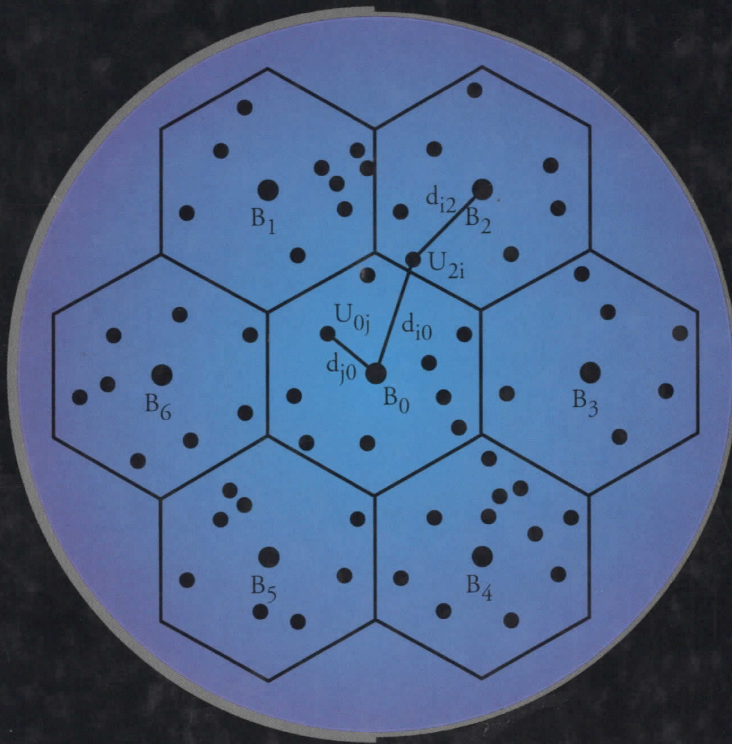


WIRELESS

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Principles  Practice

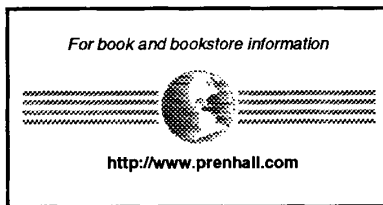


 Theodore S. Rappaport

Wireless Communications

Principles and Practice

Theodore S. Rappaport



Prentice Hall PTR
Upper Saddle River, New Jersey 07458

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Mobile Radio Propagation: Small-Scale Fading and Multipath

Small-scale fading, or simply *fading*, is used to describe the rapid fluctuation of the amplitude of a radio signal over a short period of time or travel distance, so that large-scale path loss effects may be ignored. Fading is caused by interference between two or more versions of the transmitted signal which arrive at the receiver at slightly different times. These waves, called *multipath waves*, combine at the receiver antenna to give a resultant signal which can vary widely in amplitude and phase, depending on the distribution of the intensity and relative propagation time of the waves and the bandwidth of the transmitted signal.

4.1 Small-Scale Multipath Propagation

Multipath in the radio channel creates small-scale fading effects. The three most important effects are:

- Rapid changes in signal strength over a small travel distance or time interval
- Random frequency modulation due to varying Doppler shifts on different multipath signals
- Time dispersion (echoes) caused by multipath propagation delays.

In built-up urban areas, fading occurs because the height of the mobile antennas are well below the height of surrounding structures, so there is no single line-of-sight path to the base station. Even when a line-of-sight exists, multipath still occurs due to reflections from the ground and surrounding structures. The incoming radio waves arrive from different directions with different propagation delays. The signal received by the mobile at any point in space may consist of a large number of plane waves having randomly distributed amplitudes,

phases, and angles of arrival. These multipath components, combine vectorially at the receiver antenna, and can cause the signal received by the mobile to distort or fade. Even when a mobile receiver is stationary, the received signal may fade due to movement of surrounding objects in the radio channel.

If objects in the radio channel are static, and motion is considered to be only due to that of the mobile, then fading is purely a spatial phenomenon. The spatial variations of the resulting signal are seen as temporal variations by the receiver as it moves through the multipath field. Due to the constructive and destructive effects of multipath waves summing at various points in space, a receiver moving at high speed can pass through several fades in a small period of time. In a more serious case, a receiver may stop at a particular location at which the received signal is in a deep fade. Maintaining good communications can then become very difficult, although passing vehicles or people walking in the vicinity of the mobile can often disturb the field pattern, thereby diminishing the likelihood of the received signal remaining in a deep null for a long period of time. Antenna space diversity can prevent deep fading nulls, as shown in Chapter 6. Figure 3.1 shows typical rapid variations in the received signal level due to small-scale fading as a receiver is moved over a distance of a few meters.

Due to the relative motion between the mobile and the base station, each multipath wave experiences an apparent shift in frequency. The shift in received signal frequency due to motion is called the Doppler shift, and is directly proportional to the velocity and direction of motion of the mobile with respect to the direction of arrival of the received multipath wave.

4.1.1 Factors Influencing Small-Scale Fading

Many physical factors in the radio propagation channel influence small-scale fading. These include the following:

- **Multipath propagation** — The presence of reflecting objects and scatterers in the channel creates a constantly changing environment that dissipates the signal energy in amplitude, phase, and time. These effects result in multiple versions of the transmitted signal that arrive at the receiving antenna, displaced with respect to one another in time and spatial orientation. The random phase and amplitudes of the different multipath components cause fluctuations in signal strength, thereby inducing small-scale fading, signal distortion, or both. Multipath propagation often lengthens the time required for the baseband portion of the signal to reach the receiver which can cause signal smearing due to intersymbol interference.
- **Speed of the mobile** — The relative motion between the base station and the mobile results in random frequency modulation due to different Doppler shifts on each of the multipath components. Doppler shift will be positive or negative depending on whether the mobile receiver is moving toward or away from the base station.

- **Speed of surrounding objects** — If objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components. If the surrounding objects move at a greater rate than the mobile, then this effect dominates the small-scale fading. Otherwise, motion of surrounding objects may be ignored, and only the speed of the mobile need be considered.
- **The transmission bandwidth of the signal** — If the transmitted radio signal bandwidth is greater than the “bandwidth” of the multipath channel, the received signal will be distorted, but the received signal strength will not fade much over a local area (i.e., the small-scale signal fading will not be significant). As will be shown, the bandwidth of the channel can be quantified by the *coherence bandwidth* which is related to the specific multipath structure of the channel. The coherence bandwidth is a measure of the maximum frequency difference for which signals are still strongly correlated in amplitude. If the transmitted signal has a narrow bandwidth as compared to the channel, the amplitude of the signal will change rapidly, but the signal will not be distorted in time. Thus, the statistics of small-scale signal strength and the likelihood of signal smearing appearing over small-scale distances are very much related to the specific amplitudes and delays of the multipath channel, as well as the bandwidth of the transmitted signal.

4.1.2 Doppler Shift

Consider a mobile moving at a constant velocity v , along a path segment having length d between points X and Y, while it receives signals from a remote source S, as illustrated in Figure 4.1. The difference in path lengths traveled by the wave from source S to the mobile at points X and Y is $\Delta = d \cos \theta = v \Delta t \cos \theta$, where Δt is the time required for the mobile to travel from X to Y, and θ is assumed to be the same at points X and Y since the source is assumed to be very far away. The phase change in the received signal due to the difference in path lengths is therefore

$$\Delta \phi = \frac{2\pi \Delta l}{\lambda} = \frac{2\pi v \Delta t}{\lambda} \cos \theta \quad (4.1)$$

and hence the apparent change in frequency, or Doppler shift, is given by f_d , where

$$f_d = \frac{1}{2\pi} \cdot \frac{\Delta \phi}{\Delta t} = \frac{v}{\lambda} \cdot \cos \theta \quad (4.2)$$

Equation (4.2) relates the Doppler shift to the mobile velocity and the spatial angle between the direction of motion of the mobile and the direction of arrival of the wave. It can be seen from equation (4.2) that if the mobile is moving toward the direction of arrival of the wave, the Doppler shift is positive (i.e., the apparent received frequency is increased), and if the mobile is moving away from the direction of arrival of the wave, the Doppler shift is negative (i.e. the

$$B_D = f_m = \frac{vf_c}{c} = \frac{50 \times 1900 \times 10^6}{3 \times 10^8} = 316.66 \text{ Hz}$$

4.5 Types of Small-Scale Fading

Section 4.3 demonstrated that the type of fading experienced by a signal propagating through a mobile radio channel depends on the nature of the transmitted signal with respect to the characteristics of the channel. Depending on the relation between the signal parameters (such as bandwidth, symbol period, etc.) and the channel parameters (such as rms delay spread and Doppler spread), different transmitted signals will undergo different types of fading. The time dispersion and frequency dispersion mechanisms in a mobile radio channel lead to four possible distinct effects, which are manifested depending on the nature of the transmitted signal, the channel, and the velocity. While multipath delay spread leads to *time dispersion* and *frequency selective fading*, Doppler spread leads to *frequency dispersion* and *time selective fading*. The two propagation mechanisms are independent of one another. Figure 4.11 shows a tree of the four different types of fading.

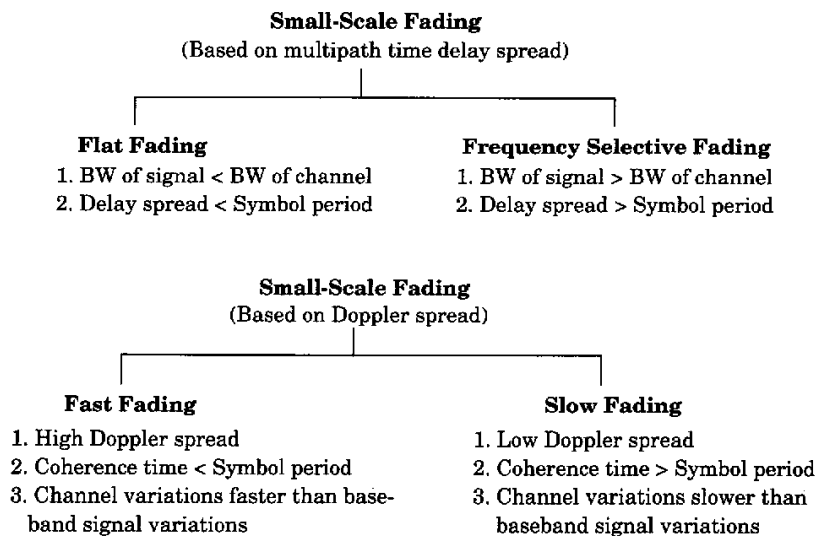


Figure 4.11
Types of small-scale fading.

4.5.1 Fading Effects Due to Multipath Time Delay Spread

Time dispersion due to multipath causes the transmitted signal to undergo either flat or frequency selective fading.

4.5.1.1 Flat fading

If the mobile radio channel has a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, then the received signal will undergo *flat fading*. This type of fading is historically the most common type of fading described in the technical literature. In flat fading, the multipath structure of the channel is such that the spectral characteristics of the transmitted signal are preserved at the receiver. However the strength of the received signal changes with time, due to fluctuations in the gain of the channel caused by multipath. The characteristics of a flat fading channel are illustrated in Figure 4.12.

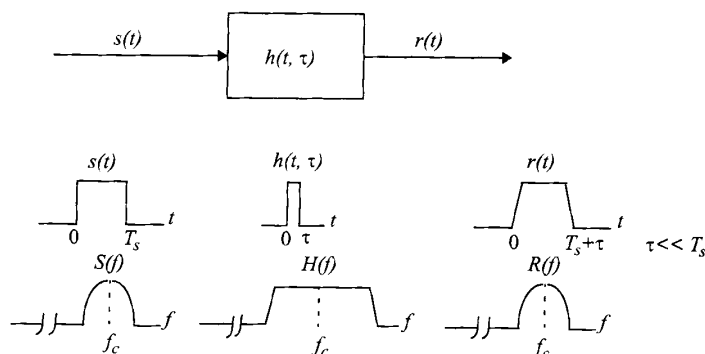


Figure 4.12
Flat fading channel characteristics.

It can be seen from Figure 4.12 that if the channel gain changes over time, a change of amplitude occurs in the received signal. Over time, the received signal $r(t)$ varies in gain, but the spectrum of the transmission is preserved. In a flat fading channel, the reciprocal bandwidth of the transmitted signal is much larger than the multipath time delay spread of the channel, and $h_b(t, \tau)$ can be approximated as having no excess delay (i.e., a single delta function with $\tau = 0$). Flat fading channels are also known as *amplitude varying channels* and are sometimes referred to as *narrowband channels*, since the bandwidth of the applied signal is *narrow* as compared to the channel flat fading bandwidth. Typical flat fading channels cause deep fades, and thus may require 20 or 30 dB more transmitter power to achieve low bit error rates during times of deep fades as

Equalization, Diversity, and Channel Coding

Mobile communication systems require signal processing techniques that improve the link performance in hostile mobile radio environments. As seen in Chapters 3 and 4, the mobile radio channel is particularly dynamic due to multipath fading and Doppler spread, and as shown in the latter part of Chapter 5, these effects have a strong negative impact on the bit error rate of any modulation technique. Mobile radio channel impairments cause the signal at the receiver to distort or fade significantly as compared to AWGN channels.

6.1 Introduction

Equalization, diversity, and channel coding are three techniques which can be used independently or in tandem to improve received signal quality.

Equalization compensates for *intersymbol interference* (ISI) created by multipath within time dispersive channels. As shown in Chapters 4 and 5, if the modulation bandwidth exceeds the coherence bandwidth of the radio channel, ISI occurs and modulation pulses are spread in time. An equalizer within a receiver compensates for the average range of expected channel amplitude and delay characteristics. Equalizers must be adaptive since the channel is generally unknown and time varying.

Diversity is another technique used to compensate for fading channel impairments, and is usually implemented by using two or more receiving antennas. As with an equalizer, the quality of a mobile communications link is improved without increasing the transmitted power or bandwidth. However, while equalization is used to counter the effects of time dispersion (ISI), diversity is usually employed to reduce the depth and duration of the fades experienced by

The correlation coefficient is determined by three factors: polarization angle; offset angle from the main beam direction of the diversity antenna and the cross polarization discrimination. The correlation coefficient generally becomes higher as offset angle β becomes larger. Also, ρ generally becomes lower as polarization angle α increases. This is because the horizontal polarization component becomes larger as α increases.

Because antenna elements V_1 and V_2 are polarized at $\pm\alpha$ to the vertical, the received signal level is lower than that received by a vertically polarized antenna. The average value of signal loss L , relative to that received using vertical polarization is given by

$$L = a^2/\Gamma + b^2 \quad (6.78)$$

The results of practical experiments carried out using polarization diversity [Koz85] show that polarization diversity is a viable diversity reception technique.

6.10.5 Frequency Diversity

Frequency diversity transmits information on more than one carrier frequency. The rationale behind this technique is that frequencies separated by more than the coherence bandwidth of the channel will not experience the same fades [Lem91]. Theoretically, if the channels are uncorrelated, the probability of simultaneous fading will be the product of the individual fading probabilities (see equation (6.58)).

Frequency diversity is often employed in microwave line-of-sight links which carry several channels in a frequency division multiplex mode (FDM). Due to tropospheric propagation and resulting refraction, deep fading sometimes occurs. In practice, *1:N protection switching* is provided by a radio licensee, wherein one frequency is nominally idle but is available on a stand-by basis to provide frequency diversity switching for any one of the N other carriers (frequencies) being used on the same link, each carrying independent traffic. When diversity is needed, the appropriate traffic is simply switched to the backup frequency. This technique has the disadvantage that it not only requires spare bandwidth but also requires that there be as many receivers as there are channels used for the frequency diversity. However, for critical traffic, the expense may be justified.

6.10.6 Time Diversity

Time diversity repeatedly transmits information at time spacings that exceed the coherence time of the channel, so that multiple repetitions of the signal will be received with independent fading conditions, thereby providing for diversity. One modern implementation of time diversity involves the use of the