Chapter 2 Pass Loss and Shadowing

In a mobile system, signals are transmitted through a very hostile transmission environment. The distortions introduced during transmission can raise error nearly in every fraction of a signal during transmission. It is thus important to model transmission channels using relatively simple mathematical method, so as to predict the system behaviors and to minimize the detrimental effect of the distortions.

The following is a list of typical distortions,

- additive noise;
- path loss;
- random delay;
- large-scale and small-scale fading;
- frequency shift;
- interference from same-cell and other-cell users.

In a practical environment, the effect of distortions can be any combination of the ones listed above.

The mechanisms behind electromagnetic wave propagation are diverse, which makes it difficult to describe the characteristics of the signals in mobile channel. Many propagation models have been studied with focus on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity to a particular location.

Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver (T-R) separation distance are useful in estimating the radio coverage area of a transmitter and are called large-scale fading models. They characterize signal strength over large T-R separation distances (several hundreds or thousands of meters). On the other hand, propagation models that characterize the rapid fluctuations of the received signal strength over very short travel distances (a few wavelengths) or short time durations (on the order of seconds) are called small-scale fading models.

In this chapter, we discuss large-scale fading models incurred during wireless signal propagation. Such losses are mainly related to distance and blockage of objects.

Part 1 Path loss

Free space propagation model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. Satellite communication systems and microwave line-of-sight radio links typically undergo free space propagation.

In free space, the received power decays as a function of the transmitter - receiver separation distance d. It follows that

$$\frac{P_r}{P_t} = \left(\frac{\left(\sqrt{G_t G_r}\lambda\right)^2}{4\pi} \right) \left(\frac{1}{4\pi d^2} \right) = \left(\frac{\sqrt{G_t G_r}\lambda}{4\pi d} \right)^2 \tag{2.1}$$

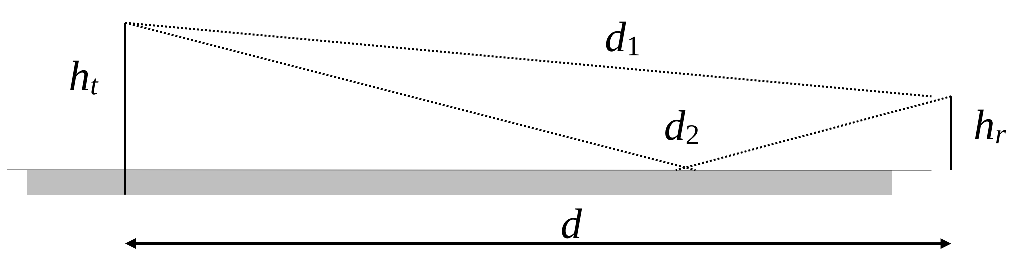
where P_t is the transmitted power, P_r is the received power, G_tG_r is the product of transmitter and receiver antenna gain, λ is the wavelength in meters. Then (2.1) can be rewritten in the dB form as

$$10\log_{10}\left(\frac{P_r}{P_t}\right) = 10\log_{10}\left(G_t G_r \lambda^2\right) - 10\gamma\log_{10}(4\pi d) \tag{2.2}$$

Here the index γ is called the "path loss slope" or "pass loss exponent". Clearly, in free spcace, $\gamma = 2$.

Ground reflection (2-ray) model

In a mobile radio channel, there are usually multiple paths between the transmitter and receiver. Hence propagation modeling is quite different from that in free space. In the following, we will discuss a two-ray model that results in a path loss exponent of 4. This model has been widely adapted for predicting the large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (heights which exceed 50 m), as well as for line-of-sight micro cell channels in urban environments.



In this model, we assume $d >> h_r$, h_t. Then the power attenuation on each path is given by (2.1). However, we need to pay special attention to the interaction of the signals from the two pathes: one line-of-sight and one reflected from earth surface. The plain earth can be regarded as approximately conductive. The reflection coefficient of the earth is then given by $\rho = -1$. The combined received power can be calculated as

$$\begin{aligned} P_r &= G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left|e^{-j2\pi f t_1} + \rho e^{-j2\pi f t_2}\right|^2 P_t \\ &= G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left|1 - e^{\frac{j2\pi f(d_1-d_2)}{c}}\right|^2 P_t \\ &= G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left|1 - e^{\frac{j2\pi\Delta d}{\lambda}}\right|^2 P_t \end{aligned} \tag{2.3}$$

where $\Delta d = d_1 - d_2$ is the difference between the lengths of two paths. Now consider approximation

$$1 - e^{\frac{j2\pi\Delta d}{\lambda}} = 1 - \left(1 + \frac{j2\pi\Delta d}{\lambda} + \frac{1}{2}\left(\frac{j2\pi\Delta d}{\lambda}\right)^2 + \ldots +\right) \tag{2.4}$$

Then (2.3) can be rewritten as for $\Delta d << \lambda$ (see a tutorial question)

$$P_r \approx G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left|\frac{2\pi\Delta d}{\lambda}\right|^2 P_t = G_t G_r \left|\frac{\Delta d}{2d}\right|^2 P_t \tag{2.5}$$

It can be shown that when $d >> h_r, h_t$,

$$\Delta d \approx \frac{2h_r h_t}{d} \tag{2.6}$$

Substitute (2.6) into (2.5) we have

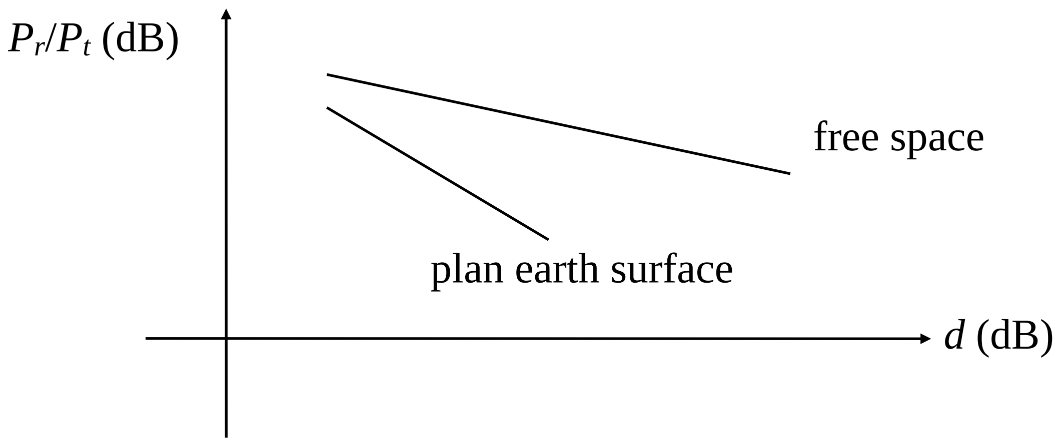
$$\frac{P_r}{P_t} = \frac{G_t G_r h_r^2 h_t^2}{d^4} \tag{2.7}$$

which can be rewritten in dB form as

$$10\log_{10}\left(\frac{P_r}{P_t}\right) = 10\log_{10}\left(G_t G_r\right) + 20\log_{10}\left(h_t h_r\right) - 10\gamma\log_{10}\left(d\right) \tag{2.8}$$

Thus on the surface of the earth the path loss slope is $\gamma = 4$.

The key in the above derivation is the assumption that $\rho = -1$. This leads to the cancellation between the direct and reflected signals in (2.4). This cancelation is not complete. The residual part (related to Δd in (2.4)) reduces with d as shown in (2.6). This leads to the loss exponent of 4.



Question 1) Do we prefer a path loss exponent γ of 2 or 4 from a battery life point of view?

Question 2) Do we prefer a path loss exponent γ of 2 or 4 from a cellular capacity point of view?

<u>Other path loss factors</u>

There are many other factors that can cause path loss. For example, in an indoor environment, path loss can be affected by the materials used for walls and floors, the layout of rooms, hallways, windows and open areas, the location and material of obstructing objects, and the size of each room and the number of floors. All of these factors have a significant impact on path loss in an indoor environment. Thus, it is difficult to find generic models that can be accurately applied to determine empirical path loss in a specific indoor setting.

Some measurements for the partition loss at different frequencies for different partition types are summarized in Table 2.1 at 900-1300 MHz range.

Partition Type	Partition Loss in dB
Cloth Partition	1.4
Double Plasterboard Wall	3.4
Foil Insulation	3.9
Concrete wall	13
Aluminum Siding	20.4
All Metal	26

Table 2.1: Typical Partition Losses

Inlcuding other loss factors, we rewrite the path model as

$$P_r \text{ dB} = P_t \text{ dB} + K \text{ dB} - 10\gamma \log_{10}(d). \qquad (2.9)$$

In this expression, K is a unitless constant that depends on the antenna characteristics and channel conditions, and γ is the path loss exponent. The values for K and γ are used to approximate either an analytical or empirical model. In particular, the free space path loss model and the two-ray model (as well as the COST model discussed below) are special cases of (2.9). Due to scattering phenomena in the antenna near-field, the model (2.9) is generally only valid at transmission distances $d > d_0$, where d_0 is typically assumed to be 1-10 m indoors and 10-100 m outdoors.

Practical path loss exponents

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 from empirical measurements. Alternatively, γ can also be obtained from an appropriate model that takes into account carrier frequency and antenna height. A table summarizing γ values for different indoor and outdoor environments and antenna heights at 900 MHz to 1.9 GHz is given below. Path loss exponents at higher frequencies tend to be higher while path loss exponents at higher antenna heights tend to be lower. Note that the wide range of empirical path loss exponents for indoor propagation may be due to attenuation caused by floors, objects, and partitions.

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

Table 2.2: Typical Path Loss Exponents

<u>COST 231 model</u>

The European cooperative for scientific and technical research (EURO-COST) specifies the following model systems.

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

where $a(h_r)$ is a correction factor and C_M is 0dB for medium sized cities and suburbs, and 3dB for metropolitan areas. This model is referred to as the COST 231 model, and is restricted to the following range of parameters:

$1.5 \text{ GHz} < f_c < 2 \text{ GHz}$,
$30 \text{ m} < h_t < 200 \text{ m}$,
$1 \text{ m} < h_r < 10 \text{ m}$, and
$1 \text{ Km} < d < 20 \text{ Km}$.

This model has been widely used for system simulations. The COST model provides a unified platform to compare different technologies, as physical measurements are very expensive. New proposals for cellular systems are usually first simulated, assessed and compared using the COST model before going to field experiment.

Part 2 Shadowing
Shadow Fading

A log-normal distribution is defined as follows. Let ψ be a random variable. Denote

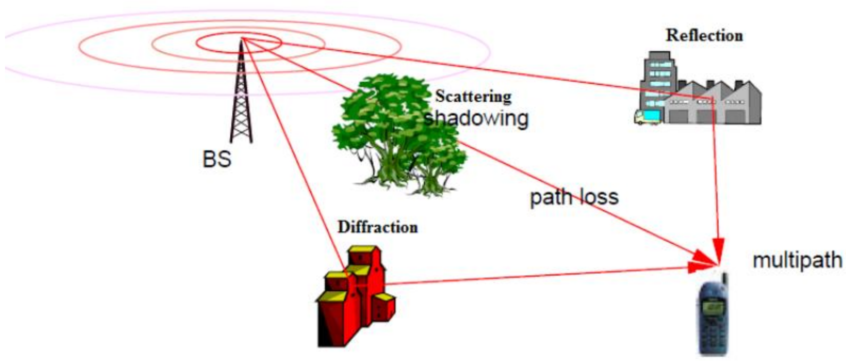
$$\psi_{\mathrm{dB}} \equiv 10\log_{10}(\psi) \tag{2.10}$$

Then the distribution of ψ is log-normal if the distribution of ψ_{dB} is Gaussian, i.e.,

$$p(\psi_{\mathrm{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi\mathrm{dB}}}\exp\left(-\frac{(\psi_{\mathrm{dB}}-\mu_{\psi\mathrm{dB}})^2}{2\sigma_{\psi\mathrm{dB}}^2}\right) \tag{2.11}$$

with $\mu_{\psi\mathrm{dB}}$ the mean of ψ_{dB} and $\sigma_{\psi\mathrm{dB}}$ the standard deviation, both in dB.

The log-normal distribution is widely used to characterize the so-called shadowing loss. The latter is caused by blockage from objects in the signal path. Such objects are randomly located and so statistical models must be used.



The combined effect of distance loss and shadowing loss can be described by the following path model.

$$\frac{P_r}{P_t} = \frac{K}{\psi} d^{-\gamma}, \tag{2.12a}$$

or in the dB form as

$$10\log_{10}\left(\frac{P_r}{P_t}\right) = 10\log_{10} K - 10\gamma \log_{10}(d) - \psi_{dB}, \tag{2.12b}$$

where K is an appropriate constant depending on antenna characteristics. Typical parameters (obtained empirically) for ψ_{dB} are $\mu_{\psi\mathrm{dB}} = 0$ and $\sigma_{\psi dB} = 8$. The range of γ can be found in Table 2.2.

The above is a very simplified model. More sophisticated models can also be eveloped similar to the COST model.

The figure below illustrates the contour of constant received power based on a fixed transmit power at the base station. For path loss and average shadowing, the constant power contour forms a circle around the base station. For path loss and random shadowing, the constant contour forms an amoeba-like shape due to the random shadowing variations.

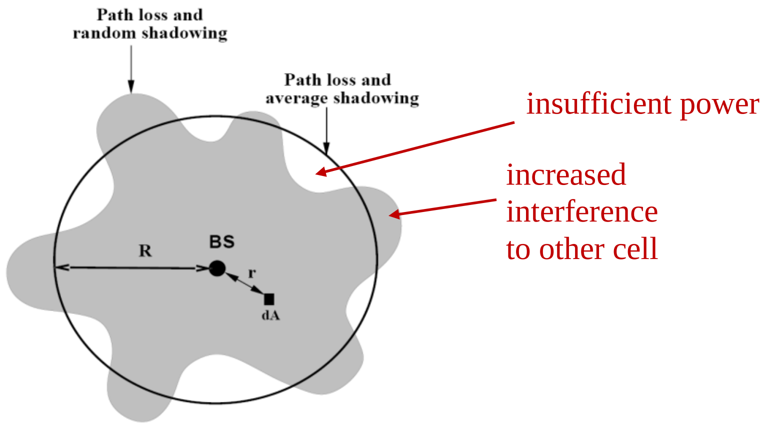


Figure 2.10: Contours of Constant Received Power.

The above figure shows a potential problem caused by shadowing. Assume that the contour is given by the minimum required SNR. Some users in the cell may not have enough SNR if they are outside the contour. On the other hand, we can increase the transmit power to extend the contour. But then the interference to other cell may become a serious issue.

The effects of reflection and diffraction will be discussed in Chapter 3.

Chapter 2 Summary

The main results for large-scale fading are summarized in (2.12a) as

$$\frac{P_r}{P_t} = \frac{K}{\psi} d^{-\gamma},$$

or in dB

$$10\log_{10}\left(\frac{P_r}{P_t}\right) = 10\log_{10} K - 10\gamma \log_{10}(d) - \psi_{dB}.$$

The above provides an overall view of large-scale loss. The distribution of ψ_{dB} is Gaussian and the related fading is called log-normal fading.

On the earth surface, the typical path loss slope is 4. In reality, the path loss slope varies in a very large range.