# 1

# Introduction

The history of wireless communications stretches back many centuries. Many of the earliest systems were inherently *line of sight* (LOS) using such techniques as smoke signals, flashing lights and semaphore. For example, in Napoleonic times, the French had an elaborate, essentially countrywide, semaphore system, developed by Claude Chappe (1763–1805) and consisting of chains of relay stations [1, 2]. Possibly, the first non-LOS systems were the drum signaling techniques used by tribes in Africa.

Guglielmo Marconi (1874–1937) first demonstrated modern wireless technology, also known as radio, in 1895 [1, 3, 4]. The first such systems were in a sense digital since they used Morse code, which had been invented by Samuel Finley Breese Morse (1791–1872) for use in telegraphy. Speech communication, using analog modulation, followed only a few years later, and prior to the 1980s almost all wireless systems used analog transmission techniques. However, the widespread deployment of telephony based on *pulse code modulation* (PCM) and the development of digital satellite transmission and microwave relay systems fostered the development of digital transmission techniques. These systems are now being augmented and to a large extent supplanted for point-to-point communications by terrestrial digital wireless systems coupled with high speed backbone networks implemented using optical fiber. Satellite systems retain a very valuable niche in the area of wide area broadcasting to which they are well suited. They also retain an application in some data transfer systems, where delay is not of prime importance. Microwave relay systems are falling into disuse in many regions as they are replaced by fiber links.

The development of modern terrestrial wireless systems has been driven in large measure by the development of *cellular radio systems* [5, 6]. The cellular principle introduced the concept of *frequency reuse* over large spatial domains. This leads to a very efficient use of the available radio spectrum and allows for a very large number of simultaneous users of a given system. As a result the world is today moving to an untethered mobile wireless communications environment based on cellular-like system architectures.

AT&T deployed the first cellular system in Chicago in 1983 following several years of development. It used an analog transmission format and was completely saturated by 1984, the developers having grossly underestimated the public appetite for mobile phone services. Since then there has been an almost explosive growth of cellular radio, and this continues today. In the early 1990s the first digital cellular or second generation systems appeared. These provided increased capacity and performance using digital transmission formats coupled with improved digital signal techniques and hardware platforms. Today there are cellular systems based on both *time division multiple access* (TDMA) and *code division multiple access* (CDMA).

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The advent of digital cellular systems paved the way for mobile data services. There is now an increasing demand for these and, as a result, third generation cellular systems are being deployed. These provide for higher data rates and offer many new applications and services. In addition to cellular systems, there are numerous other wireless systems being developed and deployed. Moreover, there is now a convergence taking place to common transmission and networking environments for voice, data and multimedia communications. Consequently, there is an increasing demand for higher and higher data rates coupled with the requirement to make even more efficient use of the limited available radio spectrum.

Today there are numerous distinct wireless systems in use. These modern systems, while distinct, all use digital signaling formats and network architectures and there is a distinct trend toward convergence to a small number of these coupled with the ability to interwork between different systems and networks. Some of the systems that are currently deployed or being developed for deployment include the following:

1. Cellular telephone systems. While these ignited the wireless revolution, they are still undergoing development to improve their transmission rates and the range of applications to which they can cater.
2. Cordless telephones. These initially were developed to provide tetherless connections within the limited space of a single dwelling. However, with the development of CT-2 in North America followed by that of DECT in Europe [5, 6], their space has enlarged and there are signs of their convergence to the cellular telephone system.
3. *Wireless local area networks* (WLANs). These have seen a great deal of development in the past few years. Standardization of signaling formats to the IEEE 802.11b, 802.11a and 802.11g formats and their widespread use in unlicensed bands around 800 MHz, 2.4 GHz and 5 GHz has led to an almost explosive growth in mobile computing. This has fostered the development of networks of high data rate wireless *access points* (APs) interconnected by high speed backbone networks, thereby leading essentially to a cellular network architecture. In addition to the IEEE standards-based networks, there have been similar developments in Europe known as the Hiperlan I and II standards.
4. Broadband wireless access networks. These are in large measure based on the IEEE 802.16 standard [7] and are intended to provide high rate, wide area coverage similar to that of WLANs. These systems are just now beginning to be deployed, and it appears that they may subsume some of the functionality now provided by cellular networks.
5. Low-cost, low-power systems. Such systems, which include Bluetooth [8] and Zigbee [9], were initially intended to provide relatively low data rates with limited range and in small-scale networks. Bluetooth is primarily focused on so-called personal area networks (PANs) that support a very limited number of devices requiring limited data rates. Zigbee was developed primarily for use in sensor networks requiring low data rates with long-lived battery powered terminals.
6. *Ultra wideband* (UWB) systems. These are systems based at least initially on the concepts of *impulse radio* (IR) [10] and are characterized by percentage bandwidths in excess of 20% of the carrier frequency or by a bandwidth exceeding 500 MHz. Today there are two further basic system approaches, one based on spread spectrum and the other on multiband *orthogonal frequency division multiplexing* (OFDM). System deployment has only recently been licensed in North America and many of their applications are uncertain at this stage. However, it does appear that they may subsume many of the functions now provided by systems such as Bluetooth and Zigbee.

In addition to the system types mentioned above, there is today a trend toward *cognitive* or "smart" radios as first described by J. Mitola [11, 12]. Cognitive radio may be loosely thought of as overlay on a software-defined radio that causes a system to recognize its channel and interference environment and then to automatically adjust its parameters. There are many possible approaches to such systems and we will not make any attempt to categorize them here.

Finally, there are undoubtedly many wireless systems and applications that have not been mentioned here. Moreover, there are almost certainly others that have not yet been conceived. The world is moving rapidly to an untethered communications environment and there will be many new applications of both existing and new wireless systems appearing in the next few years.

This book is focused on the so-called *physical layer* of wireless communications systems. In particular, it is focused on techniques for mitigating the effects of the wireless channel including dispersion due to multipath propagation that causes *intersymbol interference* (ISI), adjacent and co-channel interference. It is also concerned with achieving high-rate, high-integrity communications in a power-efficient manner. The overall focus is the development and analysis of transmission techniques and algorithms for accomplishing this. The book considers both *single-input single-output* (SISO) systems and *multiple-input multiple-output* (MIMO) systems that utilize transmit and receiver diversity to achieve high-capacity signaling coupled with high-integrity transmission.

In the remainder of this introductory chapter, we will first provide an overview of both SISO and MIMO system architectures. We will then briefly describe the structure of the book and, finally, provide some suggestions for further reading.

## 1.1 Structure of a Digital Communication System

The overall focus here is on the structure of a digital communication system operating over a wireless channel. We will consider *conventional* systems, using a single antenna at the transmitter and, possibly, *diversity reception*, and MIMO systems. One of the most powerful techniques available to improve the performance and throughput of wireless transmission is that of *diversity*. In fact, diversity creates multiple copies of the transmitted signal at the receiver. In principle, these copies are uncorrelated, so that when one copy is deeply faded due to the wireless channel, the others are not. This allows for significant improvement in both the error performance and throughput of wireless transmission systems. The concept of diversity in receivers has been known for many years [13]; however, in recent years there has been much work in developing techniques to achieve diversity at the transmitter [14, 15] and to combine transmit and receive diversity through the use of *space-time coding* [16].

Systems that combine transmit and receive diversity are known as MIMO systems, which may in a sense be considered as the most general system architecture. Such systems include space-time coded systems [16] and the so-called *Bell Labs Layered Space-Time* (BLAST) [17] or *spatial multiplexing* architectures. The latter have been shown to allow for major increases in the available channel capacity [18] and a consequent increase in the efficiency of use of the available radio spectrum. Note that capacity provides a theoretical upper limit on the throughput that can be achieved in a given channel.

SISO systems that contain no diversity are clearly the simplest in structure. *Single-input multiple-output* (SIMO) systems encompass the classical architecture, providing diversity only at the receiver. *Multiple-input single-output* (MISO) systems provide only transmit diversity usually through the mechanism of space-time coding [16], which introduces both temporal and spatial correlation among multiple transmitted signal streams in such a manner that a single receiver can decode the multiple received signals and obtain the diversity effect introduced at the transmitter.

Generic system architectures are depicted for SIMO and MIMO systems in Figures 1.1 and 1.2, respectively. In the following chapters of this book a number of algorithmic techniques implemented in the various functional blocks forming the point-to-point wireless communication systems[1] illustrated in Figures 1.1 and 1.2 will be considered in detail. Here we confine ourselves to a more or less qualitative description of their various functions.

Let us consider the functions performed by the various system blocks, referring first to Figure 1.1, for simplicity. To begin, we consider the blocks over which a system designer does not usually

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[1] Note that both systems are characterized by a single information source and a single destination; *multiuser* systems will not be investigated in the following.

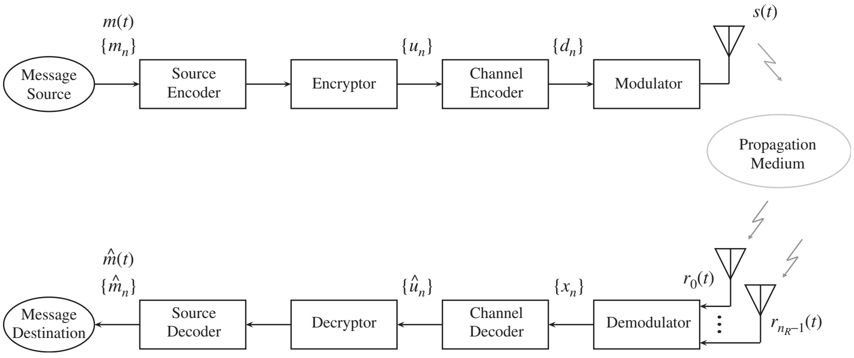

**Figure 1.1** Block diagram of a conventional digital communication system with *diversity reception*.

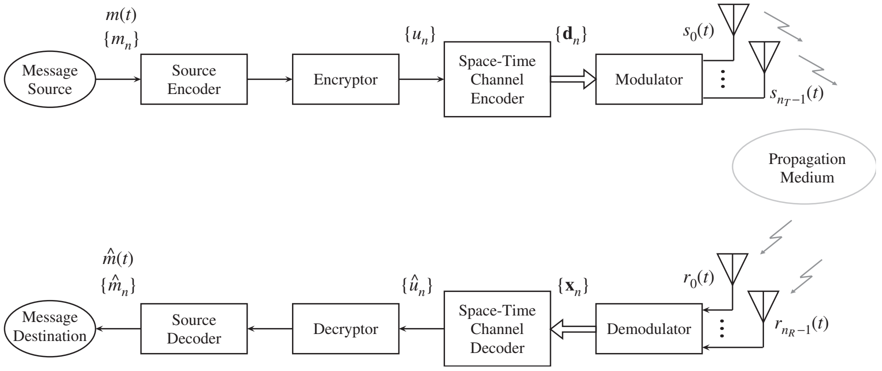

**Figure 1.2** Block diagram of a *space-time* digital communication system.

have direct control, namely the *message source* and the *message destination*. The source generates a sequence of discrete[2] messages $\{m_n\}$ (where $m_n$ denotes the $n$th message in the sequence). In the case where the source produces an analog signal, it is assumed that the source encoder accomplishes analog-to-digital conversion, producing a data stream or discrete message sequence. The message destination is relevant to the present discussion only because an appropriate *fidelity criterion* (i.e., a quality index), describing system performance, is usually defined for a given source–destination pair. Quality indexes commonly adopted to assess the performance of a digital communication system are the bit error probability and the symbol error probability.

A wireless communication system designer does not usually have complete control over the *communication channel*. With reference to Figures 1.1 and 1.2, this includes the *propagation medium* (i.e., the physical space through which the electromagnetic signal radiated by the transmit antenna travels), the final section of the transmitter (e.g., the transmit antenna and filtering/amplification stages preceding it), and the initial section of the receiver (e.g., the receive antenna and low noise amplifier and filter stages following it). In the present work, we will not focus on the details of the "channel" subsystem. Instead, we will limit ourselves to a mathematical description of its input–output behavior.

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[2] This means that the message alphabet has a *finite cardinality*. Throughout the book, we will consider only discrete sources whose alphabet has this property.

As will be seen later, a wireless communication channel changes the shape of the transmitted signal, introducing linear (and, eventually, nonlinear) distortions and adding random noise.

The *distortions* due to a wireless channel can cause substantial changes in the temporal and spectral properties of transmitted signals. These often originate from the fact that electromagnetic waves do not propagate from the transmit to the receive antenna along a direct path, but are reflected and scattered by objects in the surrounding environment. As a result, receiver antennas collect *multiple copies* (echoes) of the same transmitted signal. These have usually traveled along distinct *paths*, with different propagation times, and generally arrive with different phases and amplitudes. As a result, in some spatial locations, these copies can interfere destructively, canceling each other, so that the useful component of the received signal *fades*. In other words, the presence of multiple paths generates the so-called *fading* phenomenon, representing one of the most significant impairments encountered in wireless system design. The oldest countermeasure to fading is known as *diversity reception*. This consists of equipping digital receivers with multiple antennas, which, when adequately spaced, collect *different* (i.e., distorted in different and, possibly, independent ways) replicas of the transmitted signal [19].

Any communication channel also adds *random noise*, which is generated by both external sources (e.g., cosmic and atmospheric signals, and interference) and by the electronic devices in the receiver. A brief discussion of its statistical properties will be provided later. At this point, we merely note that it usually has a Gaussian distribution and a white or constant power spectral density over the frequency bands of interest.

Let us summarize the functions of the other blocks of the *transmitter* (i.e., the source encoder), the encryptor, the channel encoder and the modulator:

- The *source encoder* processes the source message stream to remove its natural *redundancies*. This can result in appreciable reduction of the bit rate, sometimes achieved, however, at the price of an information loss. Despite this, the original message stream can be recovered by the source decoder at the receiver within some *specified fidelity*.
- The *encryptor*, if present, adds security coding to the data sequence generated by the source encoder. This result is achieved by a coding algorithm turning the unciphered data (usually called *plaintext*) into a new discrete sequence $\{u_n\}$ (called *ciphertext*). The encryption algorithm involves a parameter, called the *key*, knowledge of which at the receiver is essential to deciphering. One class of modern and well-known ciphering techniques, known as *public-key encryption*, relies on a double key mechanism, that is, on the use of a *public key* (potentially known to anyone) for enciphering and on a *private key* (known, in principle, only to the message destination) for deciphering [20].
- The *channel encoder* introduces an error-correction capability, so that most (possibly all) of the errors due to channel noise and distortion can be removed or corrected at the receiver. To achieve this target, the channel encoder introduces *memory* and *redundancy* into the coded sequence. The presence of redundancy is seen from the fact that, in a given time interval, the number of bits generated by the channel encoder is larger than the number of the information bits processed by it. Memory can be related to the fact that, generally speaking, each bit feeding the encoder influences multiple bits at its output. As discussed in Part II of this book, the receiver exploits both these properties to improve the reliability of its decisions.
- The *modulator* is fed by the symbol sequence $\{d_n\}$ (each symbol belongs to a multilevel alphabet) and generates an analog signal $s(t)$, which consists of the concatenation of waveforms belonging to some *finite alphabet of signals*. In practice, this device represents the interface between the stream of discrete data and the real communication medium. Therefore, it accomplishes multiple tasks (including frequency up-conversion) and power amplification and can incorporate transducers (e.g., multiple transmit antennas).

Let us now consider some of the subsystems in the *receiver*, namely the demodulator, the channel decoder, the decryptor and the source decoder. These units accomplish functions complementary to those of the corresponding blocks in the transmitter.

In general, the receiver has $n_R \geq 1$ antennas. The $l$th antenna (with $l = 0, 1, \ldots, n_R - 1$) feeds the *demodulator* with the noisy *radio-frequency* (RF) signal:

$$r_l(t) = z_l(t) + n_l(t), \tag{1.1}$$

where $z_l(t)$ and $n_l(t)$ represent the *useful signal component* (i.e., the response to $s(t)$ of the communication channel including the transmitter and the transmit/receive antennas in the absence of noise) and the *random noise* at the receive antenna terminals, respectively. The demodulator processes the waveforms $\{r_l(t)\}$ of (1.1), to extract a set of *synchronization parameters* (such as the phase and frequency of the carrier associated with $z_l(t)$, and timing information), and in many cases an *estimate* of the communication channel response. Then it uses this information to perform signal *detection* that generates a data sequence $\{x_n\}$. This contains either *hard* or *soft* information about the transmitted data. In the first case, if we focus on the data transmitted in the $n$th symbol interval, the demodulator generates a hard estimate or decision $\hat{d}_n$ on the value of the (coded) transmitted symbol $d_n$, whereas in the second case it produces information about the reliability (i.e., the *likelihood*) of each value that $d_n$ can take.

The *channel decoder* exploits the information provided by the demodulator, to try to find the *most likely* data sequence $\{\hat{u}_n\}$ that has generated the coded sequence $\{d_n\}$. Note that the availability of soft information allows the decoder to improve the quality of its decisions with respect to the case of knowledge of hard information.

The task accomplished by the *decryptor* is the inverse to that of the encryptor. This task can be carried out successfully if both the ciphering algorithm and its key are known.

The *source decoder* processes an estimate of the binary data generated by the source encoder to generate a message in a proper format (the data sequence $\{\hat{m}_n\}$ or the analog signal $\hat{m}(t)$ in Figure 1.1) for the destination.

Finally, we note that the system of Figure 1.1 is characterized by a communication channel with a *single* input (corresponding to a single transmit antenna) and *multiple* outputs, to be processed by a receiver equipped with $n_R \geq 1$ antennas. For this reason, the communication system can be classified as SIMO. In particular, if $n_R = 1$, we have a SISO system.

The scheme illustrated in Figure 1.2 generalizes that of Figure 1.1, since it represents a system with $n_T > 1$ transmit antennas, resulting in a MIMO system. In such a system, the channel encoder, in response to the discrete data sequence $\{u_n\}$, generates a sequence of *vectors* $\{\mathbf{d}_n\}$, each consisting of $n_T$ different elements. For any $n$, the $k$th element $d_n[k]$ (with $k = 0, 1, \ldots, n_T - 1$) of $\mathbf{d}_n$ is transmitted by the modulator as the RF signal $s_k(t)$ radiated by the $k$th antenna. Therefore, the redundancy and memory introduced by the encoder are spread over both *time* (as in the SIMO scenario described above) and *space* using *distinct transmit antennas* (*transmit diversity*). This is commonly referred to as *space-time* (ST) channel coding [16]. Generally speaking, each receive antenna observes a linear combination of all $n_T$ transmitted signals. In fact, the noisy signal captured by the $l$th receive antenna can be expressed as:

$$r_l(t) = \sum_{k=0}^{n_T-1} z_{kl}(t) + n_l(t), \tag{1.2}$$

with $l = 0, 1, \ldots, n_R - 1$, where $z_{kl}(t)$ and $n_l(t)$ respectively represent the useful signal component (the channel response between the $k$th transmit and the $l$th receive antennas to $s_k(t)$ in the absence of noise) and the random noise collected by the antenna mentioned above. The demodulator processes the signals $\{r_l(t)\}$ of (1.2) and generates a sequence of $n_T$-dimensional vectors $\{\mathbf{x}_n\}$, whose elements contain, as in the previous case, hard or soft information about the sequence $\{\mathbf{d}_n\}$.

Recent studies have shown that the use of the spatial dimension in digital transmissions can substantially improve system robustness against channel fading and can allow an increase in the data rate transmitted within a given bandwidth. This explains the substantial research efforts on MIMO systems in the last decade [21, 22], to assess both their theoretical limits and to develop new digital transmission techniques for such systems. These studies have been followed by the development of *prototypes* of MIMO systems and, more recently, by the design of *application specific integrated circuits* (ASICs) for their low-cost implementation. This is illustrated by the so-called BLAST transmission technique, developed at Bell Labs by Gerard J. Foschini in 1996 [17]. In a BLAST system a data stream generated by a single source undergoes *spatial multiplexing*, that is, it is divided in $n_T$ distinct substreams, each transmitted by a distinct antenna, using, however, the same time intervals and bandwidth as all the other antennas. At the receive side an array consisting of $n_R$ antennas is used to collect the multiple linear combinations of the transmitted signals. Each receive antenna captures the superposition of all the $n_T$ transmitted signals as in equation (1.2). Note that in a *rich scattering environment*, different antennas, having distinct spatial locations, receive different replicas of the same signal. This form of diversity allows the receiver to separate and detect, using sophisticated signal processing algorithms, the $n_T$ transmitted signals, to reliably recover the overall transmitted data stream.

To assess the technical feasibility of the theoretical results derived by Foschini, in 1998 Bell Labs developed a BLAST prototype, having eight transmit antennas and 12 receive antennas. It clearly showed the possibility of achieving transmit data rates 10 times faster than those offered by traditional communication techniques in the same bandwidth [23]. On October 16, 2002, *Lucent Technologies* announced that Bell Labs had developed the prototypes of two chips for the use of the BLAST technology in mobile terminals and that the first lab tests had shown the possibility of transmitting at a rate of 19.2 Mbits/s, eight times faster than existing techniques under the same conditions.

Technically important results in the development of systems equipped with antenna arrays have also been obtained using the transmission technique known as MIMO-OFDM.[3] In this case spatial multiplexing is combined with *frequency division multiplexing* (FDM), so that spatial diversity is jointly exploited with spectral or frequency diversity. The last form of diversity arises due to the fact that, in a multipath channel, distinct spectral components of the transmitted signal undergo different phase/amplitude changes. Again in the development of MIMO-OFDM systems the derivation of many of theoretical results has been followed by the development of prototypes (e.g., see [24, 25, 26]) and, later, by the implementation of ASICs for modern wireless communications systems (e.g., in local area radio networks).

All this explains why today MIMO technology can be considered a mature technical solution for the design of digital communication systems.

In the following chapters of this book we will first focus on communication techniques employed in SISO and SIMO communication systems. We believe that a deep understanding of these techniques provides a solid foundation for the study of MIMO systems; this point will be stressed throughout the book, since various methodologies for the analysis and the design of MIMO systems will be presented as extensions of similar results derived for conventional systems, equipped with a single transmit antenna.

## 1.2 Plan of the Book

This book is divided into two parts. Part I concerns the wireless channel and the development of algorithms to process signals transmitted using uncoded transmission techniques. Part II deals with wireless systems that employ channel coding and develops algorithms to process signals that have been encoded prior to transmission. The use of coded transmission opens up the possibility of developing algorithms to jointly mitigate the distorting effect of the wireless channel and decode the information.

More specifically, in Part I, after describing the mathematical tools for both deterministic and stochastic descriptions of wireless channels in Chapter 2, an overview of the most important digital modulation techniques for radio communications is given in Chapter 3. In particular, we focus on both

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[3] The OFDM technique is analyzed in detail in Chapter 3.

single carrier formats, such as passband *pulse amplitude modulation* and *continuous phase modulation*, and multicarrier formats, namely, *orthogonal frequency division multiplexing* signaling. We illustrate, for each class of signals, the structure of the modulated signals and their spectral properties. General rules for optimal signal detection are summarized in Chapter 4, to provide an overview of available techniques and of the analytical methods for estimating their performance. Detection over wireless channels may require estimation of channel properties, and, in particular, the *channel impulse response*. This is the subject of Chapter 5, which deals with both feedforward and iterative channel estimation techniques. Chapters 4 and 5 provide the necessary tools for the design of channel equalization algorithms, which are the subject of Chapter 6. There various algorithms are illustrated for the modulation formats described in Chapter 3. In particular, algorithm classification is done first on the basis of the modulation category (single carrier or multicarrier), and then on the basis of the available *channel state information* (CSI). As far as the last point is concerned, we consider three distinct possibilities: a receiver provided with perfect CSI knowledge; a receiver provided with statistical knowledge of CSI, but not performing explicit channel estimation; and a receiver performing joint estimation of data and CSI. Moreover, for single carrier modulations, equalization strategies operating in the time domain and in the frequency domain are considered.

In Part II we first discuss some essential results about the capacity of wireless channels (Chapter 7), showing the benefits of using multiple antennas at both transmitter and receiver. Then, in Chapter 8 an introduction to channel coding schemes and to coded modulations for wireless communication techniques is provided. Classical coding schemes, such as linear block codes and convolutional codes, are described in Chapter 9. For each class, we illustrate some well-known families of coding schemes and some important decoding techniques. In addition, some classical concatenated coding schemes are presented. Modern coding schemes, such as *turbo codes* and *low-density parity check codes*, are considered in Chapter 10. Again, coding and decoding algorithms are discussed, and some performance results are presented. The coding schemes and principles analyzed in Chapters 9 and 10 also provide the tools for understanding the signal space codes analyzed in Chapter 11. In particular, in that chapter we focus on *trellis coded modulation* (TCM), *bit-interleaved coded modulation* (BICM), and *modulation codes* based on *multilevel coding*, and finally on *space-time coding*, for both frequency-flat and frequency-selective fading channels. In a digital receiver equalization and decoding can be accomplished in a noniterative or in an *iterative fashion*, the latter possibility usually being in mobile scenarios. Some basic concepts from this modern research area are discussed in Chapter 12. Finally, appendices summarize various mathematical results (on Fourier transforms, linear systems, random variables and stochastic processes, etc.), that turn out to be extremely useful in both parts of the book.

## 1.3 Further Reading

A general introduction to digital communication techniques can be found in the textbooks [27–30]. Other introductory books, explicitly devoted to such techniques and to their applications in wireless communications, are [5, 6, 31–34]. A general introduction to the topic of channel coding theory is provided by the excellent book [35]. Channel coding schemes for wireless applications are investigated in [36, 37]. A study of various space-time processing and coding techniques can be found in the books [16, 38–40]. Books explicitly devoted to various algorithmic aspects of wireless communications are [41–43].