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CHAPTER 2

CHARACTERISTICS OF THE WIRELESS MEDIUM

2.1 INTRODUCTION

In the past century, analysis, modeling, and simulation of radio propagation for a variety of applications have been studied in depth. In the 1970s, modeling of radio propagation for cellular networks operating from a mobile vehicle was investigated, and in the 1980s it was extended to include modeling of indoor radio propagation for cordless telephony and wireless LAN applications. References [JAK94], [LEE98], [RAP95], [BER00] provide details of these studies for mobile radio applications, and [PAH95] provides an overview with emphasis on indoor applications. This chapter discusses radio propagation modeling and simulation for wireless applications which we believe are necessary for a systems engineer to understand the principles of design and deployment of wireless networks. The details needed for development of an intuition and an understanding of how the wireless medium operates are discussed, and we give a number of models that can be used for simulation of the behavior of the wireless medium. We also point to current and emerging issues in radio channel modeling for wireless applications.

2.1.1 Comparison of Wired and Wireless Media

A wired medium provides a reliable, *guided* link that conducts an electric signal associated with the transmission of information from one fixed terminal to another. There are a number of alternatives for wired connection that include twisted pair (TP) telephone wiring for high-speed LANs, coaxial cables used for television distribution, and optical fiber used in the backbone of long-haul connections. Wires act as *filters* that limit the maximum transmitted data rate of the channel because of band limiting frequency response characteristics. The signal passing through a wire also radiates outside of the wire to some extent which can cause interference to close-by radios or other wired transmissions. These characteristics differ from one wired medium to another. Laying additional cables in general can duplicate the wired medium, and thereby increase the bandwidth.

Compared with wired media, the wireless medium is unreliable, has a low bandwidth, and is of broadcast nature; however, it supports mobility due to its tetherless nature. Different signals through wired media are physically conducted through different wires, but all wireless transmissions share the same medium—air. Thus it is the frequency of operation and the legality of access to the band that differentiates a variety of alternative for wireless networking. Wireless networks operate around 1 GHz (cellular), 2 GHz (PCS and WLANs), 5 GHz (WLANs), 28–60 GHz (local multipoint distribution service [LMDS] and point-to-point base station connections), and IR frequencies for optical communications. These bands are either licensed, like cellular and PCS bands, or unlicensed, like the ISM bands or U-NII bands. As the frequency of operation and data rates increase, the hardware implementation cost increases, and the ability of a radio signal to penetrate walls decreases. The electronic cost has become less significant with time, but in-building penetration and licensed versus unlicensed frequency bands have become an important differentiation. For frequencies up to a few GHz, the signal penetrates through the walls, allowing indoor applications with minimal wireless infrastructure inside a building. At higher frequencies a signal that is generated outdoors does not penetrate into buildings, and the signal generated indoors stays confined to a room. This phenomenon imposes restrictions on the selection of a suitable band for a wireless application.

Example 2.1: In-building Penetration of Signals

If one intends to bring a wireless Internet service to the rooftop of a residence and distribute that service inside the house, using other alternatives such as existing cable or TP wiring, that person may select LMDS equipment operating in licensed bands at several tens of GHz. If the intention is to penetrate the signal into the building for direct wireless connection to a computer terminal, the person may prefer equipment operating in the unlicensed ISM bands at 900 MHz or 2.4 GHz. The first approach is more expensive because it operates at licensed higher frequencies, where implementation and the electronics are more expensive and the service provider has paid to obtain the frequency bands. The second solution does not have any interference control mechanism because it operates in unlicensed bands.

Example 2.2: Licensed versus Unlicensed Bands

This example clarifies the differentiation between licensed and unlicensed bands with an analogous situation. Assume we equate radio transmission to barbequing: the interference caused by the transmission is like the smoke of the barbeque, and the frequency band of operation is similar to the property in which the barbeque grill is fixed. Then we have the affluent (cellular voice operators) that can afford a backyard (a licensed band) to operate their services with reasonable smoke (interference) from their neighbors occasionally. The less prosperous operators with larger barbeque grills (wideband data service providers) cannot afford to have huge private backyards (licensed bands) and have to use the public park (large unlicensed bands). In public parks, the space is provided on a first-come, first-serve basis. The only rule that the government can exercise is to restrict the overall smoke (interference) created by each barbeque (user) so as to allow peaceful coexistence. Although it may sound scary, both public parks as well as private backyards are used through natural selection. Because licensed bands are very expensive (the PCS bands in the United States were sold for around $20 billion), it is time-consuming to deploy a number of new applications rapidly at low costs. As such, new applications such as WLANs and Bluetooth are evolving in unlicensed bands.

Wired media provide us an easy means to increase capacity—we can lay more wires where required if it is affordable. With the wireless medium, we are restricted to a limited available band for operation, and we cannot obtain new bands or easily duplicate the medium to accommodate more users. As a result, researchers have developed a number of techniques to increase the capacity of wireless networks to support more users with a fixed bandwidth. The simplest method, comparable to laying new wires in wired networks, is to use a cellular architecture that reuses the frequency of operation when two cells are at an adequate distance from one another. Then, to further increase the capacity of the cellular network, as explained in Chapter 5, one may reduce the size of the cells. In a wired network, doubling the number of wired connections allows twice the number of users at the expense of twice the number of wired connections to the terminals. In a wireless network, reducing the size of the cells by half allows twice as many users as in one cell. Reduction of the size of the cell increases the cost and complexity of the infrastructure that interconnects the cells.

2.1.2 Why Radio Propagation Studies?

An understanding of radio propagation is essential for coming up with appropriate design, deployment, and management strategies for any wireless network. In effect, it is the nature of the *radio channel* that makes wireless networks far more complicated than their wired counterparts. Radio propagation is heavily site-specific and can vary significantly depending on the terrain, frequency of operation, velocity of the mobile terminal, interference sources, and other dynamic factors. Accurate characterization of the radio channel through key parameters and a mathematical model is important for predicting signal coverage, achievable data rates, specific performance attributes of alternative signaling and reception schemes, analysis of interference from different systems, and determining the optimum location for installing base station antennas.

In Chapter 5, we look at cellular hierarchy, where cells are classified into femto-, pico-, micro-, macro-, and megacells depending on their size. Radio propagation is different in each of these cell types. Radio propagation in open areas is much different from radio propagation in indoor and urban areas. In open areas across small distances or free space, the signal strength falls as the square of the distance. In other terrain, the signal strength often falls at a much higher rate as a function of distance depending on the environment and radio frequency. In urban areas the shortest direct path (the line-of-sight [LOS] path) between the transmitter and receiver is usually blocked by buildings and other terrain features outdoors. Similarly in indoor areas, walls, floors, and interior objects within buildings obstruct LOS communications. Such scenarios are called non-LOS (NLOS) or obstructed LOS (OLOS). This further complicates radio propagation in these areas, and the signal is usually carried by a multiplicity of indirect paths with various signal strengths. The signal strengths of these paths depends on the distance they have traveled, the obstacles they have reflected from or passed through, the architecture of the environment, and the location of objects around the transmitter and receiver. Because signals from the transmitter arrive at the receiver via a multiplicity of paths with each taking a different time to reach the receiver, the resulting channel has an associated *multipath delay spread* that affects the reception of data.

The radio frequency of operation also affects radio propagation characteristics and system design. At lower frequencies (less than 500 MHz) in the radio spectrum, the signal strength loss is much smaller at the first meter. However, bandwidth is less plentiful, and the antenna sizes required are quite prohibitive for wide-scale deployment. The separation of antennas also has to be much larger, and it is challenging to adopt diversity schemes for improving signal quality. On the other hand, ample bandwidth is available at much higher frequencies (greater than a few GHz). At such frequencies, it is still possible to use sufficiently low-power transmitters (of about 1 W) for providing adequate signal coverage over a few floors of a multistory building, or a few kilometers outdoors in LOS situations. The antenna sizes are also on the order of an inch, making transmitters and receivers quite compact and efficient. Diversity techniques can be employed to improve the quality of reception because antenna separations can be small. The downside of using higher frequencies is that they suffer a greater signal strength loss at the first meter, and also suffer larger signal strength losses while passing through obstacles such as walls. At a few tens of gigahertz, signals are usually confined within the walls of a room. From a security point of view, this is an attractive feature of these frequencies. At even higher frequencies (such as 60 GHz), atmospheric gases such as oxygen absorb signals, which results in a much larger attenuation of signal strength as a function of distance.

In the rest of this chapter, we present an overview of radio propagation characteristics and radio channel modeling techniques that are important in modern wireless networks. A more detailed discussion can be found in [PAH95]. The three most important radio propagation characteristics used in the design, analysis, and installation of wireless networks are the achievable signal coverage, the maximum data rate that can be supported by the channel, and the rate of fluctuations in the channel. The achievable signal coverage for a given transmission power determines the size of a cell in a cellular topology and the range of operation of a base station transmitter. This is usually obtained via empirical path-loss models obtained by measuring the received signal strength as a function of distance. Most of the path loss models are characterized by a distance-power or path-loss *gradient* and a random component that characterizes the fluctuations around the average path loss due to shadow fading and other reasons. For efficient data communications, the maximum data rate that can be supported over a channel becomes an important parameter. Data rate limitations are influenced by the multipath structure of the channel and the fading characteristics of the multipath components. This also influences the signaling scheme and receiver design. Another factor that is intimately related to the design of the adaptive parts of the receiver such as timing and carrier synchronization, phase recovery, and so on is the rate of fluctuations in the channel, usually caused by movement of the transmitter, receiver, or objects in between. This is characterized by the *Doppler spread* of the channel. We consider path-loss models in detail and provide a summary of the effects of multipath and Doppler spread in subsequent sections of this chapter.

Depending on the data rates that need to be supported by an application and the nature of the environment, certain characteristics are much more important than others. For example, signal coverage and slow fading are more important for low data-rate narrowband systems such as cordless telephones, low-speed data, and cellular voice telephony. The multipath delay spread also becomes important for high data rate wideband systems, especially those that employ spread spectrum such as CDMA, WLANs, and 3G cellular services. Other areas where the properties of the radio channel become important are in determining battery consumption, the design of transmitter and receivers, the design of medium access control protocols, the design of adaptive and smart antennas, link-level monitoring for higher layer protocol performance (e.g., number of retransmissions tries, window sizes, etc.), the design of wireless protocols (handoffs, power control, co-channel rejection via color codes), and system design.

2.2 RADIO PROPAGATION MECHANISMS

Radio signals with frequencies above 800 MHz, used in the wireless networks described in this book, have extremely small wavelengths compared with the dimensions of building features, so electromagnetic waves can be treated simply as rays [BER94]. This means that ray-optical methods can be used to describe the propagation within and even outside buildings by treating electromagnetic waves as traveling along localized ray paths. The fields associated with the ray paths change sequentially based on the features of the medium that the ray encounters.

In order to describe radio propagation with ray optics, three basic mechanisms [RAP95, PAH95] are generally considered while ignoring other complex mechanisms. These mechanisms are illustrated in Figures 2.1 and 2.2 for indoor and outdoor applications, respectively.

1. *Reflection and transmission.* Specular reflections and transmission occur when electromagnetic waves impinge on obstructions larger than the wavelength.

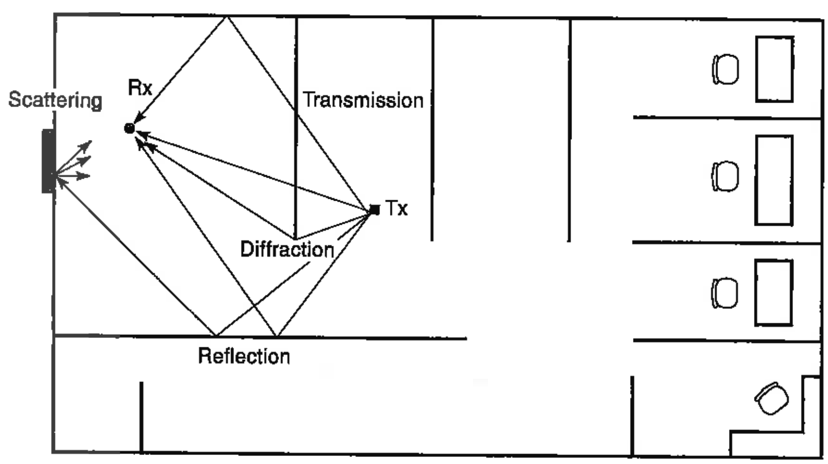

Figure 2.1 Radio propagation mechanisms in an indoor area.

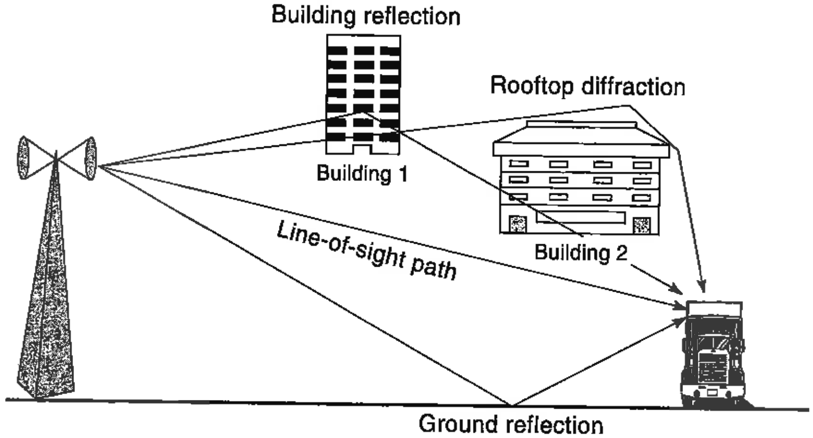

Figure 2.2 Radio propagation mechanisms in an outdoor area.

Usually rays incident upon the ground, walls of buildings, the ceiling, and the floor undergo specular reflection and transmission with the amplitude coefficients usually determined by plane wave analysis. Upon reflection or transmission, a ray attenuates by factors that depend on the frequency, the angle of incidence, and the nature of the medium (its material properties, thickness, homogeneity, etc.). These mechanisms often dominate radio propagation in indoor applications. In outdoor urban areas, this mechanism often loses its importance because it involves multiple transmissions that reduce the strength of the signal to negligible values.

2. *Diffraction.* Rays that are incident upon the edges of buildings, walls, and other large objects can be viewed as exciting the edges to act as a secondary line source. Diffracted fields are generated by this secondary wave source and propagate away from the diffracting edge as cylindrical waves. In effect, this results in propagation into *shadowed* regions because the diffracted field can reach a receiver, which is not in the line of sight of the transmitter. Because a secondary source is created, it suffers a loss much greater than that experienced via reflection or transmission. Consequently, diffraction is an important phenomenon outdoors (especially in microcellular areas) where signal transmission through buildings is virtually impossible. It is less consequential indoors where a diffracted signal is extremely weak compared to a reflected signal or a signal that is transmitted through a relatively thin wall.
3. *Scattering.* Irregular objects such as walls with rough surfaces and furniture (indoors) and vehicles, foliage, and the like (outdoors) scatter rays in all directions in the form of spherical waves. This particularly occurs when objects are of dimensions that are on the order of a wavelength or less of the electromagnetic wave. Propagation in many directions results in reduced power levels, especially far from the scatterer. As a result, this phenomenon is not that significant unless the receiver or transmitter is located in a highly cluttered environment. This mechanism dominates diffused IR propagations when the

wavelength of the signal is such that the roughness of the wall results in extensive scattering. In satellite and mobile radio applications, foliage often causes scattering.

2.3 PATH-LOSS MODELING AND SIGNAL COVERAGE

Calculation of signal coverage is essential for design and deployment of both narrowband and wideband wireless networks. Signal coverage is influenced by a variety of factors; most prominently the radio frequency of operation and the terrain. Often the region where a wireless network is providing service spans a variety of terrain. An operation scenario is defined by a set of operations for which a variety of distances and environments exist between the transmitter and the receiver. As a result, a unique channel model cannot describe radio propagation between the transmitter and the receiver, and we need several models for a variety of environments to enable system design. The core of the signal coverage calculations for any environment is a path-loss model which relates the loss of signal strength to distance between two terminals. Using path-loss models, radio engineers calculate the coverage area of wireless base stations and access points, as well as maximum distance between two terminals in an ad hoc network. In the following we consider path-loss models developed for several such environments that span different cell sizes and the terrain in the cellular hierarchy used for deployment of wireless networks.

2.3.1 Free Space Propagation

In most environments, it is observed that the radio signal strength falls as some power α of the distance, called the power-distance gradient or path-loss gradient. That is, if the transmitted power is P_t, after a distance d in meters, the signal strength will be proportional to $P_t d^{-\alpha}$. In its most simple case, the signal strength falls as the square of the distance in free space ($\alpha = 2$). When an antenna radiates a signal, the signal propagates in all directions. The signal strength density at a sphere of radius d is the total radiated signal strength divided by the area of the sphere, which is $4\pi d^2$. Depending on the radio frequency, there are additional losses, and in general the relationship between the transmitted power P_t and the received power P_r in free space is given by:

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

Here G_t and G_r are the transmitter and receiver antenna gains respectively in the direction from the transmitter to the receiver; d is the distance between the transmitter and receiver; $\lambda = c/f$ is the wavelength of the carrier; c is the speed of light in free space (3×10^8 m/s); and f is the frequency of the radio carrier. If we let $P_0 = P_t G_t G_r (\lambda / 4\pi)^2$ be the received signal strength at the first meter ($d = 1$ m), we can rewrite this equation as:

$$P_r = \frac{P_0}{d^2} \tag{2.2}$$

In decibels (dB), this equation takes the form

$$10\log(P_r) = 10\log(P_0) - 20\log(d) \tag{2.3}$$

where the logarithm is to the base 10. This means that there is a 20 dB per decade or 6 dB per octave loss in signal strength as a function of distance in free space. The transmission delay as a function of distance is given by $\tau = d/c = 3d$ ns or 3 ns per meter of distance.

Problem 1: Free Space Received Power and Path Loss

a) What is the received power (in dBm) in the free space of a signal whose transmit power is 1 W and carrier frequency is 2.4 GHz if the receiver is at a distance of 1 mile (1.6 km) from the transmitter? Assume that the transmitter and receiver antenna gains are 1.6.

b) What is the path loss in dB?

c) What is the transmission delay in ns?

Solution:

a) $10\log(P_t) = 30$ dBm because 1 W in dBm is 10 log (1 W/1 mW) = 30 dBm. Using Eq. (2.1) for $f = 2.4$ GHz, antenna gains of 1.6, distance of 1 meter, we have $10\log(P_0) = 30 - 40.046 = -10.046$ dBm and $P_r = -10.046 - 20\log(1600) = -74.128$ dBm.

b) The path loss is given by the difference between $10\log(P_t)$ and $10\log(P_r)$ (where both are in dBm). This is 104.128 dB.

c) The transmission delay is clearly $3 \times 1600 = 4800$ ns = 4.8 ms.

2.3.2 Two-Ray Model for Mobile Radio Environments

The distance-power relationship observed for free space does not hold for all environments. In free space, the signal travels from the transmitter to the receiver along a single path. In all realistic environments, the signal reaches the receiver through several different paths. The simple free space model of the previous section will not be valid for such scenarios and several complex models are required. We consider such models in the rest of this chapter.

We start with the two-path or two-ray model that is used for modeling the land mobile radio. The propagation environment and the two-ray model are shown in Figure 2.3. Here, the base station and the mobile terminal are both assumed to be at elevations above the earth, which is modeled as a flat surface in between the base station and the mobile terminal. Usually there is an LOS component that exists between the base station and the mobile terminal which carries the signal as in free space. There will also be another path over which the signal travels that consists of a reflection off the flat surface of the earth. The two paths travel different distances based on the height of the base station antenna, h_b, and the height of the mobile terminal antenna, h_m, and result in the addition of signals either constructively or destructively at the receiver.

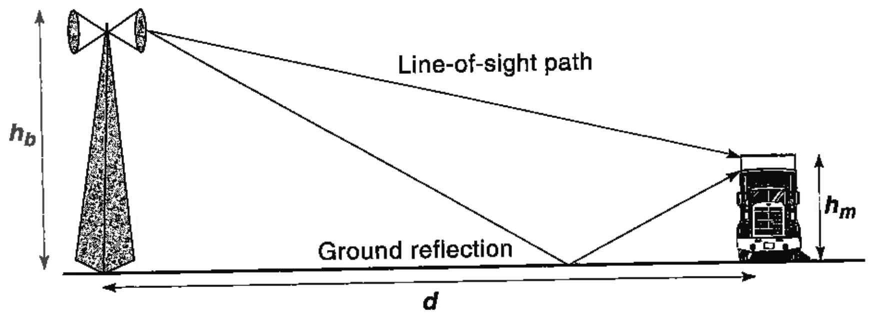

Figure 2.3 Two-ray model for mobile radio environments.

It can be shown that the relationship between the transmit power and the received power for the two-ray model can be approximated by [PAH95]:

$$P_r = P_t G_t G_r \frac{h_b^2 h_m^2}{d^4} \tag{2.4}$$

It is interesting to see that the signal strength falls as the fourth power of the distance between the transmitter and the receiver. In other words, there is a loss of 40 dB per decade or 12 dB per octave. The other interesting observation here is that the received signal strength can be increased by raising the heights of the transmit and receive antennas.

Problem 2: Comparison of Coverages

If a base station covers 1 km in a plain area modeled as a two-ray channel, what would be the coverage if it were used with a satellite?

Solution:

In the open area, the path loss gradient is 40 dB per decade of distance so the signal strength is reduced by 120 dB in covering 1 km. In free-space communication for satellites, the loss is 20 dB per decade of distance which allows 6 decades of distance or 1,000 km, for 120 dB loss of the signal.

2.3.3 Distance-Power Relationship and Shadow Fading

The simplest method of relating the received signal power to the distance is to state that the received signal power P_r is proportional to the distance between transmitter and receiver d, raised to a certain exponent α, which is referred to as the *distance-power gradient*, that is,

$$P_r = P_0 d^{-\alpha} \tag{2.5}$$

where P_0 is the received power at a reference distance (usually one meter) from the transmitter. For free-space, as already discussed, $\alpha = 2$, and for the simplified two-path model of an urban radio channel, $\alpha = 4$. For indoor and urban radio channels, the distance-power relationship will change with the building and street layouts, as well as with construction materials and density and height of the buildings in the area. Generally, variations in the value of the distance-power gradient in different outdoor areas are smaller than variations observed in indoor areas. The results of indoor radio propagation studies show values of α smaller than 2 for corridors or large open indoor areas and values as high as 6 for metallic buildings.

The distance-power relationship of Eq. (2.5) in decibels is given by

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d) \qquad (2.6)$$

where P_r and P_0 are the received signal strengths at d meters and at one meter, respectively. The last term in the right-hand side of the equation represents the power loss in dB with respect to the received power at one meter, and it indicates that for a one-decade increase in distance, the power loss is 10α dB and for a one-octave increase in distance, it is 3α dB. If we define the path loss in dB at a distance of one meter as $L_0 = 10\log_{10}(P_t) - 10\log_{10}(P_0)$, the total path loss L_p in dB is given by:

$$L_p = L_0 + 10\alpha\log(d) \qquad (2.7)$$

This presents the total path-loss as the path-loss in the first meter plus the loss relative to the power received at one meter. The received power in dB is the transmitted power in dB minus the total path loss L_p. This normalized equation is occasionally used in the literature to represent the distance-power relationship.

As we will see in Chapter 5, the path-loss models of this form are extensively used for deployment of cellular networks. The coverage area of a radio transmitter depends on the power of the transmitted signal and the path loss. Each radio receiver has particular power sensitivity, for example, it can only detect and decode signals with a strength larger than this sensitivity. Because the signal strength falls with distance, using the transmitter power, the path-loss model, and the sensitivity of the receiver, one can calculate the coverage.

Problem 3: Coverage of a Base Station

What is the coverage of a base station that transmits a signal at 2 kW given that the receiver sensitivity is -100 dBm, the path loss at the first meter is 32 dB, and the path loss gradient is $\alpha = 4$?

Solution:

The transmit power in dB is $10\log(P_t) = 10\log(2000/.001) = 63$ dBm, and the receiver sensitivity $10\log(P_r)$ is -100 dBm. The total path loss that is allowed will thus be $10\log(P_t) - 10\log(P_r) = 63 - (-100) = 163$ dB. There is a loss of 32 dB at the first meter. Using Eq. (2.7) the loss due to distance can at most be 131 dB. Because the path loss gradient $\alpha = 4$, $10\alpha\log(d) = 131$ dB will imply that $d = 10^{(131/40)} = 1{,}883$ m $= 1.88$ km. So the coverage of the cell is 1.88 km. As we will see later, the path-loss models are far more complex than the simple model discussed here.

2.3.3.1 Measurement of the Distance Power Gradient

To measure the gradient of the distance-power relationship in a given area, the receiver is fixed at one location, and the transmitter is placed at a number of locations with different distances between the transmitter and the receiver. The received power or the path loss in dB is plotted against the distance on a logarithmic scale. The slope of the best-fit line through the measurements is taken as the gradient of the distance-power relationship. Simulations can also be used to arrive at similar results. Figure 2.4 shows a set of measured data taken in an indoor area at distances from 1 to 20 meters, together with the best-fit line through the measurements.

2.3.3.2 Shadow Fading

Depending on the environment and the surroundings, and the location of objects, the received signal strength *for the same distance* from the transmitter will be different. In effect, Equation (2.6) provides the mean value of the signal strength that can be expected if the distance between the transmitter and receiver is *d*. The actual received signal strength will vary around this mean value. This variation of the signal strength due to location is often referred to as *shadow fading* or *slow fading*. The reason for calling this shadow fading is that very often the fluctuations around the mean value are caused due to the signal being blocked from the receiver by buildings (in outdoor areas), walls (inside buildings), and other objects in the environment. It is called slow fading because the variations are much slower with distance than another fading phenomenon caused due to multipath that we discuss later. It is also found that shadow fading has less dependence on the frequency of operation than multipath fading or fast fading as discussed later. The path loss of Equation (2.7) will have to be modified to include this effect by adding a random component as follows:

$$L_p = L_0 + 10\alpha \log_{10}(d) + X \tag{2.8}$$

Here X is a random variable with a distribution that depends on the fading component. Several measurements and simulations indicate that this variation can be expressed as a log-normally distributed random variable. The log-normal probability density function is given by:

$$f_{LN}(x) = \frac{1}{\sqrt{2\pi}\,\sigma x} \exp\left(\frac{-(\ln x - \mu)^2}{2\sigma^2}\right) \tag{2.9}$$

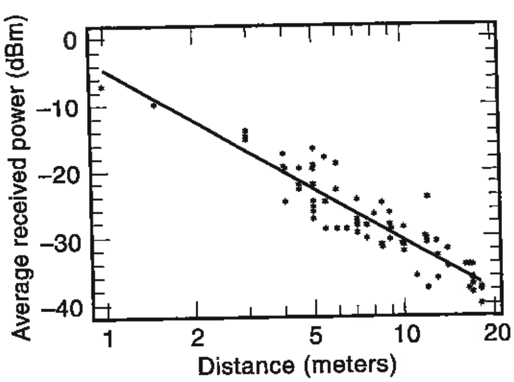

Figure 2.4 Measured received power and a linear regression fit to the data.

where μ is the mean received signal strength and σ is its standard deviation.

The problem caused by shadow fading is that all locations at a given distance may not receive sufficient signal strength for correctly detecting the information. In order to achieve sufficient signal coverage, the technique employed is to add a *fade margin* to the path loss or received signal strength. The fade margin is usually taken to be the additional signal power that can provide a certain fraction of the locations at the edge of a cell (or near the fringe areas) with the required signal strength. For computing the coverage, we thus employ the following equation:

$$L_p = L_0 + 10\alpha \log d + F_\sigma \tag{2.10}$$

where F_σ is the fade margin associated with the path loss to overcome the shadow fading effects.

The distribution of X in Eq. (2.8) is used to determine the appropriate fade margin. Note that a log-normal absolute fading component has a Gaussian distribution in dB. That is, X is a zero mean Gaussian random variable that corresponds to log-normal shadow fading in Eq. (2.8). At the fringe locations, the mean value of the shadow fading is zero dB. Fifty percent of the locations have a positive fading component, and 50 percent of the locations have a negative fading component. This will mean that the locations that have a positive fading component X will suffer a larger path loss resulting in unacceptable signal strength. To overcome this, a fading margin is employed to move most of these locations to within an acceptable received signal strength (RSS) value. This fading margin can be applied by increasing the transmit power and keeping the cell size the same, or reducing the cell size.

Problem 4: Computing the Fading Margin

A mobile system is to provide 95 percent successful communication at the fringe of coverage with a shadow fading component having a zero mean Gaussian distribution with standard deviation of 8 dB. What fade margin is required?

Solution:

Note that the location variability component X (in dB) in this case is a zero mean Gaussian random variable. In this example, the variance of X is 8 dB. We have to choose F_σ such that 95 percent of the locations will have a fading component smaller than the tolerable value. The distribution of the fading component X is Gaussian. So the fading margin depends on the tail of the Gaussian distribution that is described by the Q-function or the complementary error function erfc. Using the complementary error function and a software like Matlab, we can determine the value of F_σ as the solution to the equation $0.05 = 0.5\ \mathrm{erfc}(F_\sigma\sqrt{2})$ i.e., 5% of the fringe areas have fading values that cannot be compensated by F_σ. For this example, the fade margin to be applied is 13.16 dB.[1]

---

[1]The function $Q(x) = \int_x^\infty f_x(x)dx = 0.05$ where $Q(x)$ is the probability that the normal random variable X has a value greater than x is tabulated or it can be determined using the complementary error function via the relation: $Q(x) = 0.5\ \mathrm{erfc}\ (x/\sqrt{2})$. For a good discussion of the Q-function, see [SKL01].

So far, we have discussed achievable signal coverage in terms of the received signal strength and the path loss. In the following sections, we discuss parameters and path loss models for a variety of cellular environments. We also discuss, where relevant, the important factors that lead to these path loss models.

2.3.4 Path Loss Models for Megacellular Areas

Megacellular areas are those where the communication is over extremely large cells spanning hundreds of kilometers. Megacells are served mostly by mobile satellites (usually low-earth orbiting—LEO). The path loss is usually the same as that of free space, but the fading characteristics are somewhat different.

2.3.5 Path Loss Models for Macrocellular Areas

Macrocellular areas span a few kilometers to tens of kilometers, depending on the location. These are the traditional "cells" corresponding to the coverage area of a base station associated with traditional cellular telephony base stations. The frequency of operation is mostly around 900 MHz, though the emergence of PCS has resulted in frequencies around 1,800 to 1,900 MHz for such cells.

There have been extensive measurements in a number of cities and locations of the received signal strength in macrocellular areas that have been reported in the literature. The most popular of these measurements corresponds to those of Okumura who determined a set of path loss curves as a function of distance in 1968 for a range of frequencies between 100 MHz and 1,920 MHz. Okumura also identified the height of the base station antenna h_b and the height of the mobile antenna h_m as important parameters. Masaharu Hata [HAT80] created empirical models that provide a good fit to the measurements taken by Okumura for transmitter-receiver separations d of more than 1 km. The expressions for path loss developed by Hata are called the Okumura-Hata models or simply the Hata models. Table 2.1 provides these models.

Table 2.1 Okumura-Hata Models for Macro-Cellular Path Loss

General Formulation:

$$L_p = 69.55 + 26.16 \log f_c - 13.82 \log h_b - a(h_m) + [44.9 - 6.55 \log h_b] \log d \qquad (2.11)$$

where f_c is in MHz, h_b and h_m are in meters, and d is in km.

Range of Values

Center frequency f_c in MHz			150–1,500 MHz
h_b, h_m in meters			30–200m, 1–10m
$a(h_m)$ in dB	Large City	$f_c \le 200$ MHz	$8.29\,[\log(1.54\,h_m)]^2 - 1.1$
		$f_c \ge 400$ MHz	$3.2\,[\log(11.75\,h_m)]^2 - 4.97$
	Medium–Small City	$150 \ge f_c \ge 1{,}500$ MHz	$1.1\,[\log f_c - 0.7]\,h_m - (1.56 \log f_c - 0.8)$

Suburban Areas Formulation:

Use Eq. (2.11) and subtract a correction factor given by:

$$K_r\,(\text{dB}) = 2\,[\log (f_c/28)]^2 + 5.4 \qquad (2.12)$$

where f_c is in MHz.

Problem 5: Using the Okumura-Hata Model

Determine the path loss of a 900 MHz cellular system operating in a large city from a base station with the height of 100 m and mobile station installed in a vehicle with antenna height of 2 m. The distance between the mobile and the base station is 4 km.

Solution:

We calculate the terms in the Okumura-Hata model as follows:

$$a(h_m) = 3.2\,[\log(11.75\,h_m)]^2 - 4.97 = 1.045\text{ dB}$$

$$L_p = 69.55 + 26.16\log f_c - 13.82\log h_b - a(h_m) + [44.9 - 6.55\log h_b]\log d = 137.3\text{ dB}$$

To extend the Okumura-Hata model for PCS applications operating at 1,800 to 2,000 MHz, the European Co-operative for Scientific and Technical Research (COST) came up with the COST-231 model for urban radio propagation at 1.900 MHz, which we provide in Table 2C.1 in Appendix 2C. In this table $a(h_m)$ is chosen from Table 2.1 for large cities.

In a similar way, the Joint Technical Committee (JTC) of the Telecommunications Industry Association (TIA) has come up with the JTC models for PCS applications at 1,800 MHz [PAH95].

2.3.6 Path Loss Models for Microcellular Areas

Microcells are cells that span hundreds of meters to a kilometer or so and are usually supported by below rooftop level base station antennas mounted on lampposts or utility poles. The shapes of microcells are also no longer circular (or close to circular) because they arc deployed in streets in urban areas where tall buildings create *urban canyons.* There is little or no propagation of signals through buildings, and the shape of a microcell is more like a cross or a rectangle, depending on the placement of base station antennas at the intersection of streets or in between intersections. The propagation characteristics are quite complex with the propagation of signals affected by reflection from buildings and the ground and scattering from nearby vehicles. For obstructed paths, diffraction around building corners and rooftops become important. Many individual scenarios should be considered, unlike radio propagation in macrocells.

Bertoni and others [BER99] have developed empirical path-loss models based on signal strength measurements in the San Francisco Bay area which are similar to the Okumura-Hata models for a variety of situations. The corresponding path loss models are summarized in Table 2.2.

As usual, d is the distance between the mobile terminal and the transmitter in kilometers, h_b is the height of the base station in meters, h_m is the height of the mobile terminal antenna from the ground in meters, and f_c is now the center frequency of the carrier in GHz that can range between 0.9 and 2 GHz.

In addition, the following parameters are defined. The distance of the mobile terminal from the last rooftop (in meters) is denoted by r_h. A rooftop acts as a diffracting screen (see Fig. 2.5), and distance from the closest, such rooftop (around 250 m in many cases) becomes important in NLOS situations and introduces a correction factor. The height of the nearest building above the height of the receiver

Table 2.2 Path Loss Formulas for Microcells

Environment	Scenario	Path Loss Expression
Low Rise	NLOS	$L_p = [139.01 + 42.59 \log f_c] - [14.97 + 4.99 \log f_c]$ $\mathrm{sgn}(\Delta h)\log(1 + \lvert\Delta h\rvert) + [40.67 - 4.57\,\mathrm{sgn}(\Delta h)$ $\log(1 + \lvert\Delta h\rvert) \log d + 20 \log (\Delta h_m/7.8) + 10 \log (20/r_h)$
High Rise $h_m = 1.6\text{m}$	Streets perpendicular to the LOS streets	$L_p = 135.41 + 12.49 \log f_c - 4.99 \log h_b + [46.84 - 2.34 \log h_b] \log d$
	Streets parallel to the LOS Streets	$L_p = 143.21 + 29.74 \log f_c - 0.99 \log h_b + [47.23 + 3.72 \log h_b] \log d$
Low Rise + High Rise	LOS	$L_p = 81.14 + 39.40 \log f_c - 0.09 \log h_b + [15.80 - 5.73 \log h_b] \log d$, for $d < d_{bk}$
		$L_p = [48.38 - 32.1 \log d] + 45.7 \log f_c - (25.34 - 13.9 \log d) \log h_b + [32.10 + 13.90 \log h_b] \log d + 20 \log (1.6/h_m)$, for $d > d_{bk}$

antenna is denoted by Δh_m and introduces a correction factor similar to r_h. The average building height in the environment is an important parameter in microcellular environments. The relative height of the base station transmitter compared with the average height of buildings is denoted by Δh. Usually Δh ranges between -6 m and 8 m. In LOS situations, it is observed that there are two distinct slopes of the path loss curves, one in the near-end region and one in the far-out segment. A *breakpoint* distance d_{bk} is used to separate the two piecewise linear fits to the measured path loss. The breakpoint distance is dependent on the heights of the base station and mobile antennas, as well as the wavelength λ of the carrier (all in meters), and is given by $d_{bk} = 4\, h_b h_m / 1000\lambda$.

Problem 6: Path-Loss Calculation in a Microcell

Determine the path loss between the base station (BS) and mobile station (MS) of a 1.8 GHz PCS system operating in a high-rise urban area. The MS is located in a perpendicular street to the location of the BS. The distances of the BS and MS to the corner of the street are 20 and 30 meters, respectively. The base station height is 20 m.

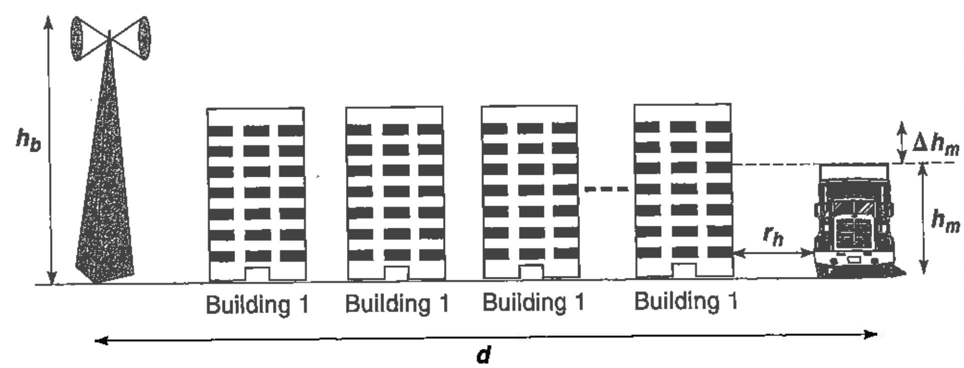

Figure 2.5 Geometry in a microcell; definitions of r_h and Δh_m.

Solution:

The distance of the mobile from the base station is $(20^2 + 30^2)^{1/2} = 36.05$ m. Using the appropriate equation from Table 2.2, we can write the path loss as:

$$L_p = 135.41 + 12.49 \log f_c - 4.99 \log h_b + [46.84 - 2.34 \log h_b] \log d = 68.89 \text{ dB}$$

In addition to the empirical models presented, there are theoretical models [BER94] that predict the path loss in microcellular environments which have been adopted by a variety of standard bodies. Another model available for the microcellular environments is the JTC model explained in [PAH95]. This model provides for PCS microcells in a manner similar to the COST model.

2.3.7 Path Loss Models for Picocellular Indoor Areas

Picocells correspond to radio cells covering a building or parts of buildings. The span of picocells is anywhere between 30 m and 100 m. Usually picocells are employed for WLANs, wireless PBX systems, and PCSs operating in indoor areas. One of the earliest statistical measurements of signal amplitude fluctuations in an office environment for a cordless telephone application is reported in [ALE82]. The measurements were made by fixing the transmitter while moving the receiver to various locations in a multiple-room office. Because of those earliest measurements, many researchers have performed narrowband measurements within buildings, primarily to determine the distance-power relationship and arrive at empirical path loss models for a variety of environments [PAH95].

2.3.7.1 Multifloor Attenuation Model

For describing the path loss in multistory buildings, signal attenuation by the floors in the building can be included as a constant independent of the distance [MOT88b]. The path loss in this case is given by

$$L_p = L_0 + nF + 10 \log (d) \tag{2.13}$$

Here F represents the signal attenuation provided by each floor; L_0 is the path loss at the first meter, shown in Equation (2.7); d is the distance between the transmitter and receiver in meters; and n is the number of floors through which the signal passes. The received power is plotted versus distance, and the best-fit line is determined for each different value of F. The value of F, which provides the minimum mean-square error between the line and the data, is taken as the value of F for the experiment. For indoor radio measurements at 900 MHz and 1.7 GHz, values of $F = 10$ dB and 16 dB respectively are reported in [MOT88a].

Interior objects such as furniture, equipment, and so on cause shadow fading as discussed earlier. Result of measurements on indoor [MOT88], [GAN91], [HOW91] radio channels show that a log-normal distribution provides the best fit to randomness introduced by shadow fading. In [MOT88b], the variations of the mean value of the signal were found to be log-normal with a standard deviation of 4 dB.

2.3.7.2 The JTC Model

In Equation (2.13) the relationship between the path loss and the number of floors is linear. However, results of measurements in [BER93] do not agree with this assumption. There a theoretical explanation indicates that diffraction out of windows becomes significant as the number of intervening floors increases. As such, an improvement to Equation (2.13) is to include a nonlinear function of the number of floors in the path loss model as follows:

$$L_p = A + L_f(n) + B\log(d) + X \tag{2.14}$$

Here $L_f(n)$ represents the function relating the power loss with the number of floors n, and X is a log-normally distributed random variable representing the shadow fading. Table 2.3 gives a set of suggested parameters in dB for the path loss calculation using Equation (2.14) at carrier frequencies of 1.8 GHz. The rows of the table provide the path loss in the first meter, the gradient of the distance-power relationship, the equation for calculation of multifloor path loss, and the standard deviation of the log-normal shadow fading parameter. It is assumed that the base and portable stations are inside the same building. The parameters are provided for three classes of indoor areas: residential, offices, and commercial buildings. This table is taken from a TIA recommendation for RF channel modeling for PCS applications [JTC94].

2.3.7.3 Path-Loss Models Using Building Material

Several other models for indoor radio propagation have been proposed in the literature. The *partition-dependent* model [RAP96] tries to improve upon standard models such as Equation (2.7) by fixing the value of the path-loss gradient α at 2 for free space and introducing losses for each partition that is encountered by a straight line connecting the transmitter and the receiver. The path loss is given by:

$$L_p = L_0 + 20\log d + \Sigma\, m_{type}\, w_{type} \tag{2.15}$$

Here m_{type} refers to the number of partitions of that type and w_{type} the loss in dB attributed to such a partition. The partition dependent model has been investigated in [SEI92]. Two partitions were considered here: soft partitions that have a loss of 1.4 dB and hard partitions that have a loss of 2.4 dB. Several other loss values (w_{type}) have been reported in [RAP96], which vary between 1 dB for dry plywood to 20 dB for concrete walls depending on the carrier frequency. Table 2.4 shows some dB loss values measured at Harris semiconductors at 2.4 GHz for different

Table 2.3 Parameters for Indoor Path-Loss Calculation (JTC model)

Environment	Residential	Office	Commercial
A (dB)	38	38	38
B	28	30	22
$L_f(n)$ (dB)	$4n$	$15 + 4(n - 1)$ dB	$6 + 3(n - 1)$ dB
Log Normal Shadowing (Std. Dev. dB)	8	10	10

Table 2.4 Partition Dependent Losses

Signal Attenuation of 2.4 GHz through	dB
Window in brick wall	2
Metal frame, glass wall into building	6
Office wall	6
Metal door in office wall	6
Cinder wall	4
Metal door in brick wall	12.4
Brick wall next to metal door	3

types of partitions. Once again, appropriate fading margins have to be included to account for the variability in path loss for the same distance *d*.

2.3.8 Path Loss Models for Femtocellular Areas

There have been few radio channel measurements or modeling work available for femtocells. Femtocells are expected to span from a few meters to a few tens of meters. Femtocells are probably going to exist in individual residences and use low-power devices employing Bluetooth chips or HomeRF equipment. Data rates are initially expected to be around 1 Mbps and increase with the availability of technology to operate at higher frequencies. Because femtocells are mostly deployed in residential environment, the JTC path loss model in the previous section for residential environments may be used to predict the coverage of a femtocell at 1.8 GHz. However, femtocells will use carrier frequencies in the unlicensed bands at 2.4 and 5 GHz. For these frequencies, path loss models are not readily available. Selected measurements [PRA92], [McD98], [GUE97] indicate indoor path loss models based on Equation (2.7) at these frequencies that are shown in Table 2.5.

Table 2.5 Path Loss Models at 2.4 GHz and 5 GHz for Femtocells

Center Frequency f_c	Environment	Scenario	Path Loss at the First Meter	Path Loss Gradient α
2.4 GHz	Indoor office	LOS	41.5 dB	1.9
		OLOS	37.7 dB	3.3
5.1 GHz	Meeting room	LOS	46.6 dB	2.22
		OLOS	61.6 dB	2.22
5.2 GHz	Suburban residences	LOS and same floor	47 dB	2 to 3
		OLOS and same floor		4 to 5
		OLOS and room in the higher floor directly above the Tx		4 to 6
		OLOS and room in the higher floor not directly above the Tx		6 to 7