Chapter 2 Pass Loss

Introduction

Introduction

In a mobile system, signals are transmitted through a very hostile channel environment. The distortions introduced during transmission can result in serious error. It is thus important to understand the channel environment and to model transmission channels accurately. This will help us to design techniques to overcome channel 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.

Introduction

The mechanisms behind electromagnetic wave propagation are diverse, which makes mobile channels a difficult topic. Different propagation models have been studied that focus on different aspects of the channel, such as the average signal power at a given distance from the transmitter, or the variation of signal power in close spatial proximity to a particular location.

Large-scale fading models characterize signal strength over relatively large travel distances (several hundreds or thousands of meters) between a transmitter and a receiver.

Small-scale fading models characterize the rapid fluctuations of the received signal strength over very short travel distances (a few wavelengths) or short time durations.

In this chapter, we discuss large-scale fading models. Such losses are mainly related to distance and blocking effect.

2.1 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

$$\text{channale gain} = \frac{P_r}{P_t} = \left(\frac{\left(\sqrt{G_t G_r}\,\lambda\right)^2}{4\pi} \right) \left(\frac{1}{4\pi d^2} \right) = \left(\frac{\sqrt{G_t G_r}\,\lambda}{4\pi d} \right)^2 \qquad (2.1)$$

where P_t is the transmitted power, P_r is the received power, $G_t G_r$ is the product of transmitter and receiver antenna gain, λ is the wavelength in meters.

Free space propagation model

Then (2.1) can be rewritten in the dB form as

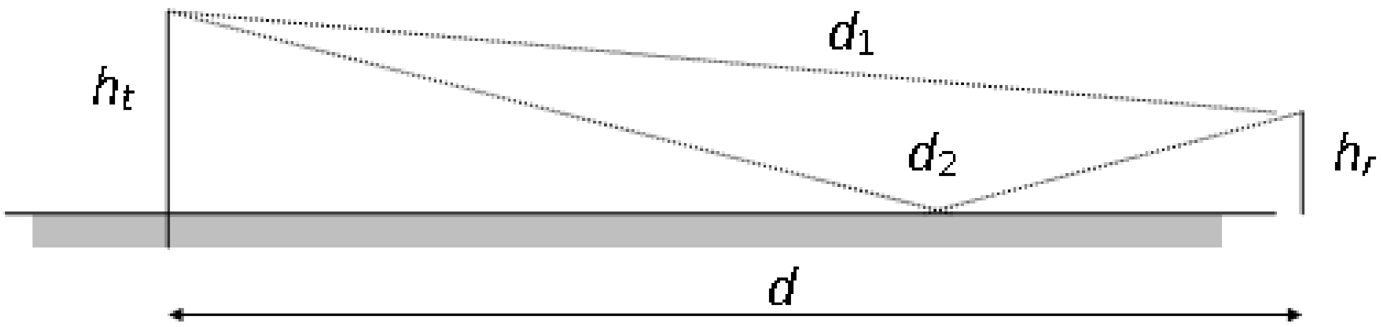
$$10\log_{10}\left(\frac{P_r}{P_t}\right)=10\log_{10}\left(G_tG_r\lambda^2\right)-\gamma 10\log_{10}(4\pi d)$$

(2.2）

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

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.



Ground reflection (2-ray) model

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 paths: 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

$$P_r = G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left| e^{\frac{-j2\pi f d_1}{c}} + \rho e^{\frac{-j2\pi f d_2}{c}} \right|^2 P_t$$

$$= G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left| 1 - e^{\frac{j2\pi f (d_1 - d_2)}{c}} \right|^2 P_t$$

$$= G_t G_r \left|\frac{\lambda}{4\pi d}\right|^2 \left| 1 - e^{\frac{j2\pi \Delta d}{\lambda}} \right|^2 P_t \qquad (2.3)$$

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

Ground reflection (2-ray) model

Now consider approximation

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

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

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

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

$$\Delta d \approx \frac{2h_r h_t}{d}. \qquad (2.6)$$

Substitute (2.6) into (2.5) we have

$$\frac{P_r}{P_t}=\frac{G_t G_r h_r^2 h_t^2}{d^4}. \qquad (2.3)$$

which can be rewritten in dB form as

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

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

Ground reflection (2-ray) model

To simplify notation, we write the two-ray as follows

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

where K represents the combined effect of transmit and receive antennas and γ is the path loss exponent. K is a unitless constant that depends on the antenna characteristics and other channel conditions.

The dB value of channel gain is given by

$$10\log_{10}(P_r/P_t) = 10\log_{10} K - 10\gamma \log_{10}(d).$$

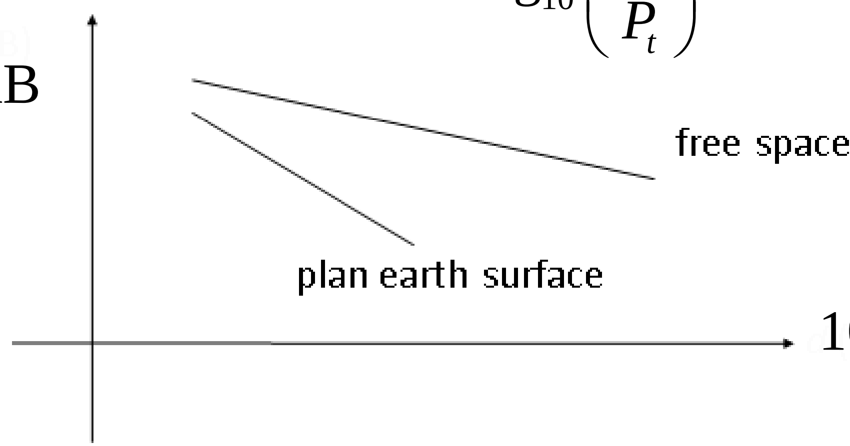
In particular, the 2-ray model is generally only valid for $d > d_0$, where d_0 is typically assumed to be 1-10 m indoors and 10-100 m outdoors. For $d < d_0$, we need to consider the line-of-sight effect.

Ground reflection (2-ray) model

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.

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

$10\log_{10}\left(\frac{P_r}{P_t}\right)$ in dB



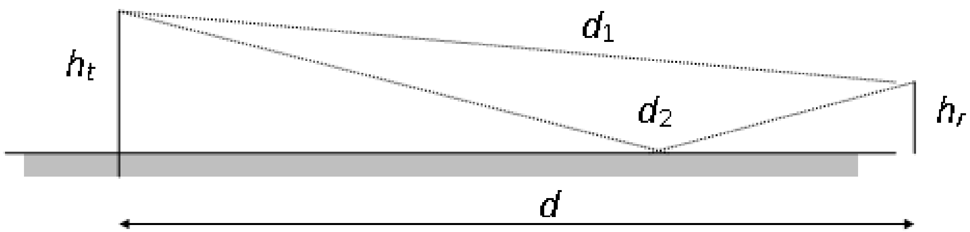
$10\log_{10}(d)$ in dB

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

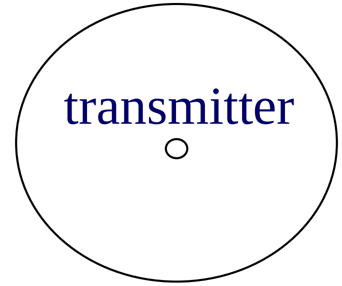
Question 2) Do we prefer a path loss exponent γ of 2 or 4 from a cellular capacity point of view?

2.2 Other Path Loss Effects

Partition loss



equal power contour



In practice, the 2-ray model is still too idealistic. Many factors can affect path loss. For example, it can be affected by the materials used for partition such as walls, floors and windows. It is difficult to find a general model that accurately predict actual path loss in a specific setting.

Partition loss

Return to the path model

$$10\log_{10}(P_r/P_t) = 10\log_{10}(K) - \gamma\, 10\log_{10}(d). \qquad (2.9)$$

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 values of K and γ for more complex environments can be obtained from measurements, or using appropriate models.

Tables summarizing K and γ values for different indoor and outdoor environments and antenna heights at 900 MHz to 1.9 GHz are given below.

Partition loss

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

Practical path-loss exponents

Measured path loss exponents tend to be higher at higher frequencies, and lower at higher antenna heights. 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

COST 231 model

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.

The above model is referred to as the COST 231 model, and is restricted to the following range of parameters:

$1.5 \text{ GHz} < f_c < 2 \text{ GHz}$, $1 \text{ Km} < d < 20 \text{ Km}$,

$30 \text{ m} < h_t < 200 \text{ m}$, $1 \text{ m} < h_r < 10 \text{ m}$.

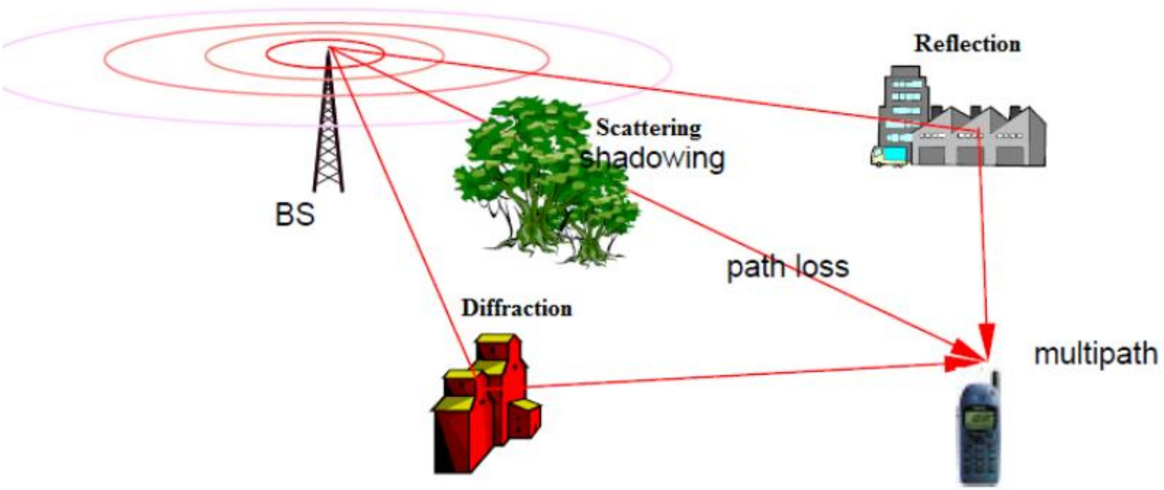
This model has been widely used for system simulations. The COST model provides a unified platform to compare different technologies.

Field measurements are very expensive. New system proposals are usually first simulated and compared using the COST model before field experiment.

2.3 Large-scale fading

Large-scale fading

Large-scale fading is also called shadowing or slow-fading. It represents the blockage effect caused by large objects such as walls, trees or buildings between the transmitter and the receiver. Such objects are randomly located. Their combined effect is statistical.



Large-scale fading

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

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

or in the dB form as

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

Here ψ_{dB} is widely modeled using the log-normal distribution. The accuracy of the modelling is verified by experiments.

Large-scale fading

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

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

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

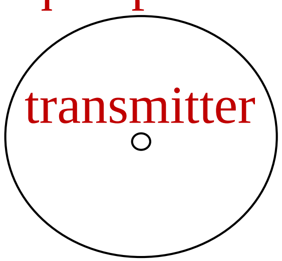
$$p(\psi_{\mathrm{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi\mathrm{dB}}}\exp\left(-\frac{(\psi_{\mathrm{dB}} - \mu_{\psi\mathrm{dB}})^2}{2\sigma_{\psi\mathrm{dB}}^2}\right) \qquad (2.11)$$

with $\mu_{\psi\mathrm{dB}}$ the mean of ψ_{dB} and $\sigma_{\psi\mathrm{dB}}$ the standard deviation, both in dB. Typical parameters (obtained empirically) for ψ_{dB} are $\mu_{\psi\mathrm{dB}} = 0$ and $\sigma_{\psi\mathrm{dB}} = 8$.

Contour of received power

Combining all the effects discussed above, the received power follows a random and highly irregular pattern. The figure below illustrates the contour of constant received power for a fixed transmit power at the base station. Ideally, the constant power contour should be a circle around the base station. In practice, the contour forms an amoeba-like shape due to the random shadowing variations.

ideal equal power contour



practial equal power contour

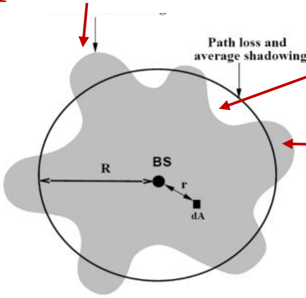


Figure 2.10: Contours of Constant Received Power.

insufficient power

increased interference to other cell

This illustrates a potential problem for a cellular system. Some users in a 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 that may lead to serious interference to other cell at certain directions.

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.