for the ith floor traversed by the signal and PAF_i represents the partition attenuation factor associated with the ith partition traversed by the signal. The number of floors and partitions traversed by the signal are N_f and N_p, respectively.

Another important factor for indoor systems whose transmitter is located outside the building is building penetration loss. Measurements indicate that building penetration loss is a function of frequency, height, and the building materials. Building penetration loss on the ground floor typically ranges from 8 dB to 20 dB for 900 MHz to 2 GHz [1; 52; 53]. The penetration loss decreases slightly as frequency increases, and it also decreases by about 1.4 dB per floor at floors above the ground floor. This decrease in loss is typically due to reduced clutter at higher floors and the higher likelihood of an LOS path. The type and number of windows in a building also have a significant impact on penetration loss [54]. Measurements made behind windows have about 6 dB less penetration loss than measurements made behind exterior walls. Moreover, plate glass has an attenuation of around 6 dB whereas lead-lined glass has an attenuation of between 3 and 30 dB.

2.6 Simplified Path-Loss Model

The complexity of signal propagation makes it difficult to obtain a single model that characterizes path loss accurately across a range of different environments. Accurate path-loss models can be obtained from complex analytical models or empirical measurements when tight system specifications must be met or the best locations for base stations or access-point layouts must be determined. However, for general trade-off analysis of various system designs it is sometimes best to use a simple model that captures the essence of signal propagation without resorting to complicated path-loss models, which are only approximations to the real channel anyway. Thus, the following simplified model for path loss as a function of distance is commonly used for system design:

$$P_r = P_t K \left[\frac{d_0}{d}\right]^{\gamma}. \tag{2.39}$$

The dB attenuation is thus

$$P_r \text{ dBm} = P_t \text{ dBm} + K \text{ dB} - 10\gamma \log_{10}\left[\frac{d}{d_0}\right]. \tag{2.40}$$

In this approximation, K is a unitless constant that depends on the antenna characteristics and the average channel attenuation, d_0 is a reference distance for the antenna far field, and γ is the path-loss exponent. The values for K, d_0, and γ can be obtained to approximate either an analytical or empirical model. In particular, the free-space path-loss model, the two-ray model, the Hata model, and the COST extension to the Hata model are all of the same form as

Table 2.2: Typical path-loss exponents

Environment	γ range
Urban macrocells	3.7–6.5
Urban microcells	2.7–3.5
Office building (same floor)	1.6–3.5
Office building (multiple floors)	2–6
Store	1.8–2.2
Factory	1.6–3.3
Home	3

(2.40). Because of scattering phenomena in the antenna near field, the model (2.40) is generally valid only at transmission distances $d > d_0$, where d_0 is typically assumed to be 1–10 m indoors and 10–100 m outdoors.

When the simplified model is used to approximate empirical measurements, the value of $K < 1$ is sometimes set to the free-space path gain at distance d_0 assuming omnidirectional antennas:

$$K \text{ dB} = 20\log_{10}\frac{\lambda}{4\pi d_0}, \tag{2.41}$$

and this assumption is supported by empirical data for free-space path loss at a transmission distance of 100 m [41]. Alternatively, K can be determined by measurement at d_0 or optimized (alone or together with γ) to minimize the mean-square error (MSE) between the model and the empirical measurements [41]. The value of γ depends on the propagation environment: for propagation that approximately follows a free-space or two-ray model, γ is set to 2 or 4 (respectively). The value of γ for more complex environments can be obtained via a minimum mean-square error (MMSE) fit to empirical measurements, as illustrated in Example 2.3. Alternatively, γ can be obtained from an empirically based model that takes into account frequency and antenna height [41]. Table 2.2 summarizes γ-values for different environments (data from [5; 33; 41; 44; 46; 47; 52; 55]). Path-loss exponents at higher frequencies tend to be higher [46; 51; 52; 56] whereas path-loss exponents at higher antenna heights tend to be lower [41]. Note that the wide range of empirical path-loss exponents for indoor propagation may be due to attenuation caused by floors, objects, and partitions (see Section 2.5.5).

EXAMPLE 2.3: Consider the set of empirical measurements of P_r/P_t given in Table 2.3 for an indoor system at 900 MHz. Find the path-loss exponent γ that minimizes the MSE between the simplified model (2.40) and the empirical dB power measurements, assuming that $d_0 = 1$ m and K is determined from the free-space path-gain formula at this d_0. (We minimize the MSE of the dB values rather than the linear values because this generally leads to a more accurate model.) Find the received power at 150 m for the simplified path-loss model with this path-loss exponent and a transmit power of 1 mW (0 dBm).

Solution: We first set up the MMSE error equation for the dB power measurements as

$$F(\gamma) = \sum_{i=1}^{5}[M_{\text{measured}}(d_i) - M_{\text{model}}(d_i)]^2,$$

where $M_{\text{measured}}(d_i)$ is the path-loss measurement in Table 2.3 at distance d_i and where $M_{\text{model}}(d_i) = K - 10\gamma\log_{10}(d)$ is the path loss at d_i based on (2.40). Now using the free-space path-loss formula yields $K = 20\log_{10}(.3333/(4\pi)) = -31.54$ dB. Thus

Table 2.3: Path-loss measurements

Distance from transmitter	$M = P_r/P_t$
10 m	−70 dB
20 m	−75 dB
50 m	−90 dB
100 m	−110 dB
300 m	−125 dB

$$\begin{aligned} F(\gamma) &= (-70 + 31.54 + 10\gamma)^2 + (-75 + 31.54 + 13.01\gamma)^2 \\ &\quad + (-90 + 31.54 + 16.99\gamma)^2 + (-110 + 31.54 + 20\gamma)^2 \\ &\quad + (-125 + 31.54 + 24.77\gamma)^2 \\ &= 21676.3 - 11654.9\gamma + 1571.47\gamma^2. \end{aligned} \tag{2.42}$$

Differentiating $F(\gamma)$ relative to γ and setting it to zero yields

$$\frac{\partial F(\gamma)}{\partial \gamma} = -11654.9 + 3142.94\gamma = 0 \implies \gamma = 3.71.$$

For the received power at 150 m under the simplified path-loss model with $K = -31.54$, $\gamma = 3.71$, and $P_t = 0$ dBm, we have $P_r = P_t + K - 10\gamma \log_{10}(d/d_0) = 0 - 31.54 - 10 \cdot 3.71 \log_{10}(150) = -112.27$ dBm. Clearly the measurements deviate from the simplified path-loss model; this variation can be attributed to shadow fading, described in Section 2.7.

2.7 Shadow Fading

A signal transmitted through a wireless channel will typically experience random variation due to blockage from objects in the signal path, giving rise to random variations of the received power at a given distance. Such variations are also caused by changes in reflecting surfaces and scattering objects. Thus, a model for the random attenuation due to these effects is also needed. The location, size, and dielectric properties of the blocking objects – as well as the changes in reflecting surfaces and scattering objects that cause the random attenuation – are generally unknown, so statistical models must be used to characterize this attenuation. The most common model for this additional attenuation is log-normal shadowing. This model has been empirically confirmed to model accurately the variation in received power in both outdoor and indoor radio propagation environments (see e.g. [41; 57]).

In the log-normal shadowing model, the ratio of transmit-to-receive power $\psi = P_t/P_r$ is assumed to be random with a log-normal distribution given by

$$p(\psi) = \frac{\xi}{\sqrt{2\pi}\sigma_{\psi_{\mathrm{dB}}}\psi} \exp\left[-\frac{(10\log_{10}\psi - \mu_{\psi_{\mathrm{dB}}})^2}{2\sigma^2_{\psi_{\mathrm{dB}}}}\right], \quad \psi > 0, \tag{2.43}$$

where $\xi = 10/\ln 10$, $\mu_{\psi_{\mathrm{dB}}}$ is the mean of $\psi_{\mathrm{dB}} = 10\log_{10}\psi$ in decibels, and $\sigma_{\psi_{\mathrm{dB}}}$ is the standard deviation of ψ_{dB} (also in dB). The mean can be based on an analytical model or