Chapter 1

Introduction

With the continued dramatic increase in demand for various types of high-speed wireless service, future generations of wireless communications will be aiming at wideband, broadband and ultrawide bandwidth (UWB) systems, which are capable of achieving the highest possible spectral efficiency by using the most advanced wireless communications techniques possible. However, in the design of wireless communications systems, particularly, for commercial applications, a well-balanced trade-off between complexity, flexibility, performance (which may include data rate, quality-of-service (QoS), etc.), and cost is often an important consideration. In light of the great progress made in the fields of microelectronics, signal processing, computing, etc., in modern wireless communications complexity has often been one of the efficient routes for improving flexibility and performance. In this book we present the principles and applications of a wide range of techniques that have been or may be applied for achieving high spectral efficiency wireless communications with high flexibility. Below, we provide an overview of the issues widely concerned in wireless communications that are also related to this book.

1.1 Spread Spectrum

The phrase '*spread spectrum*' has been a well-known terminology in the field of wireless communications for several decades. The research and application of spread-spectrum techniques have evolved from the desire to support covert communications in the 1950s and have now reached a state of maturity, finding applications in nearly every corner of wireless communications. Spread-spectrum techniques have been widely applied in providing anti-jamming and anti-detection communications. Simultaneously, these techniques have been invoked to support multiuser communications and efficiently to exploit wireless resources in military and civilian wireless communications, rendering the term '*spread spectrum*' truly ubiquitous.

Spread spectrum is a type of modulation technique that spreads the energy of a signal many times the particular bandwidth generated by the signal, under the control of a spreading sequence referred to as a 'pseudo-random' or 'pseudo-noise' (PN) sequence. Typically, there

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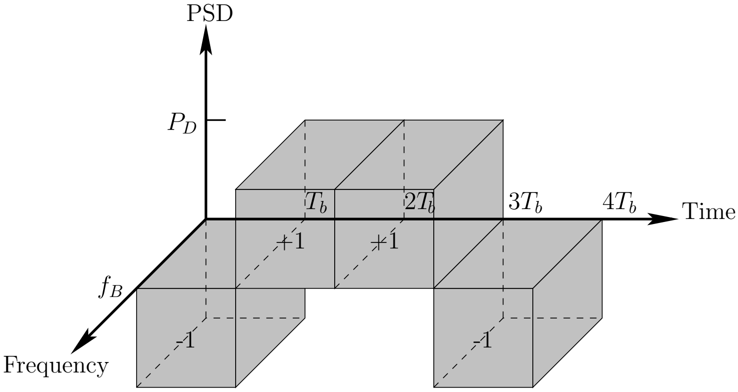

Figure 1.1: Conceptual illustration of the PSD–time–frequency relationship of conventional narrow-band signals.

are four types of basic spread-spectrum technique: the time (T)-domain direct-sequence spread spectrum (DS-SS), which is the DS-SS that we usually imply; the frequency (F)-domain direct-sequence spread spectrum which has been referred to as multicarrier spread spectrum (MC-SS); the frequency-hopping spread spectrum (FH-SS); and the time-hopping spread spectrum (TH-SS). Although the spread-spectrum operations embedded in these basic spread-spectrum schemes are different, one of their common characteristics is that the power spectral density (PSD) of the transmitted signals by these spread-spectrum schemes is usually very low, spans a very wide bandwidth and is akin to the PSD of Gaussian noise.

In more detail, we describe below the principles of the above-mentioned four types of basic spread-spectrum scheme. Let us assume that a binary sequence, say four bits expressed as $\{-1, +1, +1, -1\}$, is transmitted. Without spreading, the PSD-time-frequency (PTF) relationship of the transmitted signals in a conventional narrow-band communications system is illustrated in Fig. 1.1. Here, T_b represents the bit duration, f_B represents the bandwidth conveying the signal and P_D represents the corresponding transmission PSD. Note that in Fig. 1.1, the thickness of a block represents the transmission PSD, the blocks above the horizontal plane denote the $+1$'s transmitted, while those below the horizontal plane denote the -1's transmitted. In (binary) digital modulations the transmission bandwidth required is usually the reciprocal of the time duration conveying a binary bit. Hence, in Fig. 1.1 we have $f_B = 1/T_b$. Furthermore, the total energy spent for transmitting the four bits is determined by the volume of the four blocks.

The DS-SS signal is formed by the spreading operation, which multiplies each of the binary data bits of $\{-1, +1, +1, -1\}$ with a PN sequence, say $\{+1, -1, -1, +1, -1\}$, yielding a binary sequence

$$\underbrace{-1, +1, +1, -1, +1}_{\text{Bit 1 }(-1)};\ \underbrace{+1, -1, -1, +1, -1}_{\text{Bit 2 }(+1)};\ \underbrace{+1, -1, -1, +1, -1}_{\text{Bit 3 }(+1)};\ \underbrace{-1, +1, +1, -1, +1}_{\text{Bit 4 }(-1)} \tag{1.1}$$

where every binary is referred to as a *chip*. This chip sequence of $\{+1, -1\}$ is then transmitted within a time duration of $4T_b$. Since after the spreading operation, as shown in (1.1), there

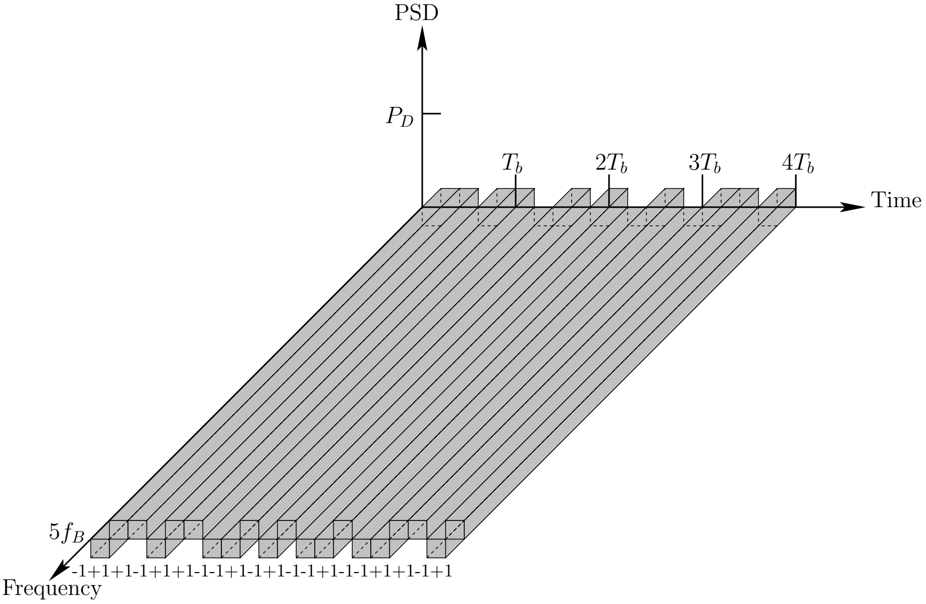

Figure 1.2: Conceptual illustration of the PSD–time–frequency relationship of DS-SS signals.

are now 20 chips that need to be transmitted within $4T_b$, the time duration for transmitting a chip is hence given by

$$T_c = \frac{4T_b}{20} = \frac{T_b}{5} \tag{1.2}$$

where T_c denotes the chip duration, which is only $1/5$ of the bit duration T_b. Therefore, the bandwidth of the DS-SS signals is $f_s = 1/T_c = 5/T_b = 5f_B$, which is five times the bandwidth of the conventional narrow-band signals without spreading, as shown in Fig. 1.1. In a DS-SS system, the bandwidth expansion is measured by the *spreading factor*, which is defined as the ratio of the bandwidth after and before spreading. In this example, the spreading factor is $N = 5f_B/f_B = T_b/T_c = 5$.

The PTF-relationship of the DS-SS signals is conceptually illustrated in Fig. 1.2. When comparing Fig. 1.2 with Fig. 1.1, we can see that the bandwidth of the DS-SS signals is five times the bandwidth of the conventional narrow-band signals. In return, the transmission PSD of the DS-SS signals is only one-fifth of that of the conventional narrow-band signals as seen in Fig. 1.1. Note that, when given the transmission energy per bit, the volume of the 20 blocks in Fig. 1.2 should be the same as that of the four blocks seen in Fig. 1.1.

The MC-SS signal is also formed by the spreading operation, which multiplies each of the binary data bits, say, $\{-1, +1, +1, -1\}$, with a PN sequence of, say $\{+1, -1, -1, +1, -1\}$, yielding a binary sequence as shown in (1.1). Then, each chip is conveyed using a bandwidth of f_B within one bit duration. The PTF relationship of the MC-SS signals is conceptually illustrated in Fig. 1.3.

As shown in Fig. 1.2, in the DS-SS scheme each bit duration is divided into five chip durations and each chip is transmitted within one chip duration using the bandwidth, $5f_B$.

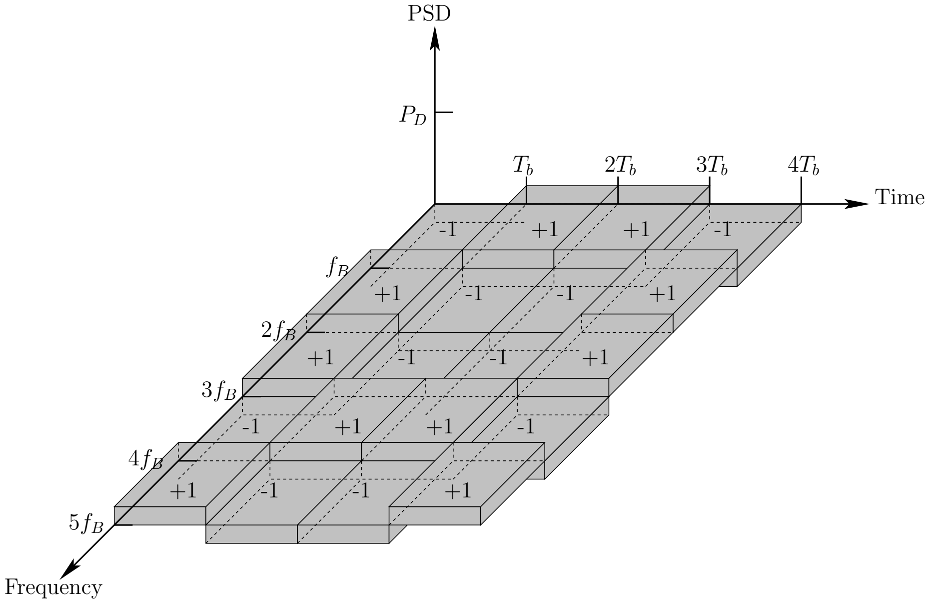

Figure 1.3: Conceptual illustration of the power–time–frequency relationship of MC-SS signals.

By contrast, in the MC-SS scheme, as shown in Fig. 1.3, the frequency band is divided into five sub-bands each with bandwidth f_B and each chip is transmitted on one sub-band within a bit duration T_b. Furthermore, for given transmission energy per bit, it can be shown that the transmission PSD in Fig. 1.3 is the same as that in Fig. 1.2 and it is one-fifth of the transmission PSD P_D seen in Fig. 1.1.

The principles behind the FH-SS can be well understood with the aid of Fig. 1.4. In the FH-SS scheme the frequency band is also divided into a number of sub-bands. In contrast to the MC-SS scheme as shown in Fig.1.3, where the transmitted signal always occupies the whole frequency band, in the FH-SS scheme the signal is transmitted only on a sub-band at any time. The transmission sub-band is activated under the control of a so-called *FH pattern*, which may be generated randomly or pseudo-randomly. In Fig. 1.4 the FH pattern was assumed to be $\{5, 1, 3, 2\}$. Therefore, the fifth, first, third and second sub-bands are activated within the first, second, third and fourth bit durations, respectively.

In comparison with Fig. 1.1, we can see that in the FH-SS scheme the transmitted signal within each bit duration is a narrow-band signal that is the same as that in Fig.1.1. In the FH-SS scheme the spectrum-spreading is obtained by the FH operation.

In the FH-SS shown in Fig. 1.4 the FH rate is the same as the bit (symbol) rate. The FH rate can be lower than the bit (symbol) rate, implying that several bits (symbols) are transmitted after one hop. This type of FH is referred to as slow FH (SFH). The FH rate can also be designed to be higher than the bit (symbol) rate, implying that one bit (symbol) is transmitted by invoking several frequency sub-bands. Correspondingly, this type of FH is called the fast FH (FFH).

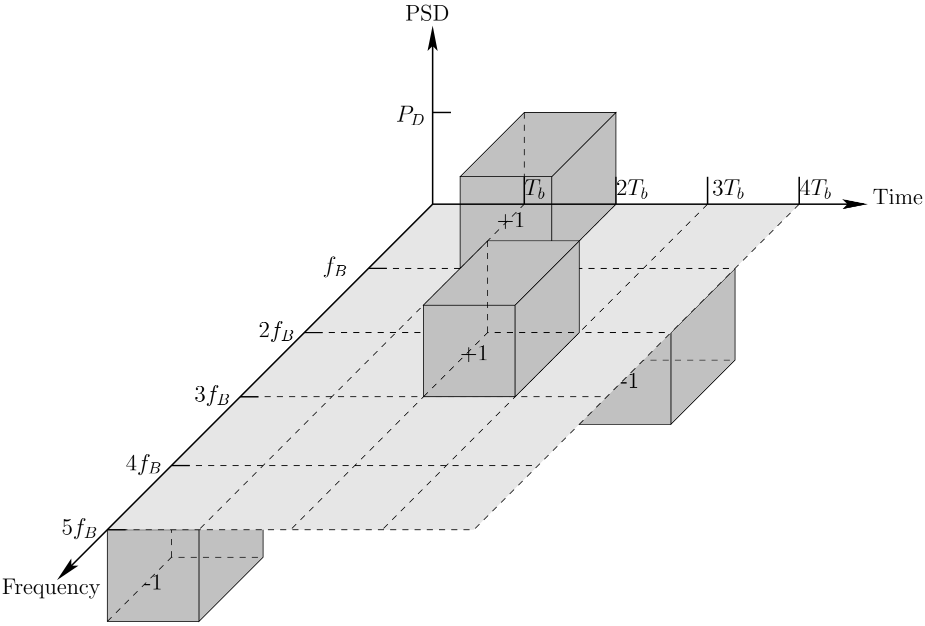

Figure 1.4: Conceptual illustration of the PSD–time–frequency relationship of FH-SS signals.

Finally, in the TH-SS scheme the time axis is divided into chips or *time slots* and the transmission is only activated at certain time slots. For example, as shown in Fig. 1.5, each bit duration is divided into five time-slots and only one-fifth of the time slots are activated for transmission. In principle, if we consider that the FH-SS scheme transmits F-domain pulses under the control of an FH pattern, then the TH-SS scheme can be viewed as a spread-spectrum scheme, which transmits T-domain pulses under the control of a TH pattern. In Fig. 1.5 the TH pattern was assumed to be $\{5, 1, 3, 2\}$. Hence, the four T-domain pulses are activated within the fifth, first, third and second time slots within the first, second, third and fourth bit durations, respectively. As shown in Fig. 1.5 the width of each T-domain pulse is only one-fifth of the bit duration T_b, hence each pulse spans a bandwidth $5f_B$.

Furthermore, in parallel with the SFH or FFH in the FH-SS scheme, the TH in the TH-SS scheme may also be implemented using slow TH (STH) or fast TH (FTH).

In addition to the above-presented four types of basic spread-spectrum scheme, as shown in Chapter 2, hybrid spread-spectrum schemes may be designed by combining two or more basic spread-spectrum schemes, in order to make use of their advantages while, simultaneously, overcoming their disadvantages.

Spread-spectrum communications have many advantages in comparison to the conventional narrow-band communications, and they have found a wide range of applications in the context of both secure military as well as civilian mobile wireless communications. It can be said that many advantages of the spread-spectrum communications schemes are inherent in their wideband noise-like signals. First, because spread-spectrum signals are noise-like, they are usually hard to detect and have a low probability of interception, except by the intended receivers which employ the knowledge of the spreading sequences used by the

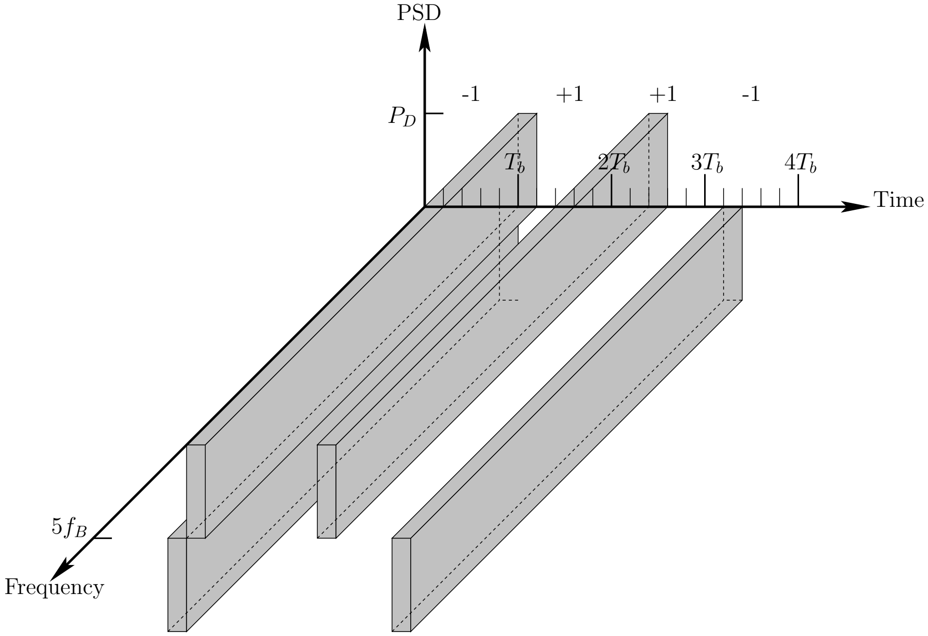

Figure 1.5: Conceptual illustration of the PSD–time–frequency relationship of TH-SS signals.

transmitter(s). Second, because spread-spectrum signals are wideband and noise-like, spread-spectrum signals are usually difficult to be interfered or jammed, even though the knowledge about the frequency band being used by the spread-spectrum systems is available. Third, their wideband, low PSD nature makes the spread-spectrum signals less likely to interfere with the other types of wideband or narrow-band wireless signal. Hence, spread-spectrum techniques may provide wireless communications design alternative approaches to overlay (fully or partially) with the existing wireless systems, in order to maximize the overall spectral-efficiency of wireless communications. Fourth, spread spectrum is a feasible technique for the implementation of multiple-access communications, yielding spread-spectrum multiple-access (SSMA) or code-division multiple-access (CDMA). In SSMA/CDMA systems different users (or terminals) can be readily distinguished by their unique spreading (or so-called signature) codes. Furthermore, wideband noise-like spread-spectrum signals have the property of high time-resolution. Spread-spectrum signals can be applied for accurate timing and location, such as in the global position system (GPS). Additionally, wideband spread-spectrum signals usually experience frequency-selective fading, which may be used to obtain the frequency diversity in order to enhance the reliability of wireless communications.

1.2 Orthogonal Frequency-Division Multiplexing

Orthogonal frequency-division multiplexing (OFDM) is a type of multicarrier modulation scheme that transmits data symbols in parallel on multiple subcarriers that share the system bandwidth using some form of frequency-division multiplexing (FDM). The idea behind

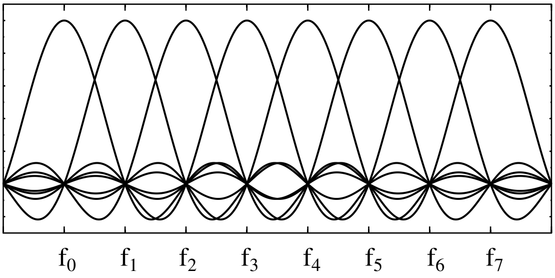

Figure 1.6: Illustration of OFDM signal's spectrum.

OFDM is to divide the system transmission bandwidth into a large number of small orthogonal sub-bands that are supported by subcarriers. The frequency spectrum of OFDM signals may be illustrated by Fig. 1.6, where the transmission bandwidth is divided into eight small orthogonal sub-bands supported by eight subcarriers. OFDM is a nature parallel data transmission scheme that transmits OFDM symbols consisting of parallel data symbols with the aid of serial-to-parallel (S/P) conversion, instead of transmitting data streams serially. For example, let the OFDM system consist of M number of subcarriers. Let

$$\boldsymbol{x} = [x(0), x(1), \ldots, x(M-1)]^T \tag{1.3}$$

denote a block of data symbols to be transmitted. Then, in OFDM the transmitted signal can be formed as

$$s(t) = \sum_{m=0}^{M-1} \Re\{A_m x(m) \exp(j2\pi f_m t)\} \tag{1.4}$$

where $\Re\{\cdot\}$ denotes the real part of the argument, A_m denotes the amplitude of the mth subcarrier signal and f_m is the mth carrier frequency.

OFDM has been proposed for both broadband and ultrawide bandwidth (UWB) wireless communications. OFDM is beneficial to high data rate transmission in broadband or UWB wireless communications systems. A central feature of OFDM is that it can take advantage of the fast Fourier transform (FFT) to implement efficiently the multicarrier modulation/demodulation. Due to employment of the FFT-assisted multicarrier modulation/demodulation, in OFDM no band-pass filters matching the subcarrier frequencies are necessary, provided that the orthogonality of the subcarrier signals can be maintained. Consequently, the transceiver's complexity in OFDM systems can be significantly reduced.

In OFDM each sub-band can be made much smaller than the coherence bandwidth of the wireless channel. Hence, the subcarrier signals expose only frequency-nonselective (flat) fading, which is beneficial for employing low-complexity equalization techniques. In OFDM systems intersymbol interference (ISI) may be efficiently mitigated by the insertion of guard intervals.

It is well recognized that one of the main implementation disadvantages at the transmitter side of OFDM systems is the high peak-to-average power ratio of the transmitted signal, which may yield nonlinear distortions. The nonlinear distortion results in out-of-band emission and co-channel interference, potentially causing degradation in the system's performance. The performance of OFDM systems is very sensitive to frequency offsets, and also to time offsets in multiuser OFDM systems. In order to take advantage of the FFT-based multicarrier modulation/demodulation, in multiuser OFDM systems accurate synchronization among the multiuser signals is essential.

OFDM was originally proposed for point-to-point communications, and is itself unsuitable for supporting multiple-access communications. In wireless communications OFDM can be combined with some other techniques, such as CDMA, spatial division multiple-access (SDMA), etc. for implementation of multiple-access communications.

1.3 Multiple Access

Multiple access is a technique allowing several (or even many) users (terminals) to communicate in the same physical medium and to share the available resources, such as capacity, spectrum, etc., among the users (terminals). In wireless communications typical multiple-access schemes include:

- frequency division multiple access (FDMA);
- time division multiple access (TDMA);
- code division multiple access (CDMA);
- spatial division multiple access (SDMA).

In FDMA systems the frequency band available is divided into a number of sub-bands and each sub-band constitutes a physical channel, for example, as shown in Fig. 1.7. In FDMA systems, whenever a user requests to communicate, a corresponding channel is assigned, provided that there is a channel available. In principle, in FDMA systems the channels may be divided evenly or unevenly, in order to support the services with different data rate requirements. A high data rate service in FDMA systems may also be supported by assigning to the service a corresponding number of channels. In FDMA each channel is associated with a (sub)carrier frequency.

In TDMA systems the time axis is first divided into frames of a certain frame length. Then, each of the frames is divided into a number of time slots of a certain duration, and each time slot is defined as a physical channel for supporting a user's communications. In TDMA systems the channels are conceptually illustrated in Fig. 1.8, where each frame is divided into five time slots for simultaneously supporting the communications of up to five users. A corresponding channel is assigned, whenever a user requests to communicate, provided that there is a channel available. In TDMA systems a high data-rate service can be supported by assigning the service more than one channel. In TDMA all the channels use the same carrier frequency.

One common feature of FDMA and TDMA is that the maximum number of channels is a constant and hence the maximum number of users supportable is fixed. In FDMA and TDMA the channels (capacity) are 'hard'; a channel cannot be assigned (even partially) to the other users once it is occupied, no matter how good the channel is. In FDMA and TDMA systems the channels are physically separated and they are orthogonal either in the frequency

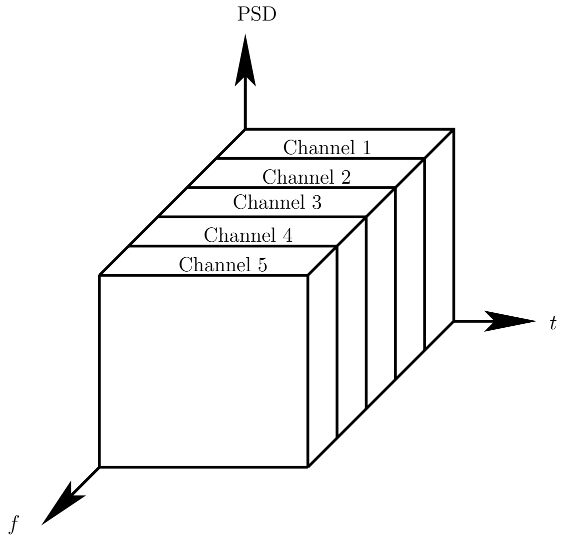

Figure 1.7: Illustration of channel configuration in FDMA systems. Different users transmit signals on different frequencies at the same time.

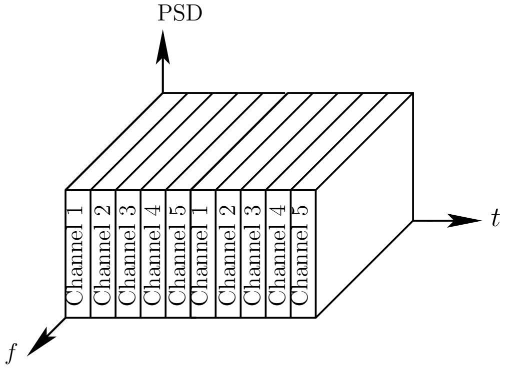

Figure 1.8: Illustration of channel configuration in TDMA systems. Different users transmit signals at different time slots using the whole frequency band available.

domain (FDMA) or in the time domain (TDMA). Hence, there is general no interchannel interference, when communicating in the same cell, unless the communications environment is deficient, thus destroying the orthogonality among the channels.

The concept of CDMA is illustrated in Fig. 1.9. All the users in CDMA communicate within the same frequency band at the same time. CDMA supports multiple users with the aid of spread-spectrum techniques as discussed in Section 1.1. In CDMA systems each user is assigned a unique spreading code, which is often referred to as the user signature code. Different users in CDMA systems can be distinguished by their unique spreading codes, provided that the cross-correlation among the spreading codes is sufficiently low, allowing the detector thereby with sufficient information to identify different users. In CDMA the

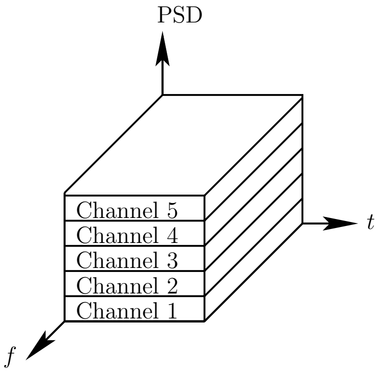

Figure 1.9: Illustration of channel configuration in CDMA systems. Different users are distinguished by their unique codes. All user signals are transmitted on the same frequency band at the same time.

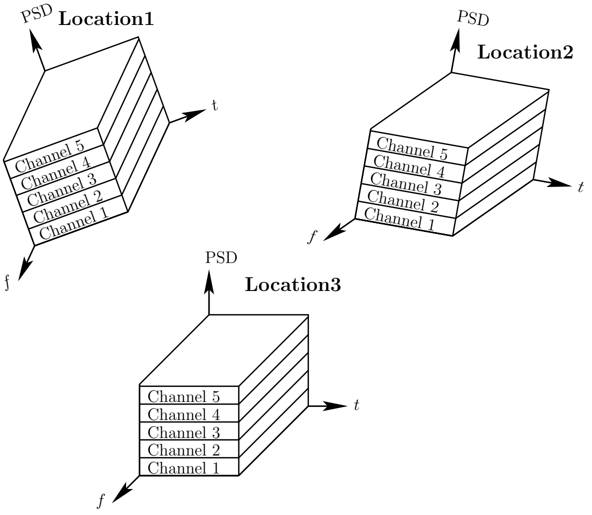

Figure 1.10: Illustration of channel configuration in SDMA systems. Different users or user sets can also be distinguished by their locations.

maximum number of channels is determined by the maximum number of spreading codes available, which is usually very high. Hence, the maximum number of users supportable by a CDMA system is generally not determined by the maximum number of spreading codes available, but mainly by the communications environment. Therefore, the maximum number of users supportable or the capacity of a CDMA system is 'soft': more users may be supported in good communications environments having high signal-to-interference-plus-noise ratio (SINR), while fewer users are allowed in worse communications environments resulting in low SINR. CDMA techniques are suitable for wideband, broadband and UWB communications.

Finally, the idea of SDMA is illustrated in Fig. 1.10, where three sets of CDMA users are geographically separated into three locations, and at each location five CDMA users share the same spectrum at the same time. Hence, we can view Fig. 1.10 as a spatial-code-division multiple-access (SCDMA) scheme. In SDMA systems different users (which use the same spreading code) may be distinguished by making use of the characteristics of wireless communications channels. Specifically, the wireless channels of different users separated geographically with sufficient distance will experience uncorrelated fading, yielding different channel impulse responses (CIRs) observed by a receiver. Once the receiver obtains the CIR information of the users, these CIRs can be viewed as the signature codes of the users as in the CDMA systems. Consequently, the receiver is capable of distinguishing the users with the aid of their unique CIRs.

In SDMA systems the CIRs are determined by the wireless communications channels, which are random, time-varying and cannot be regulated during system design. Hence, in SDMA systems powerful detectors are usually required.

1.4 Duplex

Duplex considers the techniques (or strategies) of communications against two directions, generally, incoming and outgoing, or uplink and downlink in cellular wireless systems. Below we provide a brief overview of the duplex techniques, including the well-known time-division duplex (TDD) and frequency-division duplex (FDD), the less known code-division duplex (CDD) as well as the multicarrier-division duplex (MDD) proposed in Chapter 8. Let us first consider the TDD scheme.

1.4.1 Time-Division Duplex (TDD)

In the context of the wireless communications systems based on TDD, the uplink (incoming) and downlink (outgoing) communications are separated (orthogonal) in the time domain, while communicating within the same frequency band. Specifically, as shown in Fig. 1.11, in the TDD-based wireless systems the time axis is divided into a number of time slots. A time slot can be assigned either for the uplink (U) transmission or for the downlink (D) transmission. Due to the fact that wireless channels experience delay-spread, which results in ISI, a certain amount of guard-time is usually inserted between two adjacent time slots, as shown in Fig. 1.11. TDD has a typical advantage in the case where the uplink and downlink data rates are asymmetric and variable. In this case, as the amount of downlink data increases and that of the uplink data decreases, more time slots (bandwidth) can be dynamically allocated to the downlink, while fewer time slots (bandwidth) are correspondingly allocated to the uplink. Another advantage of using TDD is that the uplink (incoming) and downlink (outgoing) channels in TDD-based systems are reciprocal. In this case, the broadcast downlink channels from base-station (BS) to mobile terminals (MTs) can be estimated or predicted using its reciprocity with the uplink channels from MTs to BS.

While the TDD-based wireless communications employ the above-mentioned advantages, especially the advantage of facilitating the downlink channel estimation at the BS, the TDD-based systems have some common disadvantages, especially when cellular communications are considered. First, the TDD-based systems place a high demand on

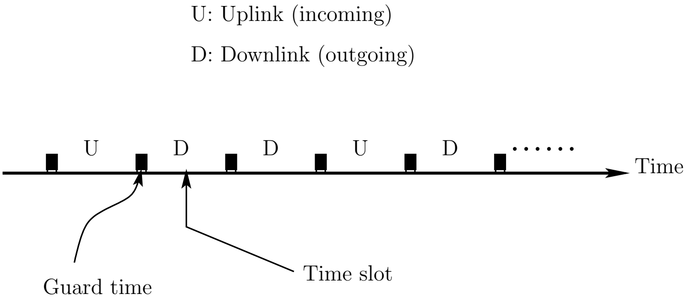

Figure 1.11: Illustrate of the time-division duplex (TDD).

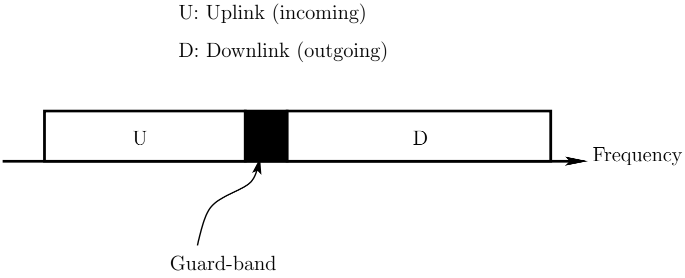

Figure 1.12: Illustrate of the frequency-division duplex (FDD).

system synchronization. Second, the TDD mode is not efficient when the uplink and downlink transmissions are symmetric. In this case, the TDD mode tends to waste bandwidth during switching frequently between transmitting and receiving. Furthermore, the fast switching between transmitting and receiving requires complex and power-hungry circuitry. Additionally, since in the TDD-based systems the uplink and downlink are operated within the same frequency band, the TDD mode tends to experience severe intra-cell and inter-cell interference. In a multicell TDD-based wireless system, an uplink (downlink) signal experiences interference not only from the other uplink (downlink) signals of its own cell but also from both the uplink and downlink signals of the other cells.

1.4.2 Frequency-Division Duplex (FDD)

For wireless communications systems based on FDD, the uplink (incoming) and downlink (outgoing) are separated (orthogonal) in the frequency domain. The principles of FDD can be well-understood with the aid of Fig. 1.12. In FDD-assisted wireless communications, the available frequency bandwidth is divided into two sub-bands – one is for the uplink transmission and the other is for the downlink transmission – which are supported by two carrier frequencies. The uplink and downlink sub-bands are separated by a so-called guard-band.

The FDD mode is efficient for the transmission of symmetric traffic of the uplink and downlink. Another advantage of the FDD is that it makes radio planning easier and

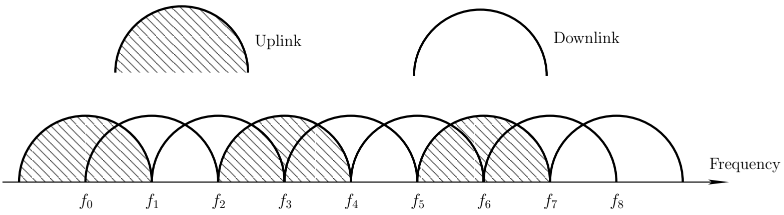

Figure 1.13: Illustration of the multicarrier-division duplex (MDD), where one-third of the sub-bands are allocated for uplink transmission and two-thirds of the sub-bands are allocated for downlink transmission.

more efficient. In FDD-based wireless systems, in principle, there is no interference between uplink and downlink signals. An uplink signal suffers interference only from the uplink signals of the intracell and intercells, while a downlink signal conflicts interference only from the downlink signals of the intracell and intercells.

Since in FDD-based systems the uplink and downlink are operated on two separate frequency bands, the uplink and downlink channels are not reciprocal. Therefore, applying transmitter preprocessing techniques, such as those studied in Chapter 8, at BS in FDD-based systems is much more difficult than applying them in TDD-based systems. In FDD-based systems the channel knowledge required for carrying out the transmitter preprocessing might have to be fed back from the receiver(s) to the transmitter(s). However, the feedback process introduces delay, which results in the transmitter preprocessing generally operating on inaccurate or even outdated channel information. Furthermore, feeding back the channel knowledge requires extra bandwidth – more bandwidth for feedback is required when the channel fading becomes faster – which may substantially reduce the communications efficiency.

1.4.3 Multicarrier-Division Duplex (MDD)

When multicarrier communications are considered, MDD may be employed for the uplink (incoming) and downlink (outgoing) transmissions. The MDD essentially belongs to the family of FDD. The principles of MDD mode can be understood by referring to Fig. 1.13, where one-third of the subcarriers are allocated to support the uplink transmission, while the remaining two-thirds are allocated to support the downlink transmission. Generally, in MDD-mode, both the uplink and downlink channels are operated within the same frequency band. A fraction of the sub-bands (subcarriers) can be allocated to support the uplink transmission, the others to the downlink transmission. Usually, the subcarrier signals are chosen to be orthogonal with each other. In MDD-mode, according to the practical requirements, the number of sub-bands allocated to the uplink or downlink of a user can be fixed or dynamic. The number of sub-bands allocated to a user can also be different from that allocated to another user.

In short, the MDD mode employs all the advantages of the TDD-mode. First, the MDD mode is capable of supporting asymmetric and variable traffics for the uplink and downlink. This can be readily achieved by dynamically allocating the corresponding number of sub-bands for the uplink and downlink. Second, in MDD mode the channel knowledge required for carrying out transmitter preprocessing can be readily obtained with the aid of frequency-domain channel estimation or prediction. The MDD mode also inherits some of the merits of the FDD mode. For example, in FDD mode there is no switch-over between transmission and receiving. In MDD mode there is no, or only very little, chance of switch-over between transmission and receiving. Furthermore, the MDD mode may employ some merits that the TDD and FDD modes are incapable of providing. The MDD mode has the greatest flexibility for design or online reconfiguration, as, in comparison with the TDD and FDD modes, the MDD mode uses a higher number of parameters that can be adjusted according to the requirements in practice. Furthermore, it appears that the MDD mode is suitable for many types of communications environment, including short-distance and long-distance communications, different types of cellular wireless communication, indoor and outdoor, etc.

One typical problem with the MDD mode is the added intercarrier interference, which may degrade significantly the achievable performance when the channel fading becomes time-selective or when there are frequency offsets. Hence, in MDD mode the intercarrier interference should be taken care of, which may be mitigated with the aid of some advanced signal-processing techniques.

1.4.4 Code-Division Duplex (CDD)

In addition to the above-reviewed three types of duplex technique, the uplink (incoming) and downlink (outgoing) transmissions can also be operated in a scheme called as CDD [1]. As the name CDD indicates, in CDD-based systems the uplink and downlink transmissions are supported by different codes. Specifically, let $\boldsymbol{C}_U$ and $\boldsymbol{C}_D$ be two sets of codes defined for the uplink and downlink transmissions, respectively. Then, for each active user in a CDD-based wireless system, its uplink transmission is supported by a code chosen from set $\boldsymbol{C}_U$, while its downlink transmission is by a code chosen from set $\boldsymbol{C}_D$.

The CDD mode may have many advantages, including flexibility and spectral efficiency. In CDD mode, in order to reduce the interference between the uplink and downlink, the cross-correlation between any two codes, one of which is from $\boldsymbol{C}_U$ and the other from $\boldsymbol{C}_D$, should be sufficiently low. However, wireless channels are typically dynamic and experience delay-spread yielding frequency-selective fading. Hence, even though every code from $\boldsymbol{C}_U$ is orthogonal to any code from $\boldsymbol{C}_D$, it is generally hard to maintain the orthogonality in practice. In [1] a set of codes referred to as *large area synchronous* (LAS) codes has been suggested for the CDD mode. The LAS codes are capable of maintaining the orthogonality among the codes, provided that the delay-spread of wireless channels does not exceed a certain value known as the correlation window. However, the maximum number of LAS codes is inversely proportional to the width of the correlation window.

1.5 Diversity in Wireless Communications

It is well known that signals transmitted over wireless channels experience fading, which, when not being taken care of or made use of, may greatly degrade the performance of communications. In modern wireless communications, fading can be efficiently mitigated by exploiting various types of diversity, which may be extracted from the time domain, frequency domain, space domain, etc. Here, by diversity we mean that the receiver can observe the transmitted signal through different angles, yielding multiple (possibly uncorrelated) observation copies of the same transmitted signal. Let us use a simple example to show the advantages of using diversity, by considering two communications cases.

Case 1: The receiver can only obtain one observation of the transmitted signal, which is expressed as

$$r_A = \alpha s + n \tag{1.5}$$

where s represents the transmitted data symbol, α denotes the fading channel amplitude, while n denotes the additive white Gaussian noise (AWGN), which obeys the Gaussian distribution with zero mean and a variance of σ^2.

From (1.5), we know that the instantaneous signal-to-noise ratio (SNR) is $\gamma = \alpha^2 E[s^2]/(2\sigma^2)$, while the average SNR is $\gamma_c = E[\alpha^2]E[s^2]/(2\sigma^2) = \Omega E[s^2]/(2\sigma^2)$, where $E[\alpha^2] = \Omega$.

Case 2: The receiver can obtain two independent observations of the same transmitted signal, expressed as

$$r_{B1} = \alpha_1 s + n_1 \quad \text{and} \quad r_{B2} = \alpha_2 s + n_2 \tag{1.6}$$

respectively, where α_1 and α_2 are fading amplitudes, and n_1 and n_2 are AWGN samples with a common variance of σ^2.

From (1.6), the total instantaneous SNR is given by $\gamma_B = (\alpha_1^2 + \alpha_2^2)E[s^2]/(2\sigma^2)$, while the average SNR of each observation is given by $\gamma_{c_1} = \gamma_{c_2} = E[\alpha_1^2]E[s^2]/(2\sigma^2) = 0.5\Omega E[s^2]/(2\sigma^2)$, implying that $E[\alpha_1^2] = E[\alpha_2^2] = 0.5\Omega$.

From the above two cases, we can observe that first, the total average SNR for both cases is the same, which is $\gamma_c = \Omega E[s^2]/(2\sigma^2)$. Hence, when communicating over Gaussian channels corresponding to $\alpha = 1$, $\alpha_1 = \alpha_2 = 0.5$, both cases achieve the same bit error rate (BER) performance. Second, the instantaneously received SNR values for Cases 1 and 2 can be expressed as

$$\gamma = \frac{\alpha^2}{\Omega}\gamma_c \tag{1.7}$$

$$\gamma_B = \frac{(\alpha_1^2 + \alpha_2^2)}{\Omega}\gamma_c \tag{1.8}$$

Now let us consider the communications over Rayleigh fading channels. Then, α, α_1 and α_2 obey the Rayleigh distributions associated with the PDFs given by

$$p_\alpha(y) = \frac{2y}{\Omega}\exp\left(-\frac{y^2}{\Omega}\right), \quad y \geq 0 \tag{1.9}$$

$$p_{\alpha_1}(y) = p_{\alpha_2}(y) = \frac{2y}{0.5\Omega}\exp\left(-\frac{y^2}{0.5\Omega}\right), \quad y \geq 0 \tag{1.10}$$

With the aid of (1.9) and (1.10), it can be shown that γ in (1.7) and γ_B in (1.8) obey the central χ^2-distributions with two and four degrees-of-freedom, with their PDFs given by

$$f(\gamma) = \frac{1}{\gamma_c}\exp\left(-\frac{\gamma}{\gamma_c}\right), \quad \gamma \geq 0 \tag{1.11}$$

$$f(\gamma_B) = \frac{\gamma_B}{(0.5\gamma_c)^2}\exp\left(-\frac{\gamma_B}{0.5\gamma_c}\right), \quad \gamma_B \geq 0 \tag{1.12}$$

respectively.

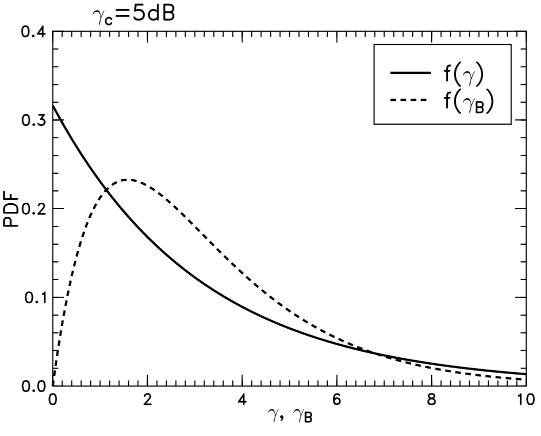

Figure 1.14: Illustration of the PDFs of γ and γ_B, shown in (1.11) and (1.12).

The PDFs of (1.11) and (1.12) are depicted in Fig. 1.14, where the total average SNR was assumed to be $\gamma_c = 5$ dB. According to Fig. 1.14, we can observe explicitly that γ_B has a relatively higher chance than γ to yield relatively high instantaneous SNR for detection, even though both cases have the same total average received power or SNR. Therefore, when, e.g., BPSK baseband modulation is assumed, the average BER of Case 1 should be higher than that of Case 2. In other words, when the receiver can obtain two independent observations (Case 2) instead of one (Case 1) of the transmitted signal, the detection performance of the communications scheme can then be improved. Correspondingly, we say that (Case 2) is capable of achieving a diversity order of two.

In the context of the general case, where the receiver can obtain L number of independent observations having the same average power of Ω/L for the same transmitted signal, the PDF of the instantaneously received SNR can be expressed as

$$f(\gamma) = \frac{\gamma^{L-1}}{(L-1)!\bar{\gamma}_l^L} \exp\left(-\frac{\gamma}{\bar{\gamma}_l}\right), \quad \gamma \geq 0 \tag{1.13}$$

which is a central χ^2-distribution with ($n = 2L$) degrees-of-freedom. In (1.13) $\bar{\gamma}_l = \Omega E[s^2]/(L \times 2\sigma^2) = \gamma_c/L$, implying that the total average received SNR is the same, regardless of the diversity order of L.

The PDFs of (1.13) associated with various values of L are depicted in Fig. 1.15. As shown, when the diversity order L increases, the shape of the PDF becomes more similar to the Gaussian PDF. When the diversity order L increases, the range that the PDF spans becomes smaller and converges to a value of $\gamma_c = 5$ dB ($= \sqrt{10} \approx 3.2$). Therefore, it can be implied that when the diversity order L tends to infinity, the PDF will converge to a Dirac delta function located at $\gamma = \gamma_c = \sqrt{10}$. Correspondingly, the BER performance of a communications scheme will converge to that achieved in Gaussian channels.

In order to illustrate this, let us assume that the BPSK baseband digital modulation scheme is used. Then, given the instantaneous SNR value of γ, it can be shown (see, e.g., [2]) that the conditional BER can be expressed as $Q(\sqrt{2\gamma})$, where $Q(x)$ is the Gaussian Q-function,

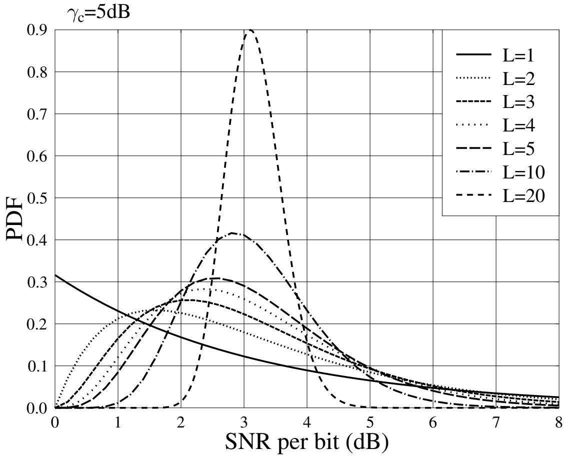

Figure 1.15: Illustration of the PDF of (1.13), when various diversity orders are assumed.

which is defined as $Q(x) = (\sqrt{2\pi})^{-1} \int_x^\infty \exp(-t^2/2)\,dt$. Furthermore, the average BER can be evaluated as [2]

$$P_e = \int_0^\infty Q(\sqrt{2\gamma}) f(\gamma)\,d\gamma \tag{1.14}$$

On substituting $Q(\sqrt{2\gamma})$ and (1.13) into the above equation and simplifying it, the average BER of the Lth-order diversity BPSK scheme can be found as [2]

$$P_e = \left[\frac{1-\mu}{2}\right]^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left[\frac{1+\mu}{2}\right]^k \tag{1.15}$$

where $\bar{\gamma}_l$ has been defined under (1.13) and $\mu = \sqrt{\bar{\gamma}_l/(1+\bar{\gamma}_l)}$.

The average BER of (1.15) is depicted in Fig. 1.16 against the SNR per bit, when various diversity order L is assumed. Figure 1.16 also shows the BER of the BPSK communicating over AWGN channels. As predicted, when the diversity order L increases, the BER performance in multipath Rayleigh fading channels becomes closer to that achieved in the AWGN channels.

The above analysis shows us that, in order for the receiver to achieve diversity, the receiver should be able to generate a number of, preferably independent, observations for the same transmitted signal. In wireless communications, diversity may be achieved in the frequency domain, time domain, space domain or jointly, through a wealth of techniques. Correspondingly, the diversity is called *frequency-diversity*, *time-diversity*, *spatial-diversity*, etc. The principles behind these types of diversity-achieving schemes are described as follows.

- **Frequency-diversity**: Wireless channels are frequency-selective, resulting in signals that are transmitted on different frequency bands sufficiently separated in frequency experiencing uncorrelated fading. Hence, when a signal is transmitted on two frequency bands sufficiently separated in frequency, e.g., higher than the *coherence bandwidth* of

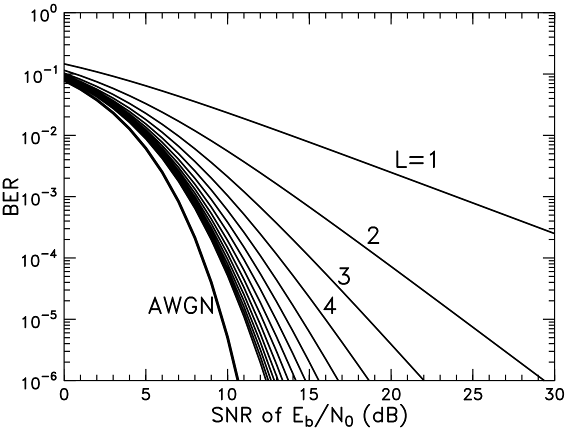

Figure 1.16: BER versus SNR per bit of E_b/N_0 performance of the BPSK system, when communicating over AWGN and multipath Rayleigh fading channels.

the channel, two uncorrelated observations of the transmitted signal may be obtained by the receiver from these two frequency bands, and a diversity order of two can then be achieved.

- **Time-diversity**: Wireless channels are typically time-variant and time-selective, resulting in signals that are transmitted on different time slots that are sufficiently separated in time experiencing uncorrelated fading. Therefore, when a signal is transmitted within two time slots sufficiently separated in time, e.g. higher than the *coherence time* of the channel, two uncorrelated observations of the transmitted signal may be obtained by the receiver from these two time slots, and a diversity order of two can then be achieved.

- **Spatial-diversity**: Wireless channels are also spatial-selective, resulting in signals that are transmitted at different locations that are sufficiently separated (usually higher than 10 wavelengths between any two locations) experiencing uncorrelated fading. Hence, when a transmitted signal is received by two receive antennas separated by a sufficient distance in space, the received signals of these two receive antennas are uncorrelated, and a diversity order of two can be achieved. Instead of using two receive antennas, when two copies of a same signal are transmitted through two transmit antennas sufficiently separated in space, two uncorrelated observations of the transmitted signal may also be obtained by a receiver and, correspondingly, a diversity order of two can be achieved.

1.6 Organization of the Book

This book is divided into nine chapters. The remaining chapters can be summarized as follows.

Chapter 2 presents the principles of various spread-spectrum schemes, including both the basic spread-spectrum schemes as well as the hybrid spread-spectrum schemes. The main objective of this chapter is to explore the principles of spread-spectrum communications in a unified treatment and to design novel hybrid spread-spectrum schemes based on attractive combinations of various spread-spectrum schemes.

Chapter 3 first considers the communications principles of OFDM. Then, the communications principles of seven types of multicarrier scheme are investigated. These seven multicarrier schemes include frequency-domain spread multicarrier CDMA (MC-CDMA), orthogonal multicarrier direct-sequence CDMA (MC DS-CDMA), single-carrier frequency-division multiple access (SC-FDMA), multitone DS-CDMA, generalized MC DS-CDMA, time-hopping multicarrier CDMA (TH/MC-CDMA) and time-frequency-domain spread MC DS-CDMA. The advantages and disadvantages of the above-listed multicarrier schemes are discussed in this chapter.

In Chapters 4 and 5 the BER performance of a variety of multicarrier systems is investigated, when communicating over AWGN channels (Chapter 4) or over frequency-selective fading channels (Chapter 5). The detectors considered in these two chapters are the single-user detectors, which are either the single-user correlation detectors or the single-user matched-filter (MF) detectors. In these two chapters we focus mainly on the analysis of the single-user BER-bound performance for various multicarrier systems. We also investigate the BER performance of the generalized time-frequency-domain spread MC DS-CDMA systems supporting multiple users.

Chapter 6 covers the multiuser detection (MUD) principles and applications in multicarrier CDMA systems. A wide range of MUD schemes are treated under various optimization principles. Many BER performance examples obtained by simulations are provided in this chapter, in order to characterize the achievable BER performance of the MUD schemes considered.

In contrast to Chapter 6, where the MUDs are derived by assuming that the corresponding receivers are capable of tracking the carrier phases, resulting in coherent MUD, in Chapter 7 noncoherent MUD is investigated in the context of the TH/MC-CDMA, since in the TH/MC-CDMA the carrier phases of the received signals are difficult to estimate owing to its time-hopping characteristics. In Chapter 7 a wide range of noncoherent MUDs are derived and the performance of the TH/MC-CDMA using these noncoherent MUDs is investigated. Note that, the noncoherent MUDs considered in Chapter 7 are general and their extension to the other noncoherent multiuser systems, such as to the FFH multiuser systems, is straightforward.

Chapter 8 investigates the multiuser transmitter preprocessing in association with three types of representative multicarrier CDMA scheme, namely the frequency-domain spread MC-CDMA, the MC DS-CDMA and the time-frequency-domain spread MC DS-CDMA. In this chapter a wide range of transmitter preprocessing schemes are derived. It can be shown that, in downlink multiuser communications, the downlink multiuser interference can be efficiently mitigated with the aid of the transmitter preprocessing carried out at the BS. In this chapter, furthermore, the acquisition of the channel knowledge for transmitter preprocessing is discussed in the context of the TDD-, FDD-, and MDD-based systems.

Finally, in Chapter 9 we explore the space–time processing in multiple-antenna (multi-antenna) multicarrier CDMA systems. Capacity of multiple-input multiple-output (MIMO) channels is first considered, followed by the principles of a range of spatial diversity techniques, including receive diversity, closed-loop and open-loop transmit diversity, etc.

Then, the applications of space–time processing in the context of different multicarrier CDMA schemes are analysed. Furthermore, in this chapter design of multiantenna MC DS-CDMA is considered for wireless environments experiencing simultaneously both frequency-selective and time-selective fading.