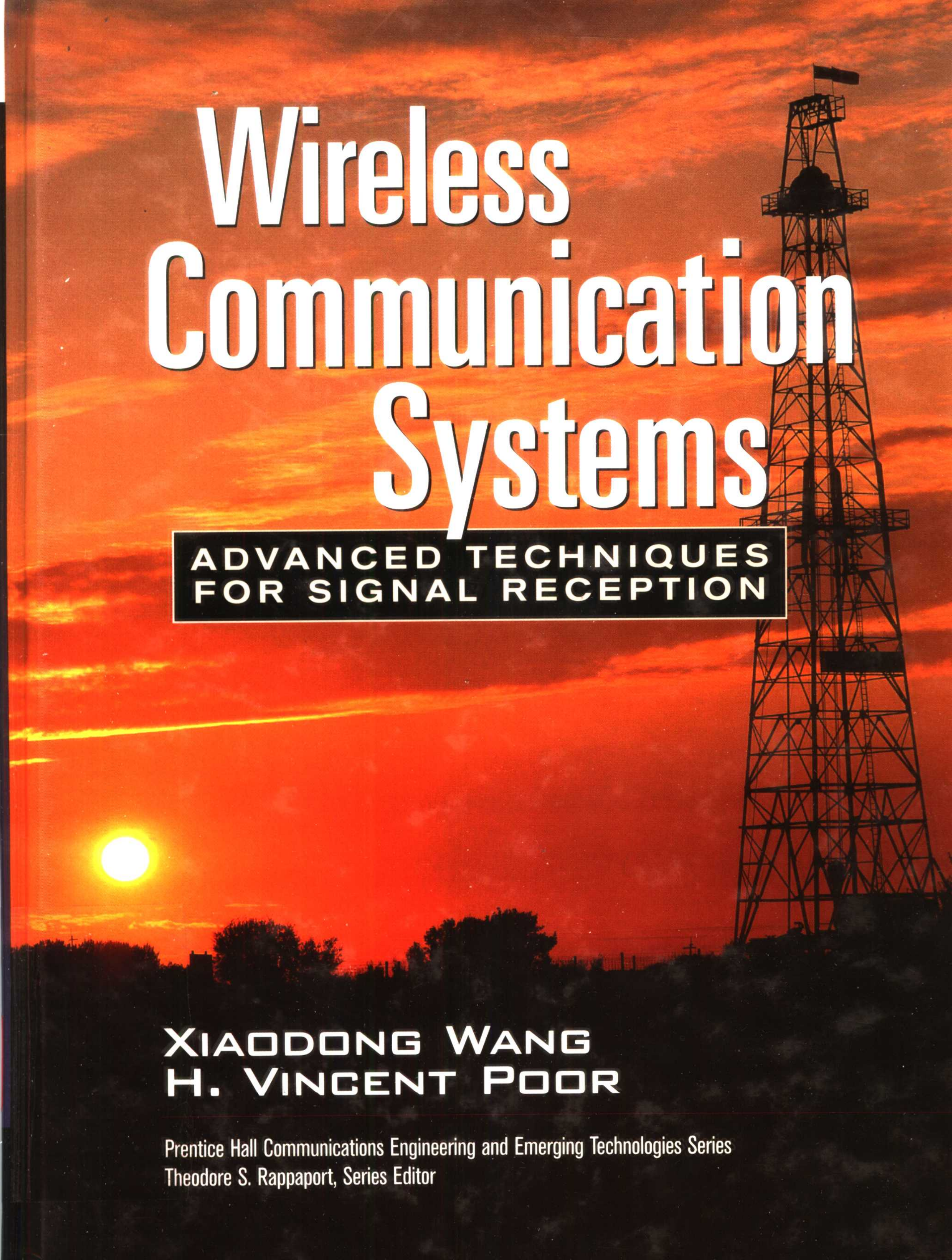
Wireless Communication Systems
ADVANCED TECHNIQUES FOR SIGNAL RECEPTION
XIAODONG WANG
H. VINCENT POOR
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Wireless Communication Systems

Advanced Techniques for Signal Reception

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PREFACE

Wireless communications, together with its applications and underlying technologies, is among today's most active areas of technology development. The very rapid pace of improvements in both custom and programmable integrated circuits for signal processing applications has led to the justifiable view of advanced signal processing as a key enabler of the aggressively escalating capacity demands of emerging wireless systems. Consequently, there has been a tremendous and very widespread effort on the part of the research community to develop novel signal processing techniques that can fulfill this promise. The published literature in this area has grown explosively in recent years, and it has become quite difficult to synthesize the many developments described in this literature. The purpose of this book is to present, in one place and in a unified framework, a number of key recent contributions in this field. Even though these contributions come primarily from the research community, the focus of this presentation is on the development, analysis, and understanding of explicit algorithms for performing advanced processing tasks arising in receiver design for emerging wireless systems.

Although this book is largely self-contained, it is written principally for designers, researchers, and graduate students with some prior exposure to wireless communication systems. Knowledge of the field at the level of Theodore Rappaport's book, *Wireless Communications: Principles and Practice* [405], for example, would be quite useful to the reader of this book, as would some exposure to digital communications at the level of John Proakis's book, *Digital Communications* [396].

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CONTENTS

Chapter 1

INTRODUCTION

1.1 Motivation

Wireless communications is one of the most active areas of technology development of our time. This development is being driven primarily by the transformation of what has been largely a medium for supporting voice telephony into a medium for supporting other services, such as the transmission of video, images, text, and data. Thus, similar to the developments in wireline capacity in the 1990s, the demand for new wireless capacity is growing at a very rapid pace. Although there are, of course, still a great many technical problems to be solved in wireline communications, demands for additional wireline capacity can be fulfilled largely with the addition of new private infrastructure, such as additional optical fiber, routers, switches, and so on. On the other hand, the traditional resources that have been used to add capacity to wireless systems are radio bandwidth and transmitter power. Unfortunately, these two resources are among the most severely limited in the deployment of modern wireless networks: radio bandwidth because of the very tight situation with regard to useful radio spectrum, and transmitter power because mobile and other portable services require the use of battery power, which is limited. These two resources are simply not growing or improving at rates that can support anticipated demands for wireless capacity. On the other hand, one resource that is growing at a very rapid rate is that of processing power. Moore's Law, which asserts a doubling of processor capabilities every 18 months, has been quite accurate over the past 20 years, and its accuracy promises to continue for years to come. Given these circumstances, there has been considerable research effort in recent years aimed at developing new wireless capacity through the deployment of greater intelligence in wireless networks (see, e.g., [145,146,270,376,391] for reviews of some of this work). A key aspect of this movement has been the development of novel signal transmission techniques and advanced receiver signal processing methods that allow for significant increases in wireless capacity without attendant increases in bandwidth or power requirements. The purpose of this book is to present some of the most recent of these receiver signal processing methods in a single place and in a unified framework.

Wireless communications today covers a very wide array of applications. The telecommunications industry is one of the largest industries worldwide, with more than $1 trillion in annual revenues for services and equipment. (To put this in perspective, this number is comparable to the gross domestic product of many of the world's richest countries, including France, Italy, and the United Kingdom.) The largest and most noticeable part of the telecommunications business is telephony. The principal wireless component of telephony is mobile (i.e., cellular) telephony. The worldwide growth rate in cellular telephony is very aggressive, and analysts report that the number of cellular telephony subscriptions worldwide has now surpassed the number of wireline (i.e., fixed) telephony subscriptions. Moreover, at the time of this writing in 2003, the number of cellular telephony subscriptions worldwide is reportedly on the order of 1.2 billion. These numbers make cellular telephony a very important driver of wireless technology development, and in recent years the push to develop new mobile data services, which go collectively under the name *third-generation* (3G) *cellular*, has played a key role in motivating research in new signal processing techniques for wireless. However, cellular telephony is only one of a very wide array of wireless technologies that are being developed very rapidly at the present time. Among other technologies are wireless piconetworking (as exemplified by the Bluetooth radio-on-a-chip) and other personal area network (PAN) systems (e.g., the IEEE 802.15 family of standards), wireless local area network (LAN) systems (exemplified by the IEEE 802.11 and HiperLAN families of standards, called WiFi systems), wireless metropolitan area network (MAN) systems (exemplified by the IEEE 802.16 family of standards, called WiMax systems), other wireless local loop (WLL) systems, and a variety of satellite systems. These additional wireless technologies provide a basis for a very rich array of applications, including local telephony service, broadband Internet access, and distribution of high-rate entertainment content such as high-definition video and high-quality audio to the home, within the home, to automobiles, and so on (see, e.g., [9, 41, 42, 132, 159, 161, 164, 166, 344, 361, 362, 365, 393–395, 429, 437, 449, 457, 508, 558, 559] for further discussion of these and related applications). Like 3G, these technologies have spurred considerable research in signal processing for wireless.

These technologies are supported by a number of transmission and channel-assignment techniques, including time-division multiple access (TDMA), code-division multiple access (CDMA), and other spread-spectrum systems, orthogonal frequency-division multiplexing (OFDM) and other multicarrier systems, and high-rate single-carrier systems. These techniques are chosen primarily to address the physical properties of wireless channels, among the most prominent of which are multipath fading, dispersion, and interference. In addition to these temporal transmission techniques, there are spatial techniques, notably beamforming and space-time coding, that can be applied at the transmitter to exploit the spatial and angular diversity of wireless channels. To obtain maximal benefit from these transmission techniques, to exploit the diversity opportunities of the wireless channel, and to mitigate the impairments of the wireless channel, advanced receiver signal processing techniques are of interest. These include channel equalization to combat dispersion, RAKE combining to exploit resolvable multipath, multiuser detection to mitigate multiple-access interference, suppression methods for co-channel interference, beamforming to exploit spatial diversity, and space-time processing to jointly exploit temporal and spatial properties of the signaling environment. These techniques are all described in the ensuing chapters.

1.2 Wireless Signaling Environment

1.2.1 Single-User Modulation Techniques

To discuss advanced receiver signal processing methods for wireless, it is useful first to specify a general model for the signal received by a wireless receiver. To do so, we can first think of a single transmitter, transmitting a sequence or *frame* $\{b[0], b[1], \ldots, b[M-1]\}$ of channel symbols over a wireless channel. These symbols can be binary (e.g., ± 1), or they may take on more general values from a finite alphabet of complex numbers. In this treatment, we consider only *linear* modulation systems, in which the symbols are transmitted into the channel by being modulated linearly onto a signaling waveform to produce a transmitted signal of this form:

$$x(t) = \sum_{i=0}^{M-1} b[i] w_i(t), \tag{1.1}$$

where $w_i(\cdot)$ is the modulation waveform associated with the ith symbol. In this expression, the waveforms can be quite general. For example, a single-carrier modulation system with carrier frequency ω_c, baseband pulse shape $p(\cdot)$, and symbol rate $1/T$ is obtained by choosing

$$w_i(t) = A\, p(t - iT)\, e^{\jmath(\omega_c t + \phi)}, \tag{1.2}$$

where $A > 0$ and $\phi \in (-\pi, \pi)$ denote carrier amplitude and phase offset, respectively. The baseband pulse shape may, for example, be a simple unit-energy rectangular pulse of duration T:

$$p(t) = p_T(t) \triangleq \begin{cases} \frac{1}{\sqrt{T}}, & 0 \le t < T, \\ 0, & \text{otherwise}, \end{cases} \tag{1.3}$$

or it could be a raised-cosine pulse, a bandlimited pulse, and so on. Similarly, a direct-sequence spread-spectrum system is produced by choosing the waveforms as in (1.2) but with the baseband pulse shape chosen to be a spreading waveform:

$$p(t) = \sum_{j=0}^{N-1} c_j \psi(t - j\, T_c), \tag{1.4}$$

where N is the spreading gain, $c_0, c_1, \ldots, c_{N-1}$, is a pseudorandom spreading code (typically, $c_j \in \{+1, -1\}$), $\psi(\cdot)$ is the chip waveform, and $T_c \triangleq T/N$ is the chip interval. The chip waveform may, for example, be a unit-energy rectangular pulse of duration T_c:

$$\psi(t) = p_{T_c}(t). \tag{1.5}$$

Other choices of the chip waveform can also be made to lower the chip bandwidth. The spreading waveform of (1.4) is periodic when used in (1.2), since the same spreading code is repeated in every symbol interval. Some systems (e.g., CDMA systems for cellular telephony) operate with *long spreading codes*, for which the periodicity is much longer than a single symbol interval. This situation can be modeled by (1.1) by replacing $p(t)$ in (1.2) by a variant of (1.4) in which the spreading code varies from symbol to symbol; that is,

$$p_i(t) \;=\; \sum_{j=0}^{N-1} c_j^{(i)} \psi(t - j\,T_c). \tag{1.6}$$

Spread-spectrum modulation can also take the form of frequency hopping, in which the carrier frequency in (1.2) is changed over time according to a pseudorandom pattern. Typically, the carrier frequency changes at a rate much slower than the symbol rate, a situation known as *slow frequency hopping*; however, *fast hopping*, in which the carrier changes within a symbol interval, is also possible. Single-carrier systems, including both types of spread spectrum, are widely used in cellular standards, in wireless LANs, Bluetooth, and others (see, e.g., [42, 131, 150, 163, 178, 247, 338, 361, 362, 392, 394, 407, 408, 449, 523, 589]).

Multicarrier systems can also be modeled in the framework of (1.1) by choosing the signaling waveforms $\{w_i(\cdot)\}$ to be sinusoidal signals with different frequencies. In particular, (1.2) can be replaced by

$$w_i(t) \;=\; A\,p(t)\,e^{\jmath(\omega_i t + \phi_i)}, \tag{1.7}$$

where now the frequency and phase depend on the symbol number i but all symbols are transmitted simultaneously in time with baseband pulse shape $p(\cdot)$. We can see that (1.2) is the counterpart of this situation with time and frequency reversed: All symbols are transmitted at the same frequency but at different times. (Of course, in practice, multiple symbols are sent in time sequence over each of the multiple carriers in multicarrier systems.) The individual carriers can also be direct-spread, and the baseband pulse shape used can depend on the symbol number i. (For example, the latter situation is used in *multicarrier CDMA*, in which a spreading code is used across the carrier frequencies.) A particular case of (1.7) is OFDM, in which the baseband pulse shape is a unit pulse p_T, the intercarrier spacing is $1/T$ cycles per second, and the phases are chosen so that the carriers are orthogonal at this spacing. (This is the minimal spacing for which such orthogonality can be maintained.) OFDM is widely believed to be among the most effective techniques for wireless broadband applications and is the basis for the IEEE 802.11a high-speed wireless LAN standard (see, e.g., [354] for a discussion of multicarrier systems).

An emerging type of wireless modulation scheme is ultra-wideband (UWB) modulation, in which data are transmitted with no carrier through the modulation of extremely short pulses. Either the timing or amplitude of these pulses can be used to carry the information symbols. Typical UWB systems involve the transmission of many repetitions of the same symbol, possibly with the use of a direct-sequence type of spreading code from transmission to transmission (see, e.g., [569] for a basic description of UWB systems).

Further details on the modulation waveforms above and their properties will be introduced as needed throughout this treatment.

1.2.2 Multiple-Access Techniques

In Section 1.2.1 we discussed ways in which a symbol stream associated with a single user can be transmitted. Many wireless channels, particularly in emerging systems, operate as multiple-access systems, in which multiple users share the same radio resources.

There are several ways in which radio resources can be shared among multiple users. These can be viewed as ways of allocating regions in frequency, space, and time to different users, as shown in Fig. 1.1. For example, a classic multiple-access technique is *frequency-division multiple access* (FDMA), in which the frequency band available for a given service is divided into subbands that are allocated to individual users who wish to use the service. Users are given exclusive use of their subband during their communication session, but they are not allowed to transmit signals within other subbands. FDMA is the principal multiplexing method used in radio and television broadcast and in first-generation (analog voice) cellular telephony systems, such as the Advanced Mobile Phone System (AMPS) and Nordic Mobile Telephone (NMT), developed primarily in the 1970s and 1980s (cf. [458]). FDMA is also used in some form in all other current cellular systems, in tandem with other multiple-access techniques that are used to further allocate the subbands to multiple users.

Similarly, users can share the channel on the basis of *time-division multiple access* (TDMA), in which time is divided into equal-length intervals, which are further divided into equal-length subintervals, or time slots. Each user is allowed to transmit throughout the entire allocated frequency band during a given slot in each interval but is not allowed to transmit during other time slots when other users are transmitting. So, whereas FDMA allows each user to use part of the spectrum all of the time, TDMA allows each user to use all of the spectrum part of the time. This method of channel sharing is widely used in wireless applications, notably in a number of second-generation cellular (i.e., digital voice) sytems, including the widely used Global System for Mobile (GSM) system [178, 407, 408] and in the IEEE 802.16 wireless MAN standards. A form of TDMA is also used in Bluetooth networks, in which one of the Bluetooth devices in the network acts as a network controller to poll the other devices in time sequence.

FDMA and TDMA systems are intended to assign orthogonal channels to all active users by giving each, for their exclusive use, a slice of the available frequency band or transmission time. These channels are said to be *orthogonal* because interference between users does not, in principle, arise in such assignments (although, in practice, there is often such interference, as discussed further below). *Code-division multiple access* (CDMA) assigns channels in a way that allows all users to use all of the available time and frequency resources simultaneously, through the assignment of a pattern or code to each user that specifies the way in which these resources