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.

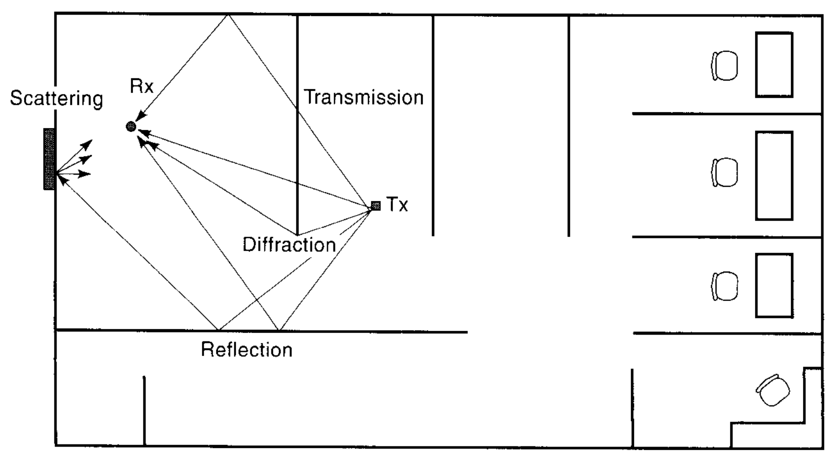

Figure 2.1 Radio propagation mechanisms in an indoor area.

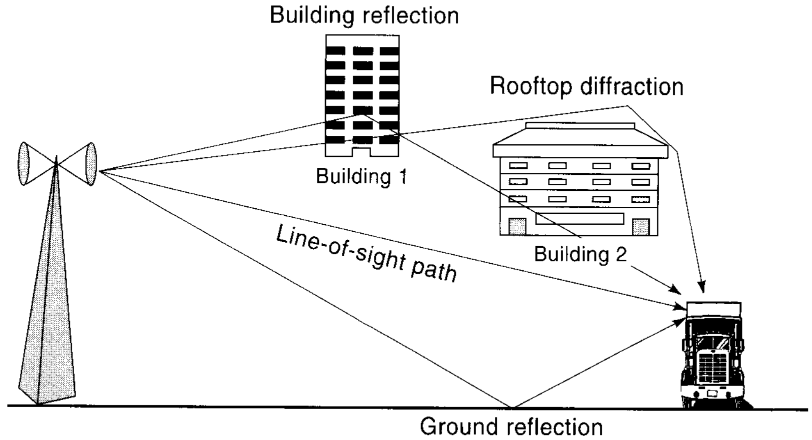

Figure 2.2 Radio propagation mechanisms in an outdoor area.

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. /1

b) What is the path loss in dB?

c) What is the transmission delay in ns?

Antenna gain is "1" not "1.6"

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. /1

b) The path loss is given by the difference between 10log (P_t) and 10log (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.

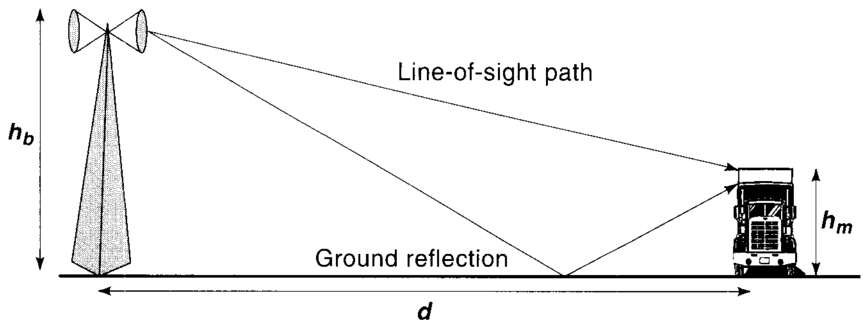

Figure 2.3 Two-ray model for mobile radio environments.

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

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d) \tag{2.6}$$

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:

$$L_p = L_0 + 10\alpha\log(d) \tag{2.7}$$

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 $\approx$ 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:

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

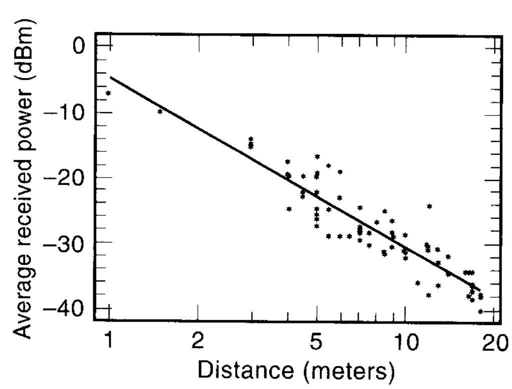

Figure 2.4 Measured received power and a linear regression fit to the data.

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 $0.05 = 0.5\,\text{erfc}(F_\sigma\sqrt{2})$ 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]

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[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: $Q(x) = 0.5\,\text{erfc}(x/\sqrt{2})$. 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	$f_c \leq 200$ MHz	$8.29\,[\log (1.54\, h_m)]^2 - 1.1$
		$f_c \geq 400$ MHz	$3.2\,[\log (11.75\, h_m)]^2 - 4.97$
	Medium–Small City	$150 \geq f_c \geq 1{,}500$ 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 are 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.

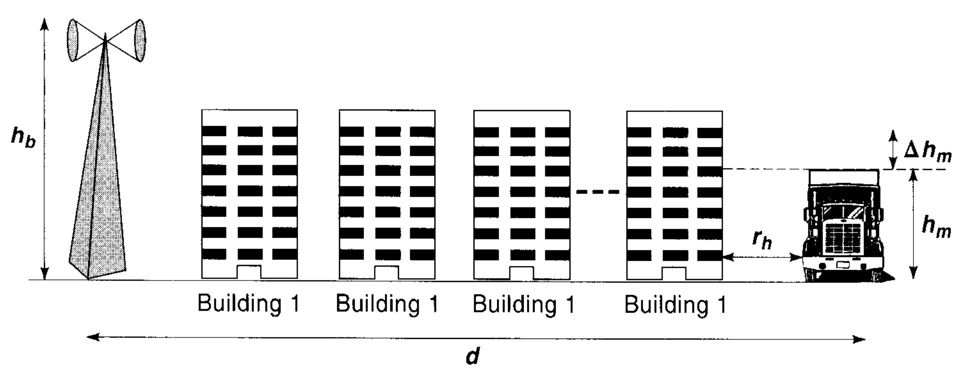

Figure 2.5 Geometry in a microcell; definitions of r_h and Δh_m.

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

2.4 EFFECTS OF MULTIPATH AND DOPPLER

So far we have considered achievable signal coverage in a variety of cell types based on the mean received signal strength or path loss suffered by a signal. Such a characterization of the received signal strength corresponds to *large-scale* average values. In reality, the received signal is rapidly fluctuating due to the mobility of the mobile terminal causing changes in multiple signal components arriving via different paths. This rapid fluctuation of the signal amplitude is referred to as *small-scale fading,* and it is the result of movement of the transmitter, the receiver, or objects surrounding them. Over a small area, the *average* value of the signal is employed to compute the received signal strength or path loss. But the characteristics of the instantaneous signal strength are also important in order to design receivers that can mitigate these effects. We briefly describe the features of small-scale fading in this section.

Two effects contribute to the rapid fluctuations of the signal amplitude. The first, caused by the movement of the mobile terminal toward or away from the base station transmitter, is called *Doppler.* The second, caused by the addition of signals arriving via different paths, is referred to as multipath fading.

2.4.1 Modeling of Multipath Fading

Multipath fading results in fluctuations of the signal amplitude because of the addition of signals arriving with different *phases.* This phase difference is caused due to the fact that signals have traveled different distances by traveling along different paths. Because the phase of the arriving paths are changing rapidly, the received signal amplitude undergoes rapid fluctuation that is often modeled as a random variable with a particular distribution.

To model these fluctuations, one can generate a histogram of the received signal strength in time. The density function formed by this histogram represents the distribution of the fluctuating values of the received signal strength. The most commonly used distribution for multipath fading is the Rayleigh distribution, whose probability density function (PDF) is given by:

$$f_{ray}(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \quad r \geq 0 \tag{2.16}$$

Here it is assumed that all signals suffer nearly the same attenuation, but arrive with different phases. The random variable corresponding to the signal amplitude is r. Theoretical considerations indicate that the sum of such signals will result in the amplitude having the Rayleigh distribution of Eq. (2.16). This is also supported by measurements at various frequencies [PAH95]. When a strong LOS signal component also exists, the distribution is found to be Ricean, and the probability density function of such a distribution is given by:

$$f_{ric}(r) = \frac{r}{\sigma^2} \exp\left(\frac{-(r^2 + K^2)}{2\sigma^2}\right) I_0\left(\frac{Kr}{\sigma^2}\right), \quad r \geq 0, K \geq 0 \tag{2.17}$$

Here K is a factor that determines how strong the LOS component is relative to the rest of the multipath signals.

Equations (2.9), (2.16), and (2.17) are used to determine what fraction of time a signal is received such that the information it contains can be decoded or what fraction of area receives signals with the requisite strength. The remainder of the fraction is often referred to as outage.

Small-scale fading results in very high bit error rates. In order to overcome the effects of small-scale fading, it is not possible to simply increase the transmit power because this will require a huge increase in the transmit power. A variety of techniques are used to mitigate the effects of small-scale fading—in particular error control coding with interleaving, diversity schemes, and using directional antennas. These techniques are discussed in Chapter 3.

2.4.2 Doppler Spectrum

Equations (2.16) and (2.17) provide the distributions of the amplitude of a radio signal that is undergoing small-scale fading. In general, it is also important to know for what time a signal strength will be below a particular value (duration of fade) and how often it crosses a threshold value (frequency of transitions or fading rate). This is particularly important to design the coding schemes and interleaving sizes for efficient performance. We see that this is a second-order statistic, and it is obtained by what is known as the *Doppler spectrum* of the signal.

Doppler spectrum is the spectrum of the fluctuations of the received signal strength. Figure 2.6 [HOW90] demonstrates the results of measurements of amplitude fluctuations in a signal and its spectrum under different conditions. In Figure 2.6(a), the transmitter and receiver are kept stationary, and nothing is moving in their vicinity. The received signal has constant envelope, and its spectrum is only an impulse. In Figure 2.6(b), the transmitter is randomly moved, resulting in fluctuation of the received signal. The spectrum of this signal is now expanded to around 6 Hz, reflecting the rate of variations of the received signal strength. This spectrum is referred to as the Doppler spectrum.

In mobile radio applications, the Doppler spectrum for a Rayleigh fading channel is usually modeled by:

$$D(\lambda) = \frac{1}{2\pi f_m} \times [1 - (\lambda/f_m)^2]^{-1/2} \qquad \text{for } -f_m \leq \lambda \leq f_m \tag{2.18}$$

Here f_m is the maximum Doppler frequency possible and is related to the velocity of the mobile terminal via the expression $f_m = v_m/\lambda$, where v_m is the mobile velocity and λ is the wavelength of the radio signal. This spectrum, commonly used in mobile radio modeling, is also called the classical Doppler spectrum and is shown in Figure 2.7. Another popular model for the Doppler spectrum is the uniform distribution that is used for indoor applications [PAH95].

From the rms Doppler spread, it is possible to obtain the fade rate and the fade duration for a given mobile velocity [PAH95]. These values can then be used in the design of appropriate coding and interleaving techniques for mitigating the effects of fading. Diversity techniques are useful to overcome the effects of fast fading by providing multiple copies of the signal at the receiver. Because the probability

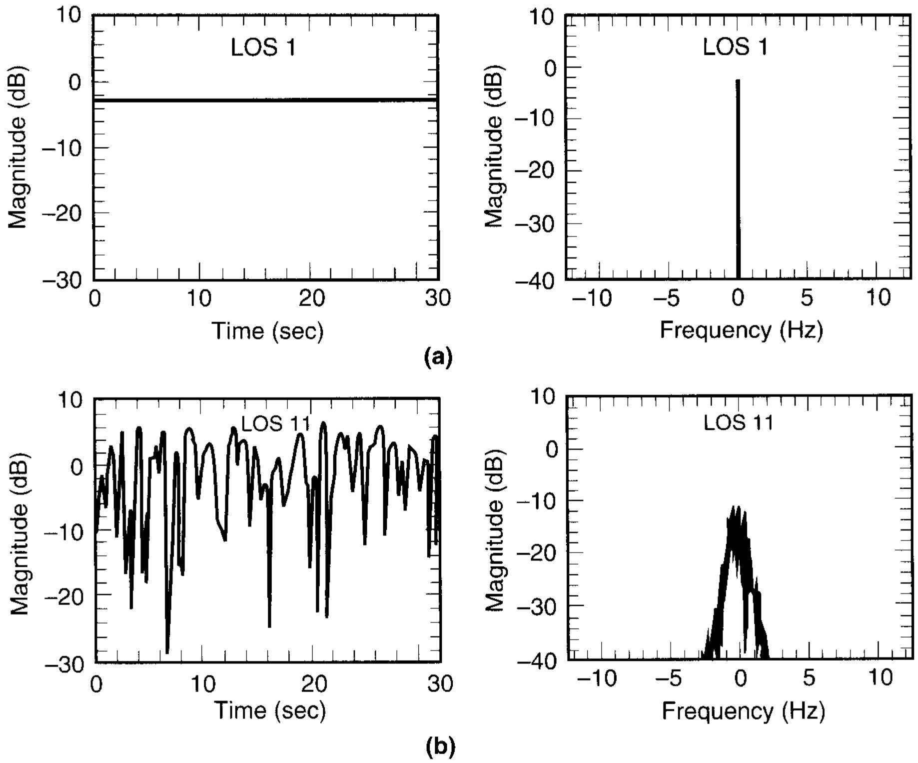

Figure 2.6 Measured values of the Doppler.

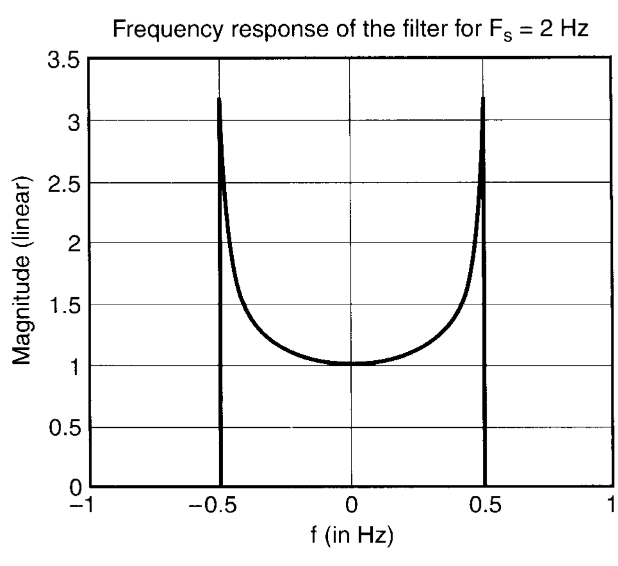

Figure 2.7 The classical Doppler spectrum.

that all these copies suffer fading is small, the receiver is able to correctly decode the received data. Frequency hopping is another technique that can be used to combat fast fading. Because all frequencies are not simultaneously under fade, transmitting data by hopping to different frequencies is an approach to combat fading. This is discussed in Chapter 3.

2.4.3 Multipath Delay Spread

Figure 2.8 shows a sample measured time and frequency response of a typical radio channel. In time domain, shown in Figure 2.8(a), a transmitted narrow pulse arrives as multiple paths with different strengths and arriving delay. In the frequency domain, shown in Figure 2.8(b), the response is not flat, and it suffers from deep frequency selective fades. From Figure 2.8(a) we observe that radio signals arrive at a receiver via a multiplicity of paths. One of the significant problems caused by this phenomenon along with fading is intersymbol interference (ISI). If the multipath delay spread is comparable to or larger than the symbol duration, the received waveform spreads into neighboring symbols and produces ISI. The ISI results in irreducible errors that are caused in the detected signal. This effect is modeled using a *wideband* multipath channel model, sometimes called the delay power spectrum, shown in Figure 2.9, which is usually given by the impulse response:

$$h(t) = \sum_{i=1}^{L} \alpha_i \delta(t - \tau_i) e^{j\varphi_L} \qquad (2.19)$$

/ φ_i — "φ_i" instead of "φ_L"

Here the model assumes that α_i is a Rayleigh distributed amplitude of the multipath with mean local strength $E\{\alpha_i^2\} = 2\sigma_i^2$ and the multipath arrives at a time delay τ_i with phase φ_i assumed to be uniformly distributed in $(0, 2\pi)$.

The delays and multipath interarrival times have various models [PAH95]. In many of the models, the time delays are assumed to be fixed and only the mean-square values of the amplitudes are provided. In Appendix 2D we list several wideband channel models with the multipath delays and mean square values of the amplitudes.

A measure of the data rate that can be supported over the channel without additional receiver techniques is determined by the RMS multipath delay spread given by:

$$\tau_{rms} = \sqrt{\frac{\sum_{k=1}^{N} \tau_k^2 \sigma_k^2}{\sum_{k=1}^{N} \sigma_k^2} - \left(\frac{\sum_{k=1}^{N} \tau_k \sigma_k^2}{\sum_{k=1}^{N} \sigma_k^2}\right)^2} \qquad (2.20)$$

A rule of thumb is that it is possible to support data rates that are less than the *coherence bandwidth* of the channel that is approximately $1/5\tau_{rms}$. The coherence bandwidth is the range of frequencies that are allowed to pass through the channel without distortion. The RMS delay spread varies depending on the type of environment. In indoor areas, it could be as small as 30 ns in residential areas or as large as 300 ns in factories [PAH95]. In urban macrocells, the RMS delay spread is on the order of a few microseconds. This means that the maximum data rates can

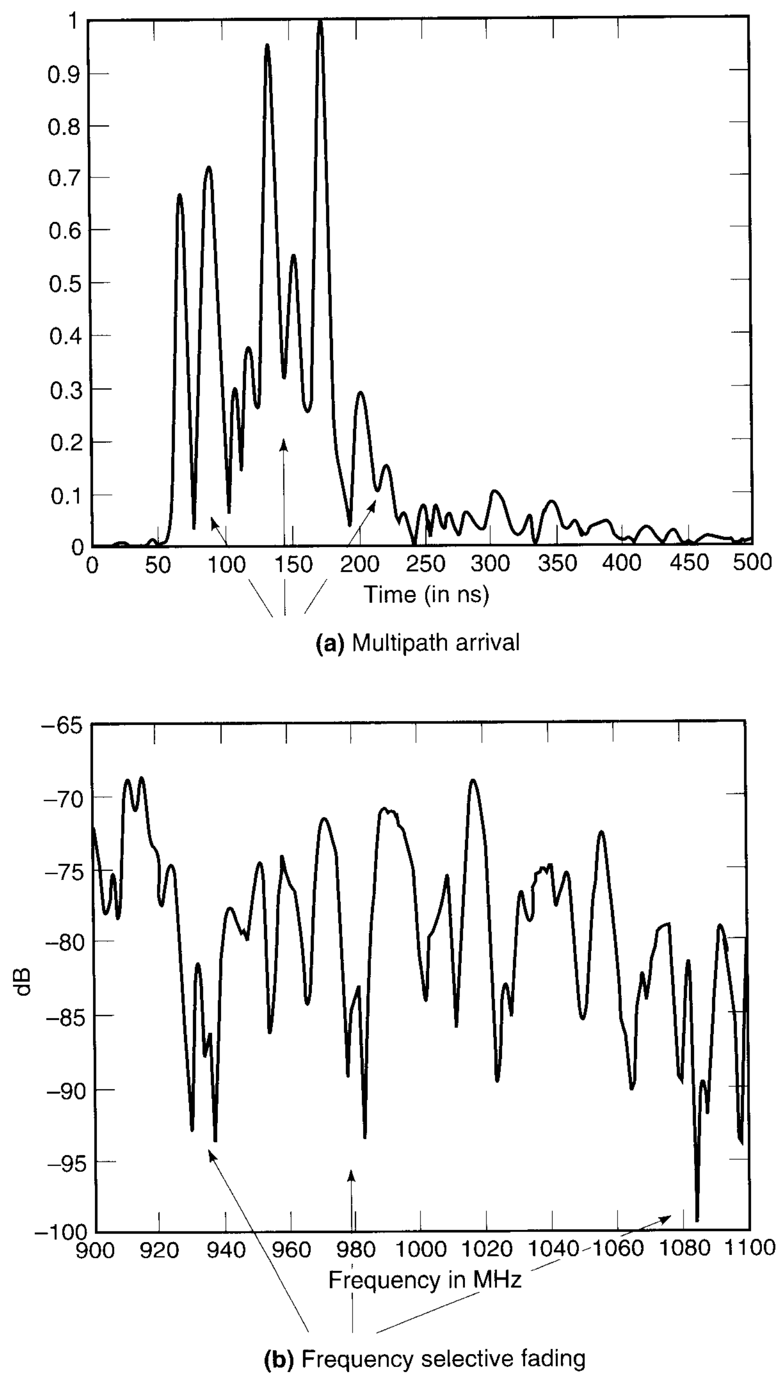

Figure 2.8 Time and frequency response of a typical radio channel over 200 MHz of bandwidth at 1 GHz.

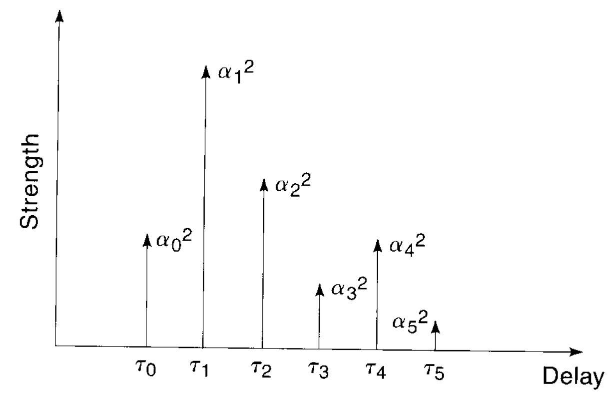

Figure 2.9 Wideband multipath channel model.

be supported in indoor areas is around 6.7 Mbps (at 30 ns) and 50 kbps in outdoor areas (at 4 μs).

In order to support higher data rates, different receiver techniques are necessary. Equalization is a method that tries to cancel the effects of multipath delay spread in the receiver. Direct sequence spread spectrum enables resolving the multipath components and using them to improve performance. OFDM uses multiple carriers, spaced closely in frequency, each carrying low data rates to avoid ISI. Directional antennas reduce the number of multipath components, thereby reducing the total delay spread itself. We discuss these topics in Chapter 3.

2.4.4 Summary of Radio Channel Characteristics and Mitigation Methods

In the previous sections, we have looked at various issues in radio propagation—signal coverage and shadow fading, multipath and Doppler fading leading to large bit error rates, and multipath delay spread that causes irreducible errors in the detected bits due to ISI. Table 2.6 summarizes these effects and techniques to combat them.

Table 2.6 Radio Channel Effects on Performance and Techniques to Improve Performance

Issue	Performance Affected	Mitigation Technique
Shadow fading	Received signal strength	Fade margin—Increase transmit power or decrease cell size
Fast fading	Bit error rate Packet error rate	Error control coding Interleaving Frequency hopping Diversity
Multipath delay spread	ISI and irreducible error rates	Equalization DS-spread spectrum OFDM Directional antennas

2.4.5 Emerging Channel Models

In this section we discuss some new radio channel models that are gaining importance for different applications. Position location is becoming important for emergency and location-aware applications (see Chapter 16), and models developed for communication systems are no longer sufficient to address the performance of geolocation schemes. The use of smart antennas and adaptive antenna arrays require knowledge of the *angle of arrival* (AOA) of the multipath components in order to steer antenna beams in the right directions.

2.4.5.1 Wideband Channel Models for Geolocation

With the advent of widespread wireless communications, the location of people, mobile terminals, pets, equipment, and the like by employing radio signals is gaining importance as well. Several new position location applications [COM00] are rapidly emerging in the market. Civilian applications include intelligent transportation systems (ITS), public safety (enhanced 911 or E-911 services) [NJW97], automated billing, fraud detection, cargo tracking, accident reporting, and so on. It is possible to employ position location for additional benefits such as cellular system design [COM98] and futuristic *intelligent office* environments [WAR97]. Most tactical military units on the other hand are also heavily reliant on wireless communications. Ad hoc connectivity among individual warfighters (for instance in the *Small Unit Operations* (SUO) [DAR97]) in restrictive RF propagation environments such as inside buildings, tunnels, and other urban structures, caves, mountainsides, and double canopy coverage in jungles and forests requires *situation awareness systems* (SAS) that enable the individual warfighters to determine their location and associated information. In either case, the position location service will have to operate within buildings where traditional geolocation techniques such as the global positioning system (GPS) fail due to a lack of sufficient signal power and the harsh multipath environment.

Although RF propagation studies in the past have focused on telecommunications applications, position location applications require a different characterization of the indoor radio channel [PAH98]. For position location applications, accurately detecting the *direct line-of-sight* (DLOS) path between the transmitter and receiver is extremely important. The DLOS path corresponds to the straight line connecting the transmitter and receiver even if there are obstructions like walls in between. Detecting the DLOS path is important because the time of arrival (TOA) or the AOA of the DLOS path corresponds to the distance between the transmitter and receiver (or to the direction between them). This information is used in conjunction with multiple such measurements to locate either the transmitter or the receiver as the case may be. This is in contrast to telecommunications applications where the emphasis is on how data bits can be sent over a link efficiently and without errors. Another issue in positioning systems is the relation between the bandwidth of the transmitted signal and the required accuracy in ranging. An error of 100 ns in estimating the delay of an arriving multipath component could result in an error of 30 meters in calculation of the distance between a transmitter and a receiver. Therefore, positioning systems using TOA often require wide bandwidths to resolve multipath components and detect the arrival of the first path.

In wideband indoor radio propagation studies for telecommunications applications often channel profiles measured in different locations of a building are divided into LOS and OLOS because the behavior of the channel in these two classes has substantially different impacts on the performance of a telecommunications system.

A logical way to classify channel profiles for geolocation applications is to divide them into three categories as shown in Figure 2.10. The first category is the dominant direct path (DDP) case in which the DLOS path is detected by the measurement system, and it is the strongest path in the channel profile. In this case, traditional GPS receivers [ENG94], [GET93], [KAP96] designed for outdoor applications where multipath components are significantly weaker than the DLOS path lock on to the DLOS path and detect its TOA accurately. The second category is the nondominant direct path (NDDP) case where the DLOS path is detected by the measurement system, but it is not the dominant path in the channel profile. For these profiles traditional GPS receivers, expected to lock to the strongest path, will make an erroneous decision on the TOA that leads to an error in position estimation. The amount of error made by a traditional receiver is the distance associated with the difference between the TOA of the strongest path and the TOA of the

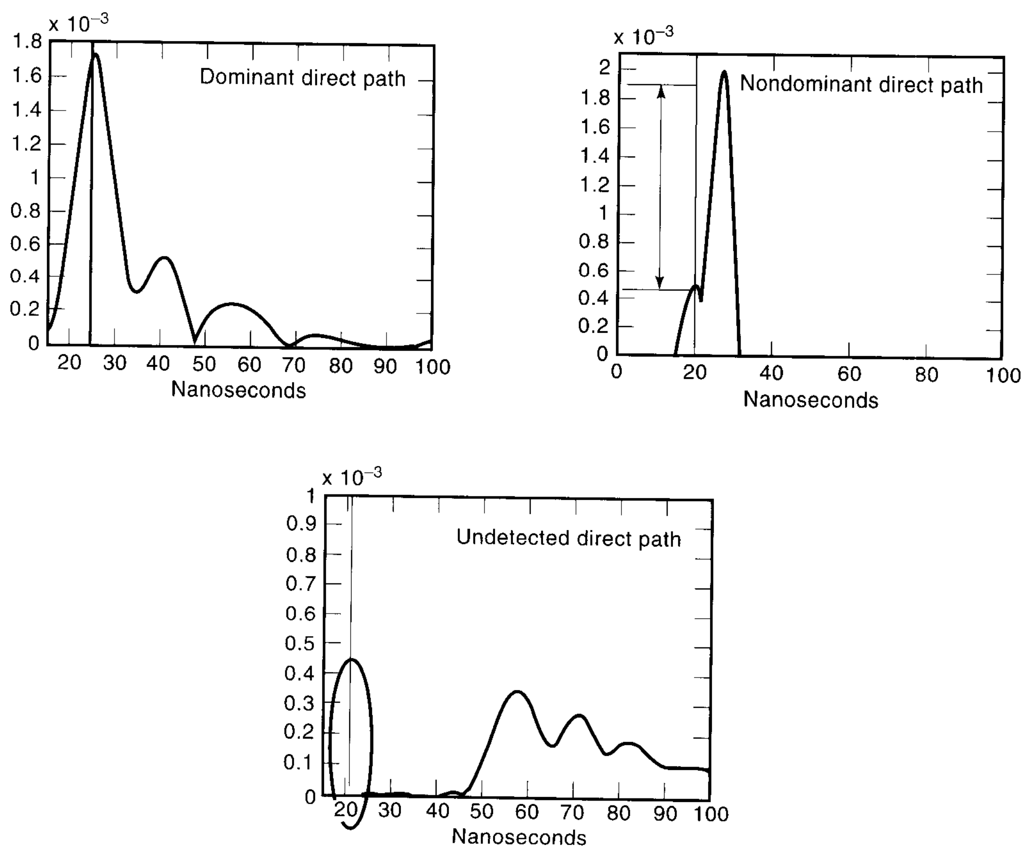

Figure 2.10 Multipath profiles for indoor geolocation.

DLOS path. For the second category locations with NDDP profiles, a more complex RAKE type receiver [PAH95a] can resolve the multipath and make an intelligent decision on the TOA of the DLOS path. The third category of channel profiles is the undetected direct path (UDP) profiles. In these profiles the measurement system cannot detect the DLOS path, and therefore traditional GPS or RAKE type receivers cannot detect the DLOS path. If we define the ratio of the power of the strongest path to the power of the weakest detectable path of a profile as the dynamic range of a receiver, then in NDDP profiles the strength of the DLOS path is within the dynamic range of the receiver and in UDP profiles it is not. If practical considerations regarding the dynamic range are neglected, one can argue that we have only two classes (DDP and NDDP) of profiles because the DLOS path always exists but sometimes we cannot detect it with a practical system. Figure 2.11 shows the results of ray tracing simulations of regions in the first floor of Atwater Kent Laboratories at Worcester Polytechnic Institute with different types of multipath profiles for a centrally located channel sounder.

In the same way that the bit error rate is the ultimate measure for comparing performance of different digital communication receivers, the error in the measurement of the TOA or AOA of the DLOS path is a measure of the performance

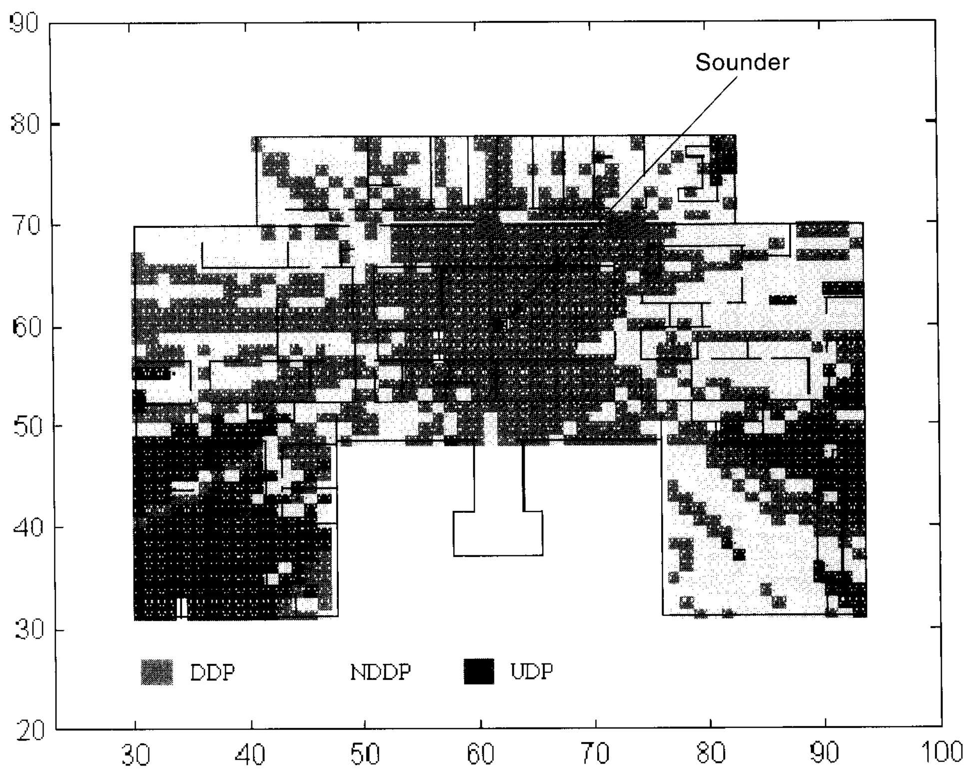

Figure 2.11 Simulated regions in the first floor of Atwater Kent Laboratories showing regions with different types of multipath profiles for a centrally located channel sounder. *Note:* Scale is in meters.

of the geolocation receivers. Traditional RF studies consider the path loss and τ_{rms} as mentioned earlier and these are not sufficient for the geolocation problem. The relative power and delay of the signal arriving via other paths, the channel noise, the signal bandwidth, and interference all influence the detection of the DLOS path and thus the error in estimating the range (distance) between the transmitter and receiver. Efforts to model the indoor radio channel for geolocation based on the error in the detection of the DLOS path are reported in [PAH98], [KRI99a,b,c]. In these efforts, parameters of importance and development of a model are based on measurements of the radio channel used as input to software simulations.

2.4.5.2 SIMO and MIMO Channel Models

Recently, there has been a lot of attention placed on *spatial wideband channel models,* that not only provide the delay-power spectrum discussed in Equation (2.19), but also the AOA of the multipath components. The advent of antenna array systems that are used for interference cancellation and position location applications has made it necessary to understand the spatial properties of the wireless communications channel.

A significant amount of research has been carried out in the area of *single-input multiple output* (SIMO) radio channel models [ERT98]. In these models, a typical cellular environment is considered where it is assumed that the mobile transmitters are relatively simple and the base station can have a complex receiver with adaptive smart antennas with M antenna elements. As shown in Figure 2.12, the multipath environment is such that up to L signals arrive at the base station from different mobile terminals (l) with different amplitudes (α) and phases (φ) at

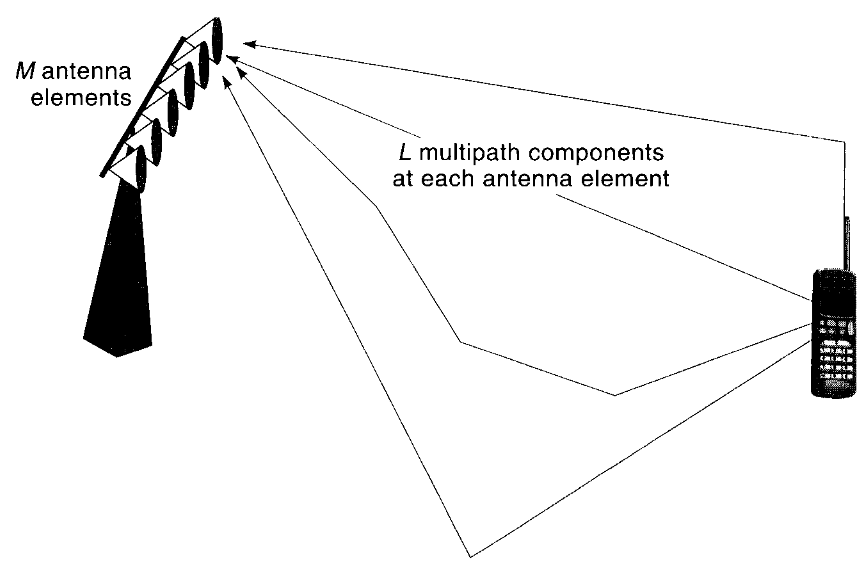

Figure 2.12 Illustration of SIMO radio channel.

different delays (τ) from different directions (θ). These are in general time-invariant, and, as a result, the channel impulse response is usually represented by:

$$\vec{h}(t) = \sum_{l=1}^{L(t)} \alpha_l(t) e^{j\varphi_l(t)} \delta(t - \tau_l(t)) \vec{a}(\theta_l(t)) \tag{2.21}$$

Note that the channel impulse response is now a *vector* rather than a scalar function of time. The quantity $\vec{a}(\theta_l(t))$ is called the array response vector and will have M components if there are M antenna array elements. Thus, there are M channel impulse responses each with L multipath components. A variety of models are available in [ERT98]. The amplitudes are usually assumed to be Rayleigh distributed although they are now dependent on the array response vector $\vec{a}(\theta_l(t))$ as well.

An extension of this model to the scenario where there are N mobile antenna elements and M base station antenna elements [PED00] is called a *multiple-input multiple-output* (MIMO) channel. In this case the channel impulse response is an $M \times N$ matrix that associates a *transmission coefficient* between each pair of antennas for each multipath component. Experimental results and models are considered in [PED00, KER00].

There appears to be tremendous potential for improving capacity using smart antenna systems. Capacity increases between 300 percent and 500 percent are possible in cellular environments as discussed in Chapter 5. In a microcellular environment, preliminary experimental results with a 4×4 antenna array system seem to indicate that over the MIMO channel, a spectral efficiency of 27.9 b/s/Hz is possible [PED00] compared with spectral efficiencies of 2 b/s/Hz in traditional radio systems.

2.5 CHANNEL MEASUREMENT AND MODELING TECHNIQUES

In order to study and model radio propagation characteristics, there is a need to perform different types of measurements and enhance them with simulations. It is extremely hard to analytically derive the expressions for how a radio signal may propagate through a complex environment. Figure 2.13 shows the general modeling procedure. Measurements of the radio channel are obtained at the site where the wireless network is required to be set up. These could be narrowband or wideband measurements or both as the case may be. The results of the measurements could be directly used or enhanced via simulations of the environment. All the data are then included in a database. Based on realistic assumptions about the nature of the channel, the data are used to construct empirical models. Path loss models are an example of such empirical models. Similarly, it is possible to generate wideband multipath models. These models are usually site-specific, dependent on the frequency and the type of measurement taken. For example, it is impossible to obtain time of arrival of multipath components or the RMS delay spread from narrow-

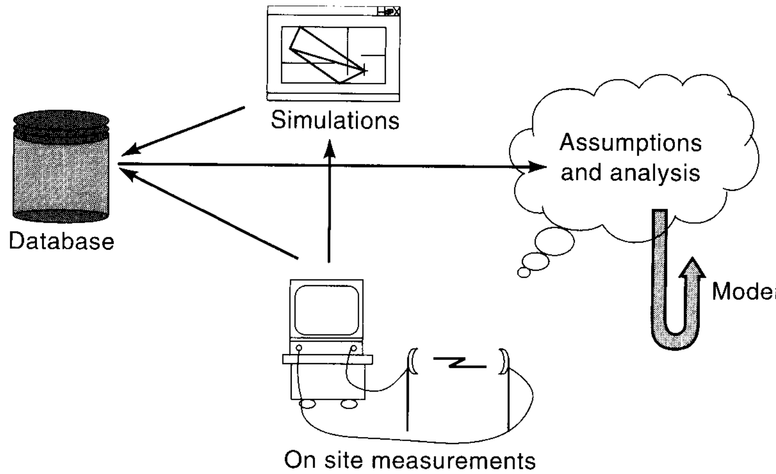

Figure 2.13 General procedure for modeling the radio channel.

band measurements. A detailed discussion of the various measurement and modeling techniques is available in [PAH95].

The procedure for narrowband radio channel measurements [PAH95, BER94], which are useful for determining the expressions for path loss, involves radiating a continuous wave signal from a radio transmitter. The receiver usually employs a vertical dipole antenna along with a position locator so that the distance from the transmitter is known for each value of the measurement. The effects of fast fading are averaged out, and the slow fading values are used in determining the path loss expression. Wideband channel measurements are more complicated [PAH95]. In order to obtain a multipath profile such as the one shown in Figure 2.7, *channel sounders* have to be used. The accuracy of the measurement depends on the channel sounder, the type of antennas used at the transmitter and receiver, the digital signal processing used, the accuracy of the synchronization between transmitter and receiver, and so on. Several channel sounding techniques have been used. Most of them employ one of three techniques: a spread spectrum signal with a matched filter receiver, transmission of a short RF pulse, or use of swept carrier techniques. Spread-spectrum channel sounders are complex to implement but provide large coverage areas. RF pulse systems require large peak power, and pulse amplifiers are expensive. Swept carrier techniques are not suitable for mobile wideband measurements but are quite useful in characterizing the RMS delay spread in indoor areas. Usually a network analyzer is employed for swept carrier wideband measurements. Figure 2.14 shows a picture of a network analyzer and a pair of wideband bicone antennas used for transmitting and receiving signals. Details of all of the measurement techniques can be found in [PAH95].

More recently 3D measurement and modeling of the radio channel characteristics, which includes the angle of arrival as well as delay of arrival of the paths, have become popular for the SIMO and MIMO types of applications. An indoor measurement system and statistical modeling of the angle of arrival of the paths is available in [TIN01]. Figure 2.15 shows a sample measurement of the 3D character-

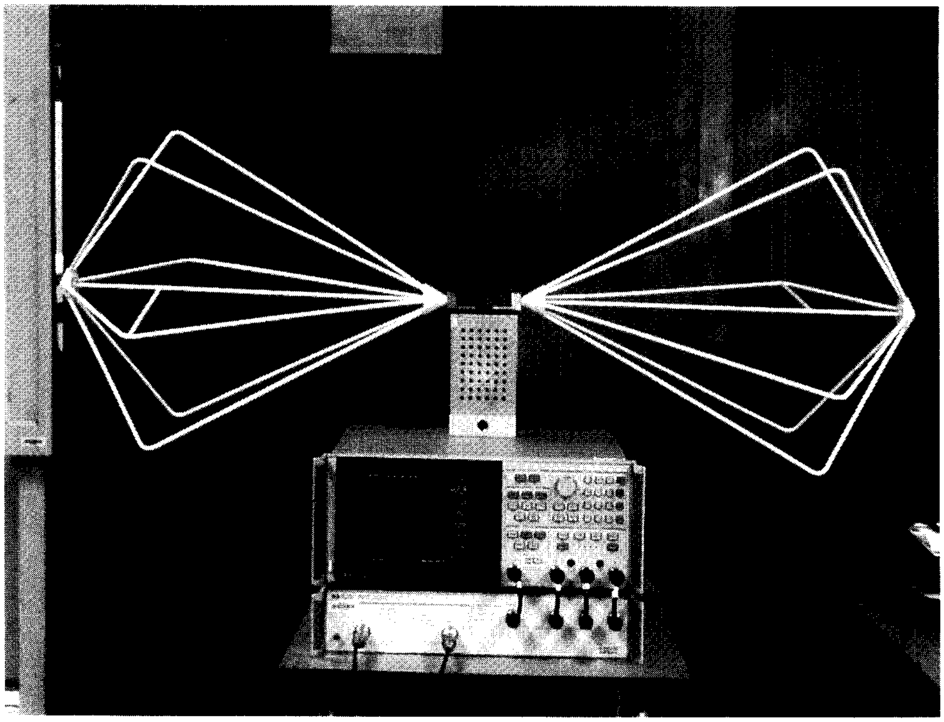

Figure 2.14 A network analyzer and wideband bicone antennas.

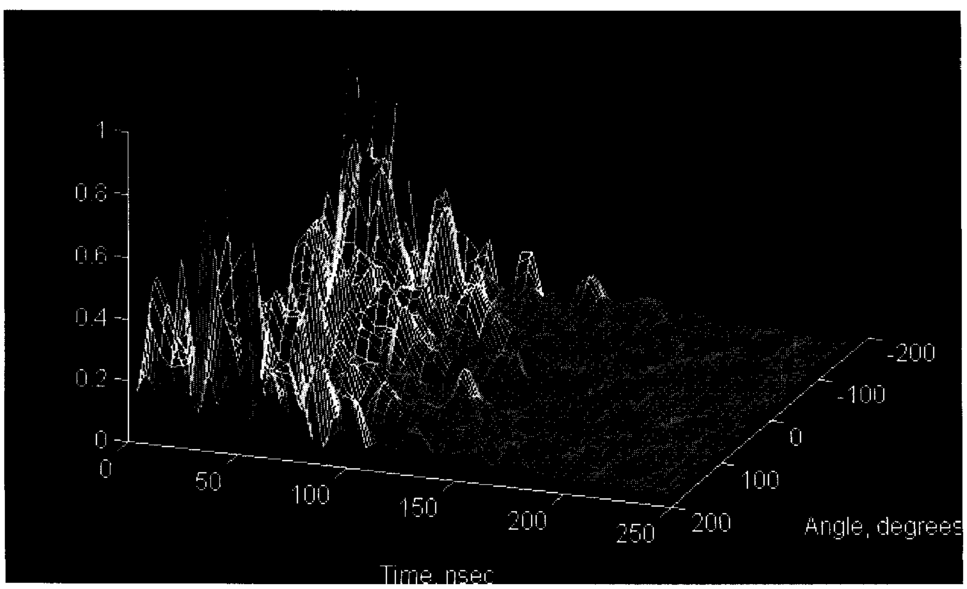

Figure 2.15 Measured time-space characteristics of a typical indoor environment.

istics using an eight-element antenna array. These measurements represent the delay-angle power spectrum that contains the angle of arrival, as well as strength of the signal at different arrival delays. The measurements can then be used for statistical modeling of the 3D characteristics that are useful in performance evaluations of the emerging communications systems exploiting time-space characteristics of the medium to improve the capacity and provide for positioning in E911 or indoor tracking systems [TIN00].

[TIN01] instead of [TIN00]

2.6 SIMULATION OF THE RADIO CHANNEL

With the basic understanding of the radio channel, system engineers can use simulations in software or hardware emulation of the radio channel in order to design, analyze, and deploy a variety of wireless communication systems. Of the many important areas where simulations play a role included are issues such as designing a cellular system where the number of base stations, frequency planning, capacity guarantees and so on can influence the economic viability and competitive edge for service providers. The radio channel models play a role in virtually all aspects of wireless systems, including performance evaluation, coverage calculation and receiver designs, and design of protocols for handoff and power control. Thus it is important to have some idea of how to simulate path loss, outage probabilities, and multipath models.

2.6.1 Software Simulation

Simulating path loss or received signal strength requires adding a random variable with the lognormal distribution to the path loss in Equation (2.7). It is fairly straightforward to simulate path-loss values based on the equations for the path loss and the shadow-fading component.

Radical optical methods can be employed to describe and model electromagnetic wave propagation within and outside buildings when the wavelengths of radio signals are smaller compared with the dimensions of objects that are in the environment [PAH95]. Such a simulation of the radio channel is called *ray tracing*. Figure 2.16 shows a graphical user interface (GUI) of a software that can do ray tracing in two dimensions.

In order to describe radio propagation with ray optics, the three basic mechanisms discussed previously are generally considered. Specular reflections and transmission occur when electromagnetic waves impinge on obstructions larger than the wavelength. Usually, rays that are incident upon the ground, walls of buildings, and so on undergo specular reflection and transmission with the amplitude coefficients determined by plane wave analysis or empirical data. Rays incident upon the edges of buildings, walls, or other large objects can be viewed as exciting the edges to act as a secondary line source. Diffracted waves cause propagation into shadowed regions that are not in clear LOS of the transmitter. Irregular objects such as rough walls, furniture, vehicles, and foliage scatter rays in all directions in the form of

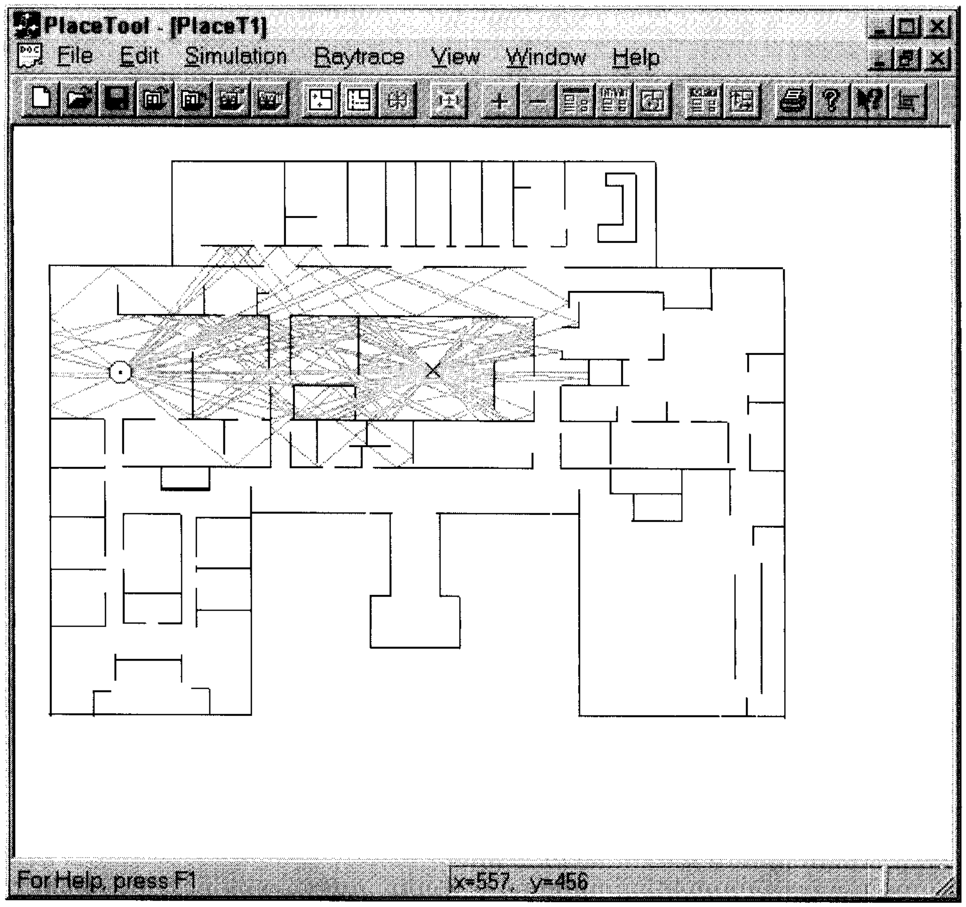

Figure 2.16 Two-dimensional ray tracing software.

spherical waves, especially when the dimensions of objects are on the order of a wavelength or less. The scattered waves are however very weak.

Specular reflection and transmission dominate in indoor environments and are extremely suitable for modeling with ray tracing. When a ray is incident upon a wall, voltage reflection coefficients (Γ) reduce the amplitude of the reflected ray. If there is no absorption, the transmission coefficient (T) will account for the rest of the energy, which will be manifest in the transmitted signal. On the other hand, there is usually some amount of diffuse scattering and absorption that reduces the transmitted energy, resulting in the sum of the reflected and transmitted energies being less than the incident energy. Detailed expressions for Γ and T are available in [PAH95].

The ray tracing approach for dealing with specular reflections and transmissions is as follows. Rays emanating from the transmitter reach the receiver after transmission through and reflection from walls. The unfolded path length determines the signal associated with a specular component. In order to determine all possible ray paths, two approaches exist in practice. In the ray shooting or ray launching approach, rays are launched from the transmitter at regular angular intervals on the order of a degree. Each ray is traced as it intersects with the first wall where it gives rise to a transmitted and reflected ray. Both new rays are traced to the next interaction and so on building a binary tree of rays that continues until some termination criterion is met. As discrete rays have a zero probability of intersecting a point, a region around the receiver is used to represent the receiver itself. The second approach called the image approach determines the exact ray paths between points by imaging the source in the plane of each wall. The former approach is easier for computer implementation. Having determined the required number of contributing rays that intersect the receiver when launched from the transmitter, the received power associated with the ith ray, assuming isotropic antennas is given by:

$$P_{r(i)} = P_0 \frac{1}{R_i^2} \prod_j |\Gamma_j(\phi_{ji})|^2 \prod_m |T_m(\phi_{mi})|^2 \tag{2.22}$$

where R_i is the total unfolded path length of the ith ray, $\Gamma_j(\phi_{ji})$ is the reflection coefficient encountered by the ith ray at the jth wall as a function of the incident angle ϕ_{ji}. $T_m(\phi_{mi})$ is the transmission coefficient encountered by the ith ray at the

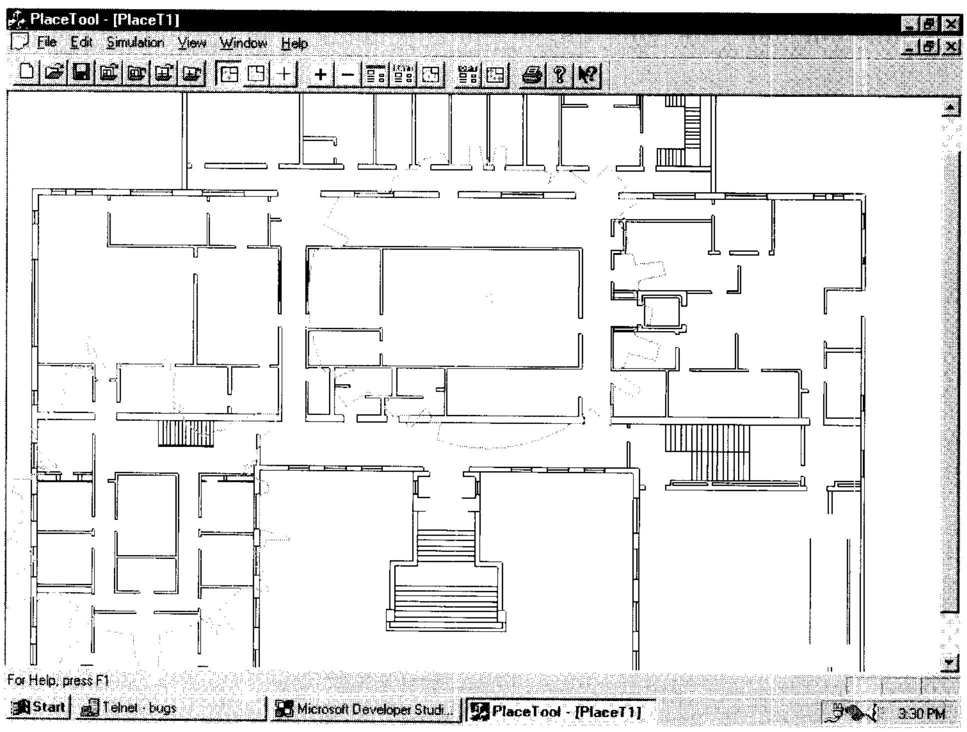

Figure 2.17 Path loss models in deployment software.

mth wall as a function of the incident angle ϕ_{mi} and P_0 is the received power at the first meter from the transmitter. The total received power is calculated by the sum of the individual received powers. The power delay profile is obtained by calculating the total delay from the unfolded path length R_i using the relation $\tau_i = R_i/c$, c being the speed of light. Ray tracing has been used successfully in predicting the signal coverage indoor, as well as in microcellular environments [PAH95].

In several commercial applications, deployment of radio transmitters (base stations and access points) becomes very important in terms of providing the required service, as well as consumer satisfaction. *Deployment tools* for macro-, micro-, and picocellular environments are used to design wireless networks. As discussed in later chapters, most wireless networks use a cellular topology where each base station or access points covers an area called a cell. Path loss models discussed earlier are used in many of the deployment tools to roughly determine the coverage area of base stations and to determine how many base stations are required for covering an area and where they should be placed. Figure 2.17 shows the GUI of one such deployment tool for indoor areas that employs the partition-dependent path loss model of Equation (2.15). Ray tracing may also be employed to estimate path loss via simulations.

2.6.2 Hardware Emulation

Real-time hardware RF channel simulators allow communication systems to be tested quickly and thoroughly under controlled, realistic, and repeatable channel conditions in the laboratory, eliminating the time and cost of lengthy field tests. There are currently several commercial real-time channel simulators available. These RF channel simulators, sometimes called RF channel emulators, are being

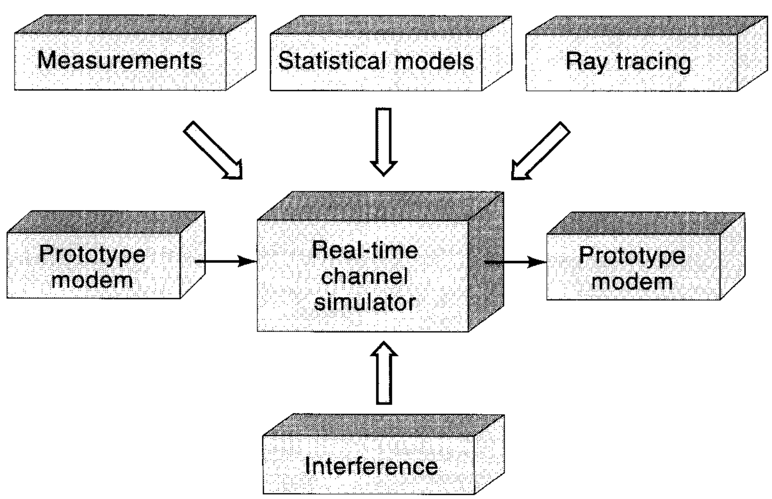

Figure 2.18 Schematic of a real-time channel simulator.

developed for testing modern wireless communications equipment (WCDMA, IS-136, IS-95, GSM, IEEE 802.11, and Bluetooth). They can emulate RF channel characteristics such as multipath fading, lognormal shadowing, path loss attenuation, delay spread, Doppler spread, and additive white Gaussian noise (AWGN). Recently these emulators are being augmented to include means for diversity testing and simulation of jamming. The emulators have embedded statistical channel models, which can use Rayleigh, Gaussian, Nakagami, constant, Ricean, and pure Doppler fading distributions (see Fig. 2.18). They can also be programmed to simulate custom channel models.

The technical specifications of an emulator depends strongly on wherever the communication system under test is for outdoor or indoor use. As an example, the specifications for the PROPSim radio channel simulator (see Fig. 2.19) from Elektrobit Ltd., which can be used for PCS and DECT indicates it has up to 312 taps, with tap spacing ranging from 25 to 3200 ns, a delay resolution as low as 2.5 ns, an RF bandwidth as high as 35 MHz and an RF frequency range from 100 to 400 MHz and from 600 to 2,650 MHz. This emulator uses DSP interpolation techniques to improve its delay resolution beyond that possible from the RF bandwidth limitations. It is possible to emulate the site-specific Ray Tracing–based channel models

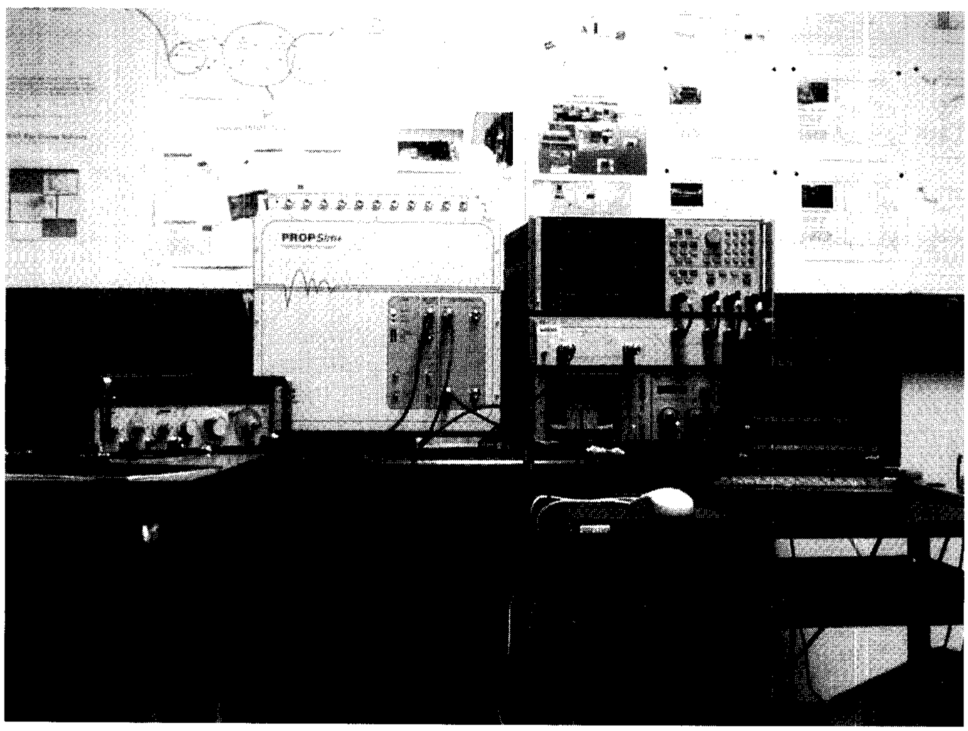

Figure 2.19 The PROPSim hardware.

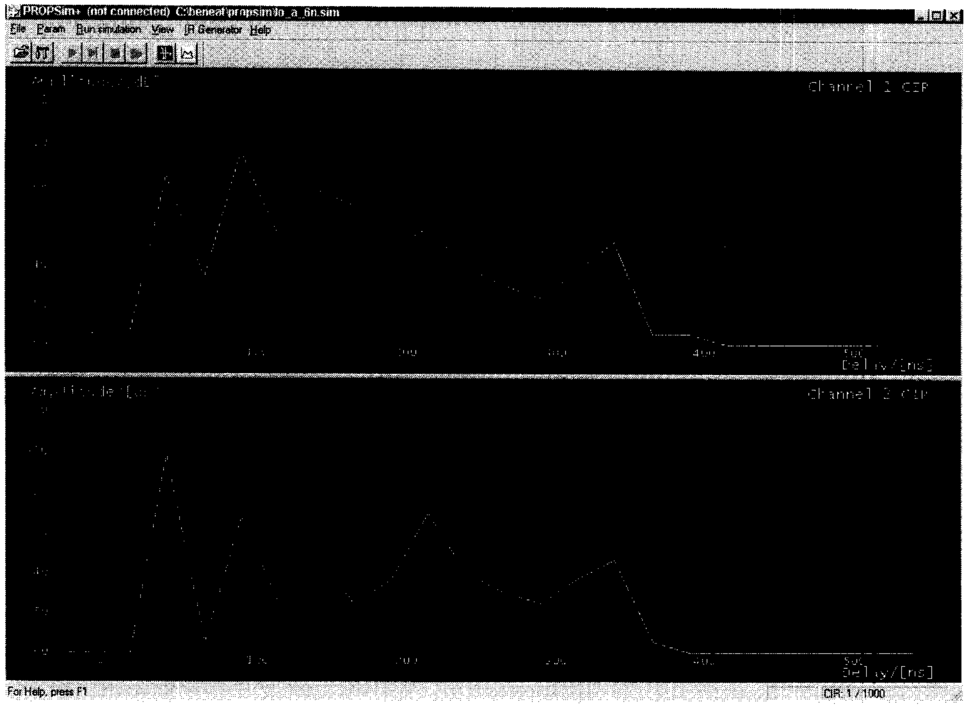

Figure 2.20 Snapshot of the GUI of PROPSim.

into the Elektrobit channel simulator. In this simulator the user interactively (see Fig. 2.20 for a snapshot of the GUI) identifies the location of transmitter and receiver in the users interface floor plan to obtain the channel model that reflects the identified communication link.

APPENDIX 2A WHAT IS dB?

Decibel or dB is usually the unit employed to compute the logarithmic measure of power and power ratios. The reason for using dB is that all computation reduces to addition and subtraction rather than multiplication and division. Every link, node,

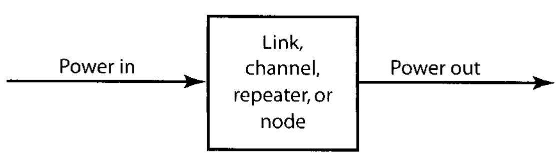

Figure 2A.1 Description of model for defining dB.

repeater, or channel can be treated as a *black box* (see Fig. 2A.1) with a particular decibel gain. The decibel gain of such a black box is given by

$$\text{db gain} = 10 \log\left(\frac{\text{power of output signal}}{\text{power of input signal}}\right) = 10 \log\left(\frac{P_{out}}{P_{in}}\right) \quad (2A.1)$$

This corresponds to the *relative* output power with respect to the input power. The logarithm is always to the base 10. If the ratio in Eq. (2A.1) is negative, it is a decibel loss.

The decibel gain relative to an absolute power of 1 mW is denoted by dBm and that relative to 1 W is denoted by dBW. For example, if the input power is 50 mW, relative to 1 mW, the input power is 10 log (50 mW/ 1 mW) = 16.98 dBm. If this is followed by a link having a loss of 10 dB, the absolute power at the output of the link will be 16.98 − 10 = 6.98 dBm. Relative to 1 W, these values will be 10 log (50×10^{-3}/ 1) = −13 dBW and −23 dBW, respectively.

Antenna gains are represented similarly with respect to an *isotropic* antenna (which radiates with a gain of unity in all directions) or a *dipole* antenna. The former gain is in units of dBi and the latter in units of dBd. The units in dBi are 2.15 dB larger than the units in dBd.

APPENDIX 2B WIRED MEDIA

The most common wired media for communications are TP wires, coaxial cables, optical fibers, and power line wires. TP wires, in shielded (STP) and unshielded (UTP) forms, is available in a variety of categories. It is commonly used for local voice and data communications in home and offices. The telephone companies use category 3 UTP to bring POTS to customer premises and distribute it in the premises. This wiring is also used for voice-band modem data communications, ISDN, DSL, and home phone networking (HPN). The wired media in local area networks are dominated by a variety of UTP and STP to support a range of local data services from several Mbps up to over a gigabit per second within 100 meters of distance.

Coaxial cable provides a wider band useful for a multichannel FDM operation, lower radiation, and longer coverage than TP, but it is less flexible in particular in indoor areas. The early LANs were operating on the so-called thick cable to cover up to 500 meters per segment. To reduce the cost of wiring, the thin cable, sometime referred to as Cheaper-LAN, that covers up to 200 meter per segment, replaced thick cables. Cabled LANs are not popular anymore, and TP wirings are taking over the LAN market. Another important application for cable is cable television which has a huge network to connect homes to the cable TV network. This network is also used for broadband access to the Internet. The cable-LANs were using baseband technology with data rates of 10 Mbps while broadband cable-modems provide comparable data rates over each of around hundred cable TV channels. Today, in addition to traditional cable TV, cable-modems are becoming a popular access method to the Internet, and some cable service providers are offering voice services over the cable connections.

Fiber optic lines provide extremely wide bandwidth, smaller size, lighter weight, less interference, and very long coverage (low attenuation). However, fiber lines are less flexible and more expensive to install, not suitable for FDM (though wavelength division multiplexing—WDM—is becoming common), and have expensive electronics for TDM operation. Because of the wide bandwidth and low attenuation, optical fiber lines are becoming the dominant wired medium to interconnect switches in all long-haul networks. In the LAN applications fiber lines mostly serve the backbone to interconnect servers and other high-speed elements of the local networks. Optical fibers have not found a considerable market for distributing any service to the home or office desktop.

Power-line wiring has also attracted some attention for low speed and high-speed home networks. The bandwidth for power lines is more restricted, the interference caused by appliances is significant, and the radiated interference in the frequency of operation of AM radio is high enough that frequency assignment agencies do not allow power line data networking in these frequencies. However, power lines have good distribution in exiting homes because power plugs are available in all rooms. In addition almost all appliances are connected to the power line, and with only one connection a terminal can connect to the network and the power supply. Existing power line networks either operate at low data rate in low frequencies, below frequency of operation of the AM radios, to interconnect evolving smart appliances or they operate at high data rates of up to 10 Mbps in frequencies above AM radio for home computing.

The wireless channels considered in this book are all for relatively short connections. For long haul transportations, these networks are complemented with wired connections. As we have discussed in this chapter, the average path loss in wireless channels is exponentially related to the distance, and we often describe the path loss in a fixed dB value per decade of distance (see Appendix 2A for a definition of dB). The path loss in wired environments is linearly related to the distance. Therefore wired connections are more power efficient for shorter distances and wireless for longer distances.

Example 2B.1: Path Loss in Wired and Wireless Media

The category 3 UTP wires used for Ethernet lose around 13 dB per 100 meters of distance [STA00]. Therefore, the path loss for 1 km is 130 dB. In free-space, the path loss of a 1 GHz radio in the first meter is around 30 dB (with an omnidirectional dipole antenna), and after that the path loss is 20 dB per decade of distance. Therefore, path loss at 100 meters is 70 dB and for 1 km it is 90 dB. Indeed for 130 dB path loss, the 1 GHz radio can cover 1,000 km. Therefore, for short distances, the path loss for wired transmission is smaller, but for long distances path loss for radio systems is smaller. This is the reason why in long haul wired transmissions, repeaters are commonly used. Also, for the same reason radio signals are able to provide for very long-distance satellite communications.

APPENDIX 2C PATH LOSS MODELS

Table 2C.1 tabulates the COST-231 path loss model. These formulas can be applied for rough calculations in terms of system dimensioning, power budget calculations, and so on, but site specific measurements are the only true way of determining what the radio propagation characteristics are in a particular area.

Table 2C.1 The COST-231 Model for PCS Applications in Urban Areas

General Formulation:

$$L_p = 46.3 + 33.9 \log f_c - 13.82 \log h_b - a(h_m) + [44.9 - 6.55 \log h_b] \log d + C_M$$

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		1,500 – 2,000 MHz
h_b, h_m in meters		30–200m, 1–10m
d		1 – 20 km
C_M	Large City	0 dB
	Medium City/ Suburban areas	3 dB

APPENDIX 2D WIDEBAND CHANNEL MODELS

Table 2D.1 is a list of the JTC wideband multipath channel models in indoor areas. Each table has three channel models. A, B, and C associated with good, medium, and bad conditions. See [PAH95] for more details.

Table 2D.1 JTC Parameters of the Wideband Multipath Channel for Indoor Commercial Buildings

	Channel A		**Channel B**		**Channel C**		
Tap	***Rel Delay*[1] *(nSec)***	***Avg Power (dB)***	***Rel Delay*[1] *(nSec)***	***Avg Power (dB)***	***Rel Delay*[1] *(nSec)***	***Avg Power (dB)***	**Doppler Spectrum $D(\lambda)$**
1	0	0	0	0	0	0	FLAT
2	100	−5.9	100	−0.2	200	−4.9	FLAT
3	200	−14.6	200	−5.4	500	−3.8	FLAT
4			400	−6.9	700	−1.8	FLAT
5			500	−24.5	2100	−21.7	FLAT
6			700	−29.7	2700	−11.5	FLAT

[1]A ± 3 percent variation about the relative delay is allowed.

Table 2D.2 JTC Parameters of the Wideband Multipath Channel for Indoor Office Buildings

	Channel A		Channel B		Channel C		
Tap	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	**Doppler Spectrum** $D(\lambda)$
1	0	0	0	0	0	0	FLAT
2	100	−8.5	100	−3.6	200	−1.4	FLAT
3			200	−7.2	500	−2.4	FLAT
4			300	−10.8	700	−4.8	FLAT
5			500	−18.0	1100	−1.0	FLAT
6			700	−25.2	2400	−16.3	FLAT

[1]A ± 3 percent variation about the relative delay is allowed.

Table 2D.3 JTC Parameters of the Wideband Multipath Channel for Indoor Residential Buildings

	Channel A		Channel B		Channel C		
Tap	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	***Rel Delay[1] (nSec)***	***Avg Power (dB)***	**Doppler Spectrum** $D(\lambda)$
1	0	0	0	0	0	0	FLAT
2	100	−13.8	100	−6.0	100	−0.2	FLAT
3			200	−11.9	200	−5.4	FLAT
4			300	−17.9	400	−6.9	FLAT
5					500	−24.5	FLAT
6					600	−29.7	FLAT

[1]A ± 3 percent variation about the relative delay is allowed.

QUESTIONS

2.1 What are the three important radio propagation phenomena at high frequencies? Which of them is predominant indoors?

2.2 Explain what path-loss gradient means. Give some typical values of the path-loss gradient in different environments.

2.3 Explain the meaning of the expression "a loss of 37 dB per decade of distance" in terms of the path loss gradient α.

2.4 Why does multipath in wireless channels limit the maximum symbols transmission rate? How can we overcome this limitation?

2.5 What is the Doppler spectrum and how can one measure it?

2.6 Differentiate between shadow fading and fast fading.

2.7 What distributions are used to model fast fading in LOS situations? In OLOS situations?

2.8 What are the differences between multipath, shadow, and frequency-selective fading? Give an example distribution function that is used to model multipath fading and an example that is used to model shadow fading.

2.9 What techniques can be used to combat the effects of frequency selective fading (multipath delay spread)?

2.10 For position location applications, how are wideband radio channels classified? How is this classification useful?

2.11 What is the difference between a SIMO and a MIMO radio channel?

2.12 Name three channel sounding techniques. Give the advantages and disadvantages of each.

2.13 Explain ray tracing.

2.14 How can we emulate a radio channel in hardware?

PROBLEMS

2.1 What is the received power (in dBm) in 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? What is the path loss is dB?

2.2 Use the Okumura-Hata and COST-231 models to determine the maximum radii of cells at 900 MHz and 1,900 MHz respectively having a maximum acceptable path loss of 130 dB. Use $a(h_m) = 3.2\,[\log(11.75\,h_m)]^2 - 4.97$ for both cases.

2.3 In a mobile communications network, the minimum required signal-to-noise ratio is 12 dB. The background noise at the frequency of operation is −115 dBm. If the transmit power is 10 W, transmitter antenna gain is 3 dBi, the receiver antenna gain is 2 dBi, the frequency of operation is 800 MHz, and the base station and mobile antenna heights are 100 m and 1.4 m respectively, determine the maximum in building penetration loss that is acceptable for a base station with a coverage of 5 km if the following path loss models are used.

a. Free space path loss model

b. Two-ray path loss model

c. Okumura-Hata model for a small city

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

2.5 Signal strength measurements for urban microcells in the San Francisco Bay area in a mixture of low-rise and high-rise buildings indicate that the path loss L_p in dB as a function of distance d is given by the following linear fits:

$$L_p = 81.14 + 39.40 \log f_c - 0.09 \log h_b + [15.80 - 5.73 \log h_b] \log d, \text{ for } d < d_{bk}$$

$$L_p = [48.38 - 32.1 \log d_{bk}] + 45.7 \log f_c + (25.34 - 13.9 \log d_{bk}) \log h_b + [32.10 + 13.90 \log h_b] \log d + 20 \log(1.6/h_m), \text{ for } d > d_{bk}$$

Here, d is in kilometers, the carrier frequency f_c is in GHz (that can range between 0.9 and 2 GHz), h_b is the height of the base station antenna in meters, and h_m is the height of the mobile terminal antenna from the ground in meters. The *breakpoint* distance d_{bk} is the distance at which two piecewise linear fits to the path loss model have been developed and it is given by $d_{bk} = 4h_b h_m/1000\lambda$, where λ is the wavelength in meters. The shadow-fading component in dB is given by a zero mean Gaussian random variable with a standard deviation of 5 db.

a. If 90 percent of the locations at the cell edge need coverage, what should be the fading margin applied? What percent of locations would be covered if a fading margin of 5 dB is used?

b. What would be the radius of a cell covered by a base station (height 15 m) operating at 1.9 GHz and transmitting a power of 10 mW that employs a directional antenna of gain 5 dBi? The fading margin is 7.5 dB and the sensitivity of the mobile receiver is −110 dBm. Assume that $h_m = 1.2$ m. How would you increase the size of the cell?

Note that the path losses predicted by the two equations are very close, but not exactly the same at $d = d_{bk}$. You can use either value in your calculation.

2.6 The path loss in a building was discovered to have two factors adding to the free space loss: a factor directly proportional to the distance and a floor-attenuation factor. In other words, path loss = free space loss + βd + FAF. If the FAF is 24 dB, and the distance between transmitter and receiver is 30 m, determine what should be the value of β so that the path loss suffered is less than 110 dB.

2.7 Sketch the power-delay profile of the following wideband channel. Calculate the excess delay spread, the mean delay, and the RMS delay spread of the following multipath channel. A channel is considered "wideband" if its coherence bandwidth is smaller than the data rate of the system. Would the channel be considered a wideband channel for a binary data system at 25 kbps? Why?

Relative delay in microseconds	Average relative power in dB
0.0	−1.0
0.5	0.0
0.7	−3.0
1.5	−6.0
2.1	−7.0
4.7	−11.0

2.8 The modulation technique used in the existing American Mobile Phone (AMP) cellular radio systems in analog FM. The transmission bandwidth is 30 kHz per channel and the maximum transmitted power from a mobile user is 3 W. The acceptable quality of the input SNR is 18 dB and the background noise in the bandwidth of the system is −120 dBm (120 dB below the 1 mW reference power). In the cellular operation we may assume that the strength of the signal drops 30 dB for the first meter of distance from the transmitter antenna and 40 dB per decade of distance for distances beyond 1 meter.

a. What is the maximum distance between the mobile station and the base station at which we have an acceptable quality of signal?

b. Repeat (a) for digital cellular systems for which the acceptable SNR is 14 dB.

2.9 The modulation technique used in the exiting Advanced Mobile Phone System (AMPS) is analog FM. The transmission bandwidth is 30 kHz per channel and the maximum transmitted power from a mobile user is 3 W. The acceptable quality of the received SNR is 18 dB and the power of the background noise in the system is −120 dBm. Assuming that the height of the base and mobile station antennas are $h_b = 100$ m and $h_m = 3$ m respectively and the frequency operation of is $f = 900$ MHz, what is the maximum distance between the mobile station and the base station for an acceptable quality of communication?

a. Assume free space propagation with transmitter and receiver antenna gains of 2.

b. Use Hata's equations for Okumura's model in a large city.

c. Use JTC model in residential areas and assume that the mobile unit is used inside a building.

2.10 The Doppler spectrum of the indoor radio is often assumed to have a uniform distribution with a maximum Doppler shift of 10 Hz.

a. Determine the rms Doppler spread of the channel.

b. Determine the average number of fades per second and the average fade duration, assuming that the threshold for fading is chosen to be 10 dB below the average rms value of the signal.

2.11 Using specifications of Channel A in Table 2D.1 for the JTC model in the indoor office areas, determine the mean delay spread of the channel. Determine the rums delay spread of the channel. Give an approximated maximum data rate that can be supported over this channel.

2.12 Consider a transmitter located in a multistory building. The receiver is located three floors below. The floor loss is 5 dB per floor. There are two brick walls, one office wall, and a glass wall between the transmitter and receiver in addition to the floors. The distance between the transmitter and receiver is 16 m. Assuming a frequency of operation of 1 GHz and transmitter and receiver antenna gains of 1.6, calculate the path-loss using:

a. The partition-dependent model described in Section 2.3.7.~~2 that assumes a distance power gradient of 1.8, 2.0, and 4.2.~~ 2.3.7.3 13

b. Using the JTC model for indoor office areas.

2.13 In Eq. (2.19) we looked at the impulse response of a multipath channel. This is a specific instance of the general characterization of a multipath channel called the *scattering function.* The uncorrelated scattering function of an indoor radio channel is defined as the product of a time function $Q(\tau)$ that represents the delay-power spectrum and a frequency function $D(\lambda)$ that represents the Doppler Spectrum (See [PAH95] for details), i.e.,

$$S(\tau;\lambda) = Q(\tau)\, D(\lambda)$$

The scattering function provides a better description of the radio channel. Suppose for τ (in ns) we have

$$Q(\tau) = 0.4\,\delta(\tau - 50) + 0.4\,\delta(\tau - 100) + 0.2\delta(\tau - 200)$$

and for λ (in Hz):

$$D(\lambda) = 0.1\,U(\lambda + 5) + 0.1\,U(\lambda - 5)$$

with $\delta(.)$ and $U(.)$ functions representing the impulse and unit step functions.

a. Determine the RMS delay spread of the channel assuming $Q(\tau)$ is similar to Eq. (2.19) and the mean square values are specified here.

b. Determine the RMS Doppler spread of the channel using an expression similar to Eq. (2.20) but with $D(\lambda)$ instead of $Q(\tau)$.

c. Give the coherence bandwidth of the channel.

2.14 Use a software tool like Matlab™ or Mathcad to generate 1,000 impulse responses of the JTC indoor residential radio channel (all three cases). Determine the RMS multipath delay spread for each sample and plot the cumulative distribution function.

2.15 The inter-arrival times of multipath components can be modeled as either a constant or as a random process. In many cases, the inter-arrival times are modeled as samples from an exponential distribution (path arrivals are from a Poisson process—see [PAH95]). If the variance of the exponential distribution used to model one such radio channel is 4 ns^2, what is the average arrival time of the process? Use a software tool to generate 100 samples of the inter-arrival times and plot arrival times of the multipath components. Compute the average for your simulations.