MULTIPATH CHANNELS

In most radio channels, the transmitted signal arrives at the receiver from various directions through multiple paths. The phase and amplitude of the signal arriving on each different path are related to the path length and the conditions of the path, and hence the multiple versions of the transmitted signal with different phase and amplitude arrive at the receiver at slightly different times. In addition, the path lengths and conditions are subject to being time-varying due to the rela-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

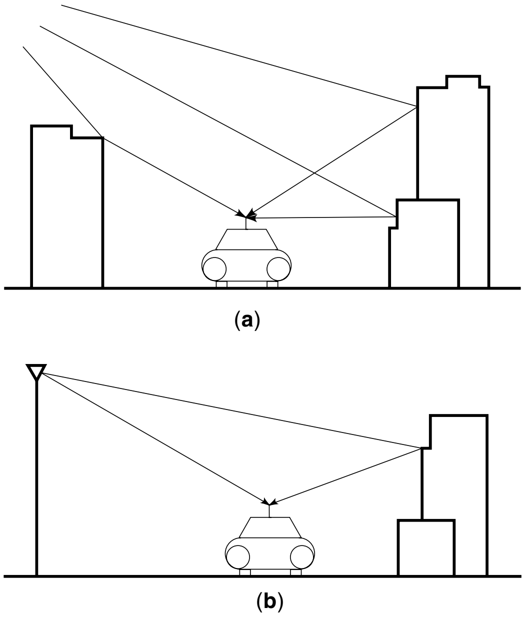

Figure 1. Examples of multipath in different environments; (a) without a line-of-sight (LOS) propagation path, (b) with a LOS propagation path.

tive movement of the receiver, transmitter, and surrounding objects. This complicated situation results in considerable rapid amplitude fluctuations of the received signal. The term *multipath fading,* or simply *fading,* is generally used to describe this phenomenon.

Figure 1 presents two examples of multipath fading radio channels in the mobile cellular communication environments. Figure 1(a) represents the scenario when the transmitted signal from the antenna of the base station through several paths bounced from large objects such as buildings arrives at the mobile. In the cellular communication system, the mobile communicates with the wireline network via the base station. The figure particularly corresponds the case when there is no line-of-sight (LOS) transmission path between the transmitter (base station) and receiver (mobile) because the mobile is surrounded by tall buildings and the height of the mobile antenna is well below the height of buildings. This happens in built-up urban areas with lots of constructions. Figure 1(b) corresponds to the LOS path which is usually seen in suburban or rural areas.

There are several physical factors in the radio propagation channel which influence and determine multipath fading. They are as follows: (1) Multipath propagation of the transmitted signal due to the existence of reflecting objects and scatterers in the channel. Fading and/or signal distortion are induced by the arrival of the multiple versions of the transmitted signal with random phase and amplitudes. (2) Speed of the mobile and/or surrounding objects. The relative motion between the base station and mobile results in random frequency modulation due to different Doppler shifts on each of the multipath components. Doppler shifts could be positive or negative depending on whether the mobile is moving toward or away from the base station. When objects such as other mobiles near the mobile under consideration are moving, they induce a time-varying Doppler shift on multipath components. If the surrounding objects are moving faster than the mobile, then the effects by the objects might dominate the fading effects. (3) The transmission bandwidth of the signal. As will be shown later, the multipath channel is characterized by a parameter called *coherence bandwidth.* Depending on the relative size of the signal bandwidth with respect to the coherence bandwidth, the fading behavior related with the time dispersion (echoes) can appear differently.

IMPULSE RESPONSE OF A MULTIPATH CHANNEL

The variations of a mobile radio signal can be directly related to the impulse response of the mobile radio channel. The impulse response is a wideband channel characterization, since the impulse function corresponds to the signal with infinite bandwidth. It contains all information necessary to simulate or analyze any type of radio transmission through the channel. This stems from the fact that a mobile radio channel may be modeled as a linear filter with a time-varying impulse response, where the time variation is due to the relative motion among transmitter, receiver, and channel. The filter nature of the channel is caused by the summation of amplitudes and delays of the multiple arriving waves at any instant of time. The impulse response is a useful characterization of the channel, because it may be used to predict and compare the performance of many different mobile communication systems and transmission bandwidths for a particular mobile channel condition.

The impulse response of a multipath channel $h(t, \tau)$ completely characterizes the channel as a function of both t and τ. The variable t corresponds to the time variations of the impulse response due to motion while the variable τ represents the channel multipath delay for a fixed value of t. When the transmitted signal is $x(t)$, the received signal $r(t)$ throughout a multipath channel with the impulse response $h(t, \tau)$ can be obtained by a convolution of $x(t)$ with $h(t, \tau)$:

$$r(t) - x(t) * h(t,\tau) = \int_{-\infty}^{\infty} x(t-\tau)h(t,\tau)\,d\tau \tag{1}$$

If the multipath channel is assumed to be a band-limited band-pass channel, which is reasonable, then $h(t, \tau)$ can be equivalently described by a complex baseband impulse response $h_b(t, \tau)$, that is

$$h(t,\tau) = \mathrm{RE}[h_b(t,\tau)e^{jw_c t}] \tag{2}$$

where w_c is the center frequency of the channel.

The received signal in a multipath channel consists of a series of attenuated, delayed, phase-shifted versions of the transmitted signal. Hence, assuming that L replicas of the transmitted signal arrive at the receiver, the baseband impulse response of a multipath channel can be expressed as

$$h_b(t,\tau) = \sum_{i=1}^{L} a_i(t,\tau)\exp[j\omega_c\tau_i(t) + \theta(t,\tau)]\delta(\tau - \tau_i(t)) \tag{3}$$

where $a_i(t, \tau)$ and $\tau_i(t)$ are the real amplitudes and *excess delays* (i.e., the relative delay of a multipath component as compared to the first arriving component) of the ith multipath component at time t, respectively. The phase term $jw_c\tau_i(t)$ +

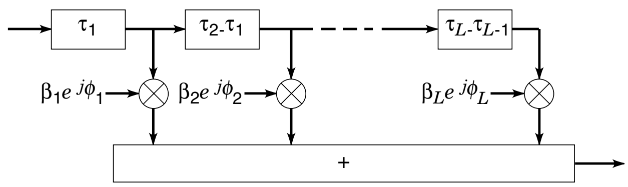

Figure 2. Block diagram for the discrete delay channel model.

$\theta(t, \tau)$ represents the phase shift due to free space propagation of the ith multipath component, plus any additional phase shifts which are encountered in the multipath channel.

If the channel impulse response is assumed to be time invariant, or is at least wide-sense stationary over a small time or distance interval, then the composite impulse response for given locations of the transmitter and receiver reduces to

$$h_{\mathrm{b}}(\tau) = \sum_{i=1}^{L} a_i e^{-j\phi_i} \delta(\tau - \tau_i) \tag{4}$$

where a_i and ϕ_i represent the amplitude and phase of the ith path arriving with delay τ_i. Figure 2 shows a block diagram of the discrete delay channel model which is helpful to understand and simulate the wideband characteristics of the multipath channel.

For multipath channel modeling, the *power delay profile* (or *multipath intensity profile,* MIP) of the channel, defined by the relative received power as a function of excess delay, is found by $|h_{\mathrm{b}}(t, \tau)|^2$, or for the wide-sense stationary case, we obtain

$$P_{\mathrm{r}}(\tau) = |a_i|^2, \qquad \text{if } \tau = \tau_i \tag{5}$$

For ideal wideband communications, the paths are isolated and independent of one another, and therefore the phase differences between arriving paths do not change the amplitude characteristics of the channel. In other words, impulses arriving at different times do not interact with each other. Accordingly, the received power in this case is given by

$$P_{\mathrm{r}} = \sum_{i=1}^{L} |a_i|^2 \tag{6}$$

That is, the received signal power is the sum of squares of all path amplitudes.

In actual wireless communication systems, the impulse response of a multipath channel is measured in the field using channel sounding techniques (1)—that is, to sound and measure the channel using a probing pulse $p(t)$ which approximates a delta function. These techniques may be classified as *direct pulse measurements* (2,3), *spread spectrum sliding correlator mesurements* (4), and *swept frequency measurements* (5).

PARAMETERS OF MULTIPATH CHANNELS

Many multipath channel parameters can be obtained from the power delay profile in Eq. (5). Power delay profiles can be measured in the real field using channel sounding techniques, and they are generally represented as plots of relative received power as a function of excess delay with respect to a fixed time delay reference.

Delay Spreads and Coherence Bandwidth

In order to compare different multipath channels and to develop some general design guidelines for wireless systems, parameters which grossly quantify the multipath channel are used. The simplest parameter of multipath delay spread is the overall span of path delays (i.e., the earliest arrival to latest arrival), which is often referred to as the *excess delay spread.* However, this parameter does not give much information about the multipath channel since different channels with the same excess delay spread can exhibit totally different power delay profiles over the delay span.

The *mean excess delay* and *root-mean-square* (*rms*) *delay spread* are important multipath channel parameters which can be determined from a power delay profile. The mean excess delay $\overline{\tau}$ is the first moment of the power delay profile given in Eq. (5) and given by

$$\overline{\tau} = \frac{\sum_k |a_k|^2 \tau_k}{\sum_k |a_k|^2} \tag{7}$$

The rms delay spread τ_{rms} is the square root of the second central moment of the power delay profile:

$$\tau_{\mathrm{rms}} = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} \tag{8}$$

where

$$\overline{\tau^2} = \frac{\sum_k |a_k|^2 \tau_k^2}{\sum_k |a_k|^2} \tag{9}$$

These delays are measured relative to the first detectable signal arriving at the receiver at $\tau_0 = 0$. Table 1 presents the typical measured values of rms delay spread (1).

In practice, values of $\overline{\tau}$ and τ_{rms} depend on the choice of noise threshold used to calculate Eqs. (7) and (9). The noise threshold is used to differentiate between received multipath signals and thermal noise. If the threshold is set too low, then noise will be processed as multipath, thus giving rise to values of $\overline{\tau}$ and τ_{rms} that are artificially high. Figure 3 shows an example of a power delay profile, along with the corresponding rms delay spread and mean excess delay for a given noise threshold level, −21 dB.

It should be noted that the power delay profile and the magnitude frequency response of the radio channel are related through the Fourier transform. Analogous to the delay spread parameters in the time domain, *coherence bandwidth* is used to characterize the channel in the frequency domain. Coherence bandwidth B_{C} is a statistical measure of the range of frequencies over which the channel can be considered “flat”; that is, all frequency components within the coherence bandwidth of the channel experience approximately equal gain and linear phase throughout the channel. In fact, the rms delay spread and coherence bandwidth are inversely proportional to one another. If the coherence bandwidth is defined as the bandwidth over which the frequency correlation func-

Table 1. Typical Values of rms Delay Spread Measured in Many Areas

Environment	Frequency (MHz)	Root-mean-square Delay Spread τ_{rms}	Notes
Urban	910	1300 ns avg.	New York City
Urban	892	10–25 μs	Worst-case San Francisco
Suburban	910	200–310 ns	Averaged typical case
Suburban	910	1960–2110 ns	Averaged extreme case
Indoor	1500	10–50 ns	Office building
Indoor	850	270 ns max.	Office building
Indoor	1900	70–94 ns avg.	Three San Francisco buildings

tion is above 0.9, then the coherence bandwidth is approximately (6)

$$B_{\mathrm{C}} \approx \frac{1}{50\tau_{\mathrm{rms}}} \tag{10}$$

It is important to note that an exact relation between coherence bandwidth and rms delay spread does not exist.

Doppler Spread and Coherence Time

Delay spread and coherence bandwidth are parameters which describe the time-dispersive nature of the channel due to the multipath signals. However, they do not provide information about the time-varying nature of the channel caused by either relative motion between the mobile and base station. *Doppler spread* and *coherence time* are parameters which describe the time-varying nature of the channel.

Doppler spread B_{D} is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel and is defined by the range of frequencies over which the received Doppler spectrum is essentially nonzero, or the maximum *Doppler shift,* given by

$$B_{\mathrm{D}} = \frac{v}{c} f_{\mathrm{c}} \tag{11}$$

where v is the mobile's velocity, c is the velocity of the radio wave, and f_{c} is the signal carrier frequency. It should be noted that if the baseband signal bandwidth is much greater than B_{D}, the effects of Doppler spread are negligible at the receiver in most cases.

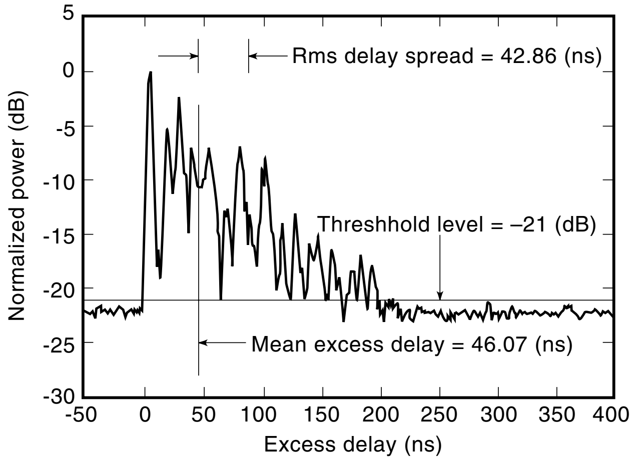

Figure 3. Example of a power delay profile in which rms delay spread, mean excess delay, and threshold level are shown.

Coherence time T_{C} is the time-domain dual of Doppler spread and is used to characterize the time-varying nature of the frequency dispersiveness of the channel in the time domain. The Doppler spread and coherence time are inversely proportional to one another, that is,

$$T_{\mathrm{C}} \approx \frac{1}{B_{\mathrm{D}}} \tag{12}$$

Coherence time is actually a statistical measure of the time duration over which the channel impulse response is essentially time-invariant, and it quantifies the similarity of the channel response at different times. In other words, coherence time is the time duration over which two received signals have a strong potential for amplitude correlation. If the symbol duration of the signal is greater than the coherence time of the channel, then the channel will change during the transmission of the baseband signal, thus causing distortion at the receiver.

CLASSIFICATION OF MULTIPATH FADING

Depending on the relation between the signal characteristics (like bandwidth, symbol duration) and the channel characteristics (like rms delay spread and Doppler spread), different transmitted signals will experience different types of fading. The time dispersion due to multipath delay spread and frequency dispersion due to Doppler spread lead to two different types of fading, respectively. Table 2 shows the four different types of fading.

Table 2. Types of Multipath Fading Based on (a) Multipath Delay Spread and (b) Doppler Spread[a]

(a) Based on Multipath Delay Spread	
Flat fading: $B_{\mathrm{S}} \ll B_{\mathrm{C}},\ T_{\mathrm{S}} \gg \tau_{\mathrm{rms}}$	Frequency-selective fading: $B_{\mathrm{S}} > B_{\mathrm{C}},\ T_{\mathrm{S}} < \tau_{\mathrm{rms}}$
(b) Based on Doppler Spread	
Fast fading: $B_{\mathrm{S}} < B_{\mathrm{D}},\ T_{\mathrm{S}} > T_{\mathrm{C}}$	Slow fading: $B_{\mathrm{S}} \gg B_{\mathrm{D}},\ T_{\mathrm{S}} \ll T_{\mathrm{C}}$

[a] Here B_{S} is the signal bandwidth, T_{S} is the symbol duration, B_{C} is the coherence bandwidth, τ_{rms} is the rms delay spread, B_{D} is the Doppler spread, and T_{C} is the coherence time.

Flat or Frequency-Selective Fading Due to Multipath Delay Spread

Depending on the time dispersiveness due to multipath, the transmitted signal undergoes either *flat* or *frequency-selective* fading as follows.

Flat Fading. If the 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 experience *flat fading*. With this fading, the received signal preserves the spectral characteristics of the transmitted signal while the strength of the received signal varies with time, due to fluctuations in the gain of the channel due to multipath. In a flat fading channel, the bandwidth of the transmitted signal is much less than the coherence bandwidth of the channel, and, correspondingly, the symbol duration of the transmitted signal is much larger than the multipath time delay spread of the channel; that is,

$$B_{\mathrm{S}} \ll B_{\mathrm{C}} \tag{13}$$

$$T_{\mathrm{S}} \gg \tau_{\mathrm{rms}} \tag{14}$$

where B_{S} is the bandwidth of the transmitted signal, B_{C} is the coherence bandwidth of the channel, T_{S} is the symbol duration of the transmitted signal, and τ_{rms} is the rms delay spread of the channel.

Flat fading channels are also called *amplitude-varying channels* and are often referred to as *narrowband channels* because the bandwidth of the transmitted signal is narrower than the bandwidth of the flat fading channel impulse response. The distribution of the gain of flat fading channels is usually modeled by Rayleigh or Ricean distribution as explained in the next section. In that model, the amplitude of the received signal varies in time according to the Rayleigh (or Ricean) distribution. Note that in the case of the flat fading channel, we can approximate the impulse response to be simply a delta function.

Frequency-Selective Fading. If the radio channel possesses a constant-gain and linear phase response over a bandwidth which is smaller than the bandwidth of transmitted signal, the received signal will undergo *frequency-selective fading*. This happens when the bandwidth of the transmitted signal is greater than the coherence bandwidth of the channel, and, correspondingly, the symbol duration of the transmitted signal is smaller than the multipath time delay spread of the channel; that is

$$B_{\mathrm{S}} > B_{\mathrm{C}} \tag{15}$$

$$T_{\mathrm{S}} < \tau_{\mathrm{rms}} \tag{16}$$

where B_{S} is the bandwidth of the transmitted signal, B_{C} the coherence bandwidth of the channel, T_{S} is the symbol duration of the transmitted signal, and τ_{rms} is the rms delay spread of the channel. The received signal through this type of fading includes multiple versions of the transmitted waveform which are attenuated and delayed in time, so the received signal is distorted. Long-time dispersion of the transmitted signal results in *intersymbol interference* (ISI) in the received signal. In the frequency domain, different frequency components of the signal undergo different gains through the channel. Frequency-selective fading channels are often called *wideband channels* because the bandwidth of the transmitted signal is wider than the bandwidth of the channel impulse response.

Fast or Slow Fading Due to Doppler Spread

Depending on how rapidly the transmitted baseband signal changes comparing with the rate of change of the channel response, a channel may be classified into either a *fast-fading* or *slow-fading* channel.

Fast Fading. If the channel impulse response changes rapidly within the symbol duration of the signal, the channel is called a *fast-fading* channel. That is, the coherence time of the channel is smaller than the symbol duration of the transmitted signal. Equivalently, the Doppler spread is greater than the signal bandwidth. Hence, a signal experiences fast fading if the following conditions are satisfied:

$$B_{\mathrm{S}} < B_{\mathrm{D}} \tag{17}$$

$$T_{\mathrm{S}} > T_{\mathrm{C}} \tag{18}$$

where B_{S} is the bandwidth of the transmitted signal, B_{D} the Doppler spread of the channel, T_{S} the symbol duration of the transmitted signal, and T_{C} the coherence time of the channel. This causes frequency dispersion (or time selective fading) due to Doppler spreading, which leads to signal distortion. In practice, fast fading only occurs for signals with very low data rates.

Slow Fading. In a *slow-fading channel,* the channel impulse response changes at a rate much slower than the transmitted baseband signal. In this case, the channel can be assumed to be static over one or several symbol durations. In frequency domain, this implies that the Doppler spread of the channel is much less than the signal bandwidth. Therefore, a signal undergoes slow fading if

$$B_{\mathrm{S}} \gg B_{\mathrm{D}} \tag{19}$$

$$T_{\mathrm{S}} \ll T_{\mathrm{C}} \tag{20}$$

where B_{S} is the bandwidth of the transmitted signal, B_{D} is the Doppler spread of the channel, T_{S} is the symbol duration of the transmitted signal, and T_{C} is the coherence time of the channel. It should be noted that the relative velocity between the mobile and base station and the baseband signaling determines if a signal undergoes fast or slow fading.

Combinations of Multipath and Doppler Spread Effects

As explained so far, the relationship between the effects of multipath spread and Doppler spread is quite orthogonal since the multipath spread is due to the multipath environment of the channel while the Doppler spread is due to the relative movement of the mobile (or the environment of the mobile). Depending on the relation between the various multipath parameters and the type of fading experienced by the signal, the types of the fading can be mainly divided into

Table 3. Classification of Multipath Fading Considering Both Multipath Delay Spread and Doppler Spread[a]

Fast Fading: $B_S \ll B_C$, $B_S < B_D$ $T_S \gg \tau_{rms}$, $T_S > T_C$	Flat Slow Fading: $B_D < B_S \ll B_C$ $\tau_{rms} \ll T_S < T_C$
Frequency-Selective Fast Fading: $B_C < B_S \ll B_D$ $T_C \ll T_S < \tau_{rms}$	Frequency-Selective Slow Fading: $B_S > B_C$, $B_S \gg D_D$ $T_S < \tau_{rms}$, $T_S \ll T_C$

[a] Here B_S is the signal bandwidth, T_S is the symbol duration, B_C is the coherence bandwidth, τ_{rms} is the rms delay spread, B_D is the Doppler spread, and T_C is the coherence time.

four classes (Table 3): (1) flat fast fading, (2) flat slow fading, (3) frequency-selective fast fading, and (4) frequency-selective slow fading.

STATISTICAL MODELS FOR MULTIPATH FADING CHANNELS

Rayleigh Fading Distribution

In mobile radio channels, the Rayleigh distribution is commonly used to describe the statistical time-varying nature of the received envelope of a flat fading signal or of an individual multipath component. By assuming that the number of multipath signal components are sufficiently large without the LOS propagation path as in Fig. 1(a), the received signal can be assumed to have two quadrature Gaussian noise components using the central limit theorem. It is well known that the envelope of the sum of two quadrature Gaussian noise signals follows a Rayleigh distribution. The distribution of a Rayleigh random variable R has a probability density function (pdf) given by

$$f_R(r) = \begin{cases} \dfrac{r}{\sigma^2} \exp\left(-\dfrac{r^2}{2\sigma^2}\right), & 0 \le r \le \infty \\ 0, & r < 0 \end{cases} \tag{21}$$

where σ is the rms value of the received voltage signal before *envelope detection,* so σ^2 is the time-average power of the received before envelope detection. The corresponding cumulative distribution function (CDF) of R is given by

$$F_R(r) = \Pr(R \le r) = 1 - \exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{22}$$

The mean value m_R of the Rayleigh distribution is given by

$$m_R = E[R] = \sigma\sqrt{\pi/2} \approx 1.2533\sigma \tag{23}$$

and the various σ_R^2, which represents the ac power in the signal envelope, is given by

$$\sigma_R^2 = E[R^2] - E^2[R] = \sigma^2(2 - \pi/2) \approx 0.4292\sigma^2 \tag{24}$$

The rms value of the envelope is the square root of the mean square, that is $\sqrt{E[R^2]} = \sqrt{2}\sigma$. Figure 4 illustrates the pdf of the Rayleigh distribution.

Ricean Fading Distribution

When there exists a dominant stationary (nonfading) signal component, such as a LOS propagation path, as in Fig. 1(b), the multipath fading envelope can be assumed to obey the Ricean distribution. When the dominant component is added to the multipath components, it appears as a dc component to the random multipath at the output of an envelope detector. As the dominant component becomes weaker, the composite signal tends to have a Rayleigh envelope. That is, the Ricean distribution degenerates to a Rayleigh distribution as the dominant signal fades away.

The Ricean distribution is given by

$$f_R(r) = \begin{cases} \dfrac{r}{\sigma^2} \exp\left(-\dfrac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\dfrac{Ar}{\sigma^2}\right), & A \ge 0, r \ge 0 \\ 0, & r < 0 \end{cases} \tag{25}$$

where the parameter A represents the peak amplitude of the dominant signal and $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order given by

$$I_0(x) = 1 + \frac{x^2}{2^2} + \frac{x^4}{2^2 \cdot 4^2} + \frac{x^6}{2^2 \cdot 4^2 \cdot 6^2} + \cdots \tag{26}$$

The Ricean distribution is often described by a parameter K, known as the *Ricean factor,* defined as the ratio between the deterministic signal power and the variance of the multipath, that is

$$K = \frac{A^2}{2\sigma^2} = 10\log\left(\frac{A^2}{2\sigma^2}\right) \text{ (dB)} \tag{27}$$

As $A \to 0$, $K \to -\infty$, and the Ricean distribution degenerates to a Rayleigh distribution as the dominant path decreases in

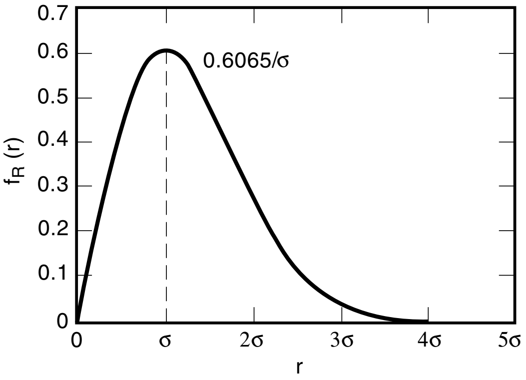

Figure 4. Probability density function (pdf) of a Rayleigh distribution.

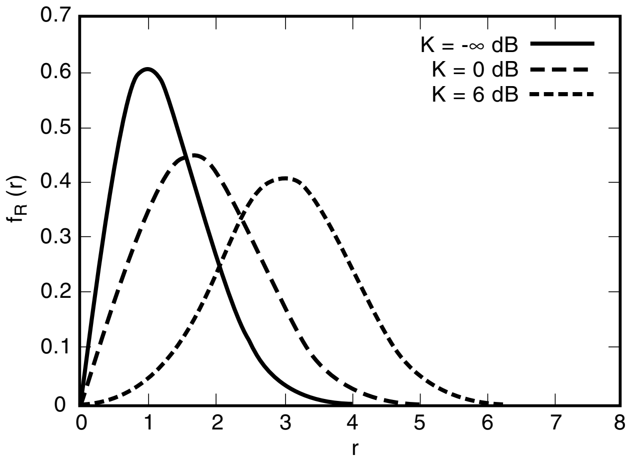

Figure 5. Probability density functions (pdf) of Ricean distributions: $K = -\infty$ (Rayleigh), 0, and 6 dB.

amplitude. Figure 5 shows the Ricean pdf for various values of K when $\sigma = 1$.

Classical Uncorrelated Scattering Model

We want to characterize a multipath fading channel in terms of *correlation functions* and *power spectral density functions.* For a transmitted signal with complex envelope $p(t)$, the complex envelope of the received signal in the case of a continuous delay function is given by

$$r(t) = \int_{-\infty}^{\infty} h_{\mathrm{b}}(t,\tau)p(t-\tau)\,d\tau \tag{28}$$

If we were to use a discrete channel model of Eq. (4), the received signal would be

$$r(t) = \sum_{i=1}^{L} a_i e^{j\phi_i} p(t-\tau_i) \tag{29}$$

Using this channel modeling, Bello (7) suggested the assumption of *wide-sense stationary uncorrelated scattering* (WSSUS). The autocorrelation of the observed impulse response at two different delays and two different times is given by

$$R_{hh}(t_1,t_2;\tau_1,\tau_2) = E\{h_{\mathrm{b}}^*(t_1,\tau_1)h_{\mathrm{b}}(t_2,\tau_2)\} = R_{hh}(\Delta t;\tau_1)\delta(\tau_1-\tau_2) \tag{30}$$

where $\Delta t = t_1 - t_2$. This function with $\Delta t = 0$ represents the power delay profile $P_{\mathrm{r}}(\tau)$ of the multipath channel, which gives the average power of the channel output as a function of the time delay τ:

$$P_{\mathrm{r}}(\tau) = R_{hh}(0;\tau) \tag{31}$$

The rms delay spread in this model can be obtained as the square root of the second central moment of this function, that is,

$$\tau_{\mathrm{rms}} = \sqrt{\frac{\int_{-\infty}^{\infty}(\tau-\overline{\tau})^2 P_{\mathrm{r}}(\tau)\,d\tau}{\int_{-\infty}^{\infty}P_{\mathrm{r}}(\tau)\,d\tau}} \tag{32}$$

where

$$\overline{\tau} = \int_{-\infty}^{\infty} \tau P_{\mathrm{r}}(\tau)\,d\tau \tag{33}$$

Mobile radio channels are often characterized by the exponential power delay profile given by

$$P_{\mathrm{r}}(\tau) = \frac{1}{\tau_{\mathrm{rms}}}\exp\left\{-\frac{\tau}{\tau_{\mathrm{rms}}}\right\} \tag{34}$$

where τ_{rms} is the rms delay spread of the channel for many different environments.

TECHNIQUES FOR MULTIPATH FADING

Because the multipath fading results in a significant distortion of signals, mobile systems usually employ some techniques to attain a desired communication performance. There are four techniques which can be used independently or in tandem to combat multipath fading: equalization, diversity, spread spectrum, and channel coding.

Equalization compensates for *intersymbol interference* (ISI) created due to the frequency-selective fading, with the signal bandwidth greater than the coherence bandwidth of the channel. An equalizer within a receiver compensates for the average range of expected channel amplitude and delay characteristics. Equalizers must be *adaptive* because the channel is generally unknown to the receiver and time varying (8).

Diversity is another technique used to compensate for fading channel impairment, and it is usually implemented by using two or more receiving antennas (9). As with an equalizer, the quality of a mobile communication link is improved without increasing the transmitted power or bandwidth. However, while equalization is used to counter the effect of time dispersion (ISI), diversity is usually employed to reduce the depth and duration of the fades experienced by a receiver in a flat fading (narrowhead) channel. Diversity techniques can be employed at both base station and mobile receivers. The most common diversity technique is called *spatial diversity,* whereby multiple antennas are strategically spaced and connected to a common receiving system. While one antenna sees a signal null, one of the other antennas may see a signal peak, and the receiver is able to select the antenna with the best signal at any time or to *combine* the signals from the different antennas in a weighted manner to maximize the performance. Other diversity techniques include antenna polarization diversity, frequency diversity, and time diversity.

Spread spectrum modulations, used in Code-Division Multiple Access (CDMA) systems like IS-95 digital cellular standard (10), spread the transmission bandwidth to several orders of magnitude of the minimum required signal bandwidth using pseudo-noise (PN) codes. Spread spectrum systems have resistance to multipath fading; first because the wideband signals are frequency selective, so that at any time only a small portion of the spectrum will undergo fading. Second, viewed in the time domain, the delayed versions of the transmitted signal through the multiple paths will be cancelled out at the receiver because of poor correlation of the delayed versions with the original version. Not only resistant to multipath fading, spread spectrum systems can also exploit the multipath components to improve the performance of the communication system. That can be done using a RAKE receiver (11), which can combine the information obtained from several resolvable multipath components through time diversity.

Channel coding (12) improves mobile communication link performance by adding redundant data bits in the transmitted message. At the baseband portion of the transmitter, a channel coder maps a digital message sequence into another specific code sequence containing a greater number of bits than originally contained in the message. The coded message is then modulated for transmission in the wireless channel. This technique is used by the receiver to detect or correct some (or all if possible) of the errors introduced by the channel. If the transmitter is to send the message at the same rate as without using the channel coding, the transmission channel bandwidth should be increased due to the redundancy, so the improved communication is achieved at the cost of the increased transmission bandwidth.

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MULTIPATH CHANNELS. See MOBILE COMMUNICATION.

MULTIPATH FADING CHANNELS. See MULTIPATH CHANNELS.

MULTIPATH PROPAGATION OF RADIOWAVES. See RADIOWAVE PROPAGATION MULTIPATH CHANNELS.

MULTIPLE ACCESS COMMUNICATIONS. See INFORMATION THEORY OF MULTIACCESS COMMUNICATIONS.