Wideband Mobile Communications Principles and Applications

(Bilingual Edition)

宽带移动通信原理及应用

（双语版）

李平安 刘 泉 编著

Pingan Li Quan Liu

高等教育出版社

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内容简介

移动通信目前已发展成为宽带无线通信的主要技术之一，在 4G 标准中，许多先进的信号处理和信息传输技术得到了应用。本书以英、中双语形式系统地介绍了宽带移动通信的基本原理及相关应用，主要包括：移动通信系统介绍、宽带无线信道、数字调制技术、扩频谱调制和 OFDM 调制、信道编码、均衡与分集技术、LTE 与 LTE-Advanced 等。

全书在编写上既注重基础原理的全面性，又能突出重点，并兼顾了知识的先进性和实用性。部分章节结合实际系统应用对宽带移动通信新技术进行了介绍，如软比特解码、OFDM、OFDMA 和 SC-FDMA、Turbo 和 LDPC编码、MIMO 和空时编码、联合的均衡与分集合并技术、自适应调制与编码等。

本书前半部分为英文内容，后半部分为对应的中文内容。

本书可用作电子信息类专业及其他相关专业的本科生和研究生教材，也可供从事研究开发的工程技术人员参考和借鉴。

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Preface

Mobile wireless communications have become one of the main wideband wireless communications approaches. The International Mobile Telecommunications are currently undergoing their standardization process towards the Fourth Generation (4G), which is referred to as IMT-Advanced, given by the International Telecommunication Union (ITU). The ITU specified that the data rate of IMT-Advanced should be up to 100 Mbps for mobile communications with high mobility and 1 Gbps for low mobility in the IMT-Advanced. To meet the requirements of IMT-Advanced on peak data rates and peak spectrum efficiency, the 3^{rd} Generation Partnership Project (3GPP) organization released the 3GPP Release 10 for developing a further evolved version of the existing *Long Term Evolution* (LTE) specifications. The standard specified by 3GPP Release 10 is referred to as LTE-Advanced. In the LTE, several advanced signal processing and information transmission approaches are deployed. The key techniques in the LTE include Orthogonal Frequency Division Multiple Access (OFDMA), Single Carrier-FDMA (SC-FDMA), spatial multiplexing and antenna diversity based on Multiple Input and Multiple Output (MIMO) transmission, Turbo coding and Hybrid Automatic Repeat Request (HARQ), etc. All these technologies are good at combating frequency selective fading in wideband multi-path transmission. As a result, the peak data rates in the LTE, 3GPP Release 8, can reach 100 Mbps in the downlink and 50 Mbps in the uplink. To achieve a peak data rate of as high as 1 Gbps as required by ITU IMT-Advanced, the 3GPP organization submitted the LTE-Advanced to ITU-T in the fall 2009, in which several new technologies including wireless relay, enhanced MIMO techniques as well as carrier aggregation are introduced to further improve the spectrum efficiency of LTE, so as to approach the goals of 4G.

This book aims at providing a fundamental introduction of advanced signal processing technologies that not only have been used in 3G and LTE systems, but also will be used in the LTE-Advanced and IMT-Advanced systems. A further goal of this book is to provide readers with a comprehensive explanation of basic wireless communications principles behind these advanced technologies. After a brief introduction of wireless mobile systems in Chapter 1, various advanced signal processing technologies for wideband wireless transmission as well as their related communications principles are presented in Chapters 2 to 8. Towards the end, Chapter 9 discusses the applications of these key technologies in the design of LTE systems. The details of the chapters are summarized in the following.

In Chapter 1, after a brief introduction about the history of wireless mobile communications, cellular system principles are presented in a concise way. Specifically, the capacity of a cellular system in terms of the number of available users in a hybrid multiple access system is analyzed.

In Chapter 2, the basic wireless propagation characteristics for mobile communications are discussed, and multi-path channel modeling techniques including wideband MIMO channel modeling approaches are introduced based on the characteristic analyses of wireless wideband signal propagation.

Chapter 3 associates with the linear digital modulation techniques, focusing on comparison of spectrum efficiency and bit error ratio performance of MPSK and MQAM techniques. The linear digital modulation techniques are introduced in a concise and comprehensive manner based on a generic orthogonal modulation model. The BER analysis is based on the constellation diagrams. Particularly, a soft-bit demodulation technique based on the Log-Likelihood Ratio (LLR) is presented to provide readers with a simple but efficient soft-bit construction approach by using the constellation related to a specific linear modulation scheme. The soft-bit demodulation technique presented is commonly suitable for all the MPSK and MQAM signals, and can be directly applied to an advanced wideband wireless system with a Turbo decoder or a LDPC decoder based on soft-bit input.

Chapter 4 provides readers with a concise introduction about spread spectrum modulation and Orthogonal Frequency Division Multiplexing (OFDM) modulation. Detailed analyses are given to their principles and advantages in wideband wireless communications. Related to the OFDM technique, two multi-user access techniques, the OFDMA and the SC-FDMA, which have been used in the LTE communications, are also introduced.

In Chapter 5, principles of the linear block codes are introduced, including an introduction about the Low Density Parity Check (LDPC) codes. Basic concepts of convolutional codes and Turbo codes are also given in this chapter. Main contributions may be attributed to comprehensive decoding procedure presentation about both the LDPC codes, convolutional codes, and the Turbo codes. The decoding algorithms for both the LDPC codes and the Turbo codes are commonly based on the Maximum A Posterior (MAP) probability criterion, and utilize the soft-bit-based information iteration.

Equalization and diversity techniques are two kinds of key signal processing approaches which can be used in wideband mobile communications for implementing interference suppression and improving system capacity. Chapter 6 concentrates on introducing basic principles of channel equalization and diversity techniques, as well as presenting typical equalization and diversity techniques which have been used in 3G and LTE systems. Aside from discussion on typical diversity forms and generic diversity combining approaches, specifically, we present detailed analyses in this chapter about diversity gains and diversity orders of the three typical diversity combining techniques, the selection diversity, the equal-gain combining, and the maximal ratio combining. As an example of diversity techniques, the RAKE detection scheme which has been widely used in CDMA mobile communications is also introduced.

MIMO systems and space-time codes are discussed in Chapter 7. Multiple antennas techniques including Smart Antenna Array (SAA) techniques and generic MIMO systems have been shown to be efficient approaches for significantly improving system capacity by combating against multi-path fading in wideband wireless communications. It has been used in IEEE 802. 11n, IEEE 802. 16e, ITU 3G, as well as in 3GPP LTE and LTE-Advanced systems. In order to facilitate readers understanding practical application skills of these two kinds of multiple antenna techniques. Fundamentals of SAA techniques and MIMO systems are introduced in advance. Those include principles of smart antenna array, signal models and capacity analysis of MIMO systems, spatial diversity and spatial multiplexing approaches used in MIMO systems. We then present in this chapter a series of multi-user systems to demonstrate the practical applications of SAA and MIMO techniques, such as SAA used in the downlink and the uplink in a multi-user system, MIMO-CDMA and MIMO-OFDM wideband wireless systems. Specifically, multi-user detection in multi-user MIMO systems is analyzed, and principles of the so-called SU-MIMO and MU-MIMO techniques are discussed. In addition to multiple antenna techniques, space time coding techniques are also introduced in this chapter, including coding criteria, linear Space-time Block Codes (STBC), and Space-time Trellis Codes (STTC). The STBC-based MIMO diversity techniques within different multi-user MIMO systems are also investigated.

Chapter 8 deals with Adaptive Modulation and Coding (AMC) which is one of the most important link adaptation technologies in advanced wideband wireless systems. Basic principles of AMC are introduced. The switching threshold determination approaches, including the BER-based, the BLER-based, and the throughput-based techniques, are discussed in detail. Focusing on real world applications of AMC in MIMO-OFDM systems, a short introduction bout the per-subcarrier-based AMC techniques followed by detailed discussions about the subband-based AMC techniques for OFDM and MIMO-OFDM systems are given in this chapter. Exponential Efficient SNR Mapping (EESM) approaches for evaluating the equivalent SNRs in AWGN for OFDM systems and MIMO-OFDM systems are presented. Finally, techniques for applying AMC to retransmissions of the HARQ are discussed.

Chapter 9 is given to demonstrate the realistic applications of advanced communications techniques, aside from providing readers with an introduction about new wireless mobile communication systems. The key techniques used in the LTE and the LTE-Advanced physical layers are introduced. Assembled LTE transmitting and receiving schemes in the baseband are presented. Main signal processing techniques associating with LTE systems are discussed.

This book can be used as a textbook for senior-year undergraduates and graduate students in communication engineering as well as in electronic & information engineering, or as a reference book for engineers in communication engineering. Specifically, it can be used by Chinese undergraduates as a text book in a bilingual teaching course related to wireless communications or mobile communications.

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Authors

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Chapter 1

Introduction to Mobile Communication Systems

Wireless networks have been experiencing an explosive growth beginning from the emerging of 3rd generation mobile communication concepts. In China, to the end of May 2009, there were about 0.68 billion mobile users. By the end of 2013, however, the number of mobile users in China had been over 1.2 billion, which was about double of that evaluated in 2009 and about 4 times of the number of fixed-line phones. One of the main reasons of fast growth is due to the fact that the new technologies and products in electronic industry, communication engineering, as well as in computer networks emerge rapidly, aside from the economic benefits in practice and flexibility in applications. Exponential growth of mobile users will result in technical challenges in design of more robust wireless networks with large capacity and desirable performance. In other words, new techniques should support higher data rates or bandwidths than those used in existing systems. The peak data rate in a basic 3G system is 2 Mbps, for example, but should reach 100 Mbps in the LTE downlink according to specifications of 3GPP. The word "wideband" in mobile communications in terms of the radio propagation characteristics can be defined as that the bandwidth of signals is larger than the coherence bandwidth of channels in a wireless system, and more than one resolvable multi-path signal can be detected in the receiver. In this case, the frequency selective fading will occur, which will result in the Inter-Symbol Interference (ISI) in received signals. Details of the coherence bandwidth of wireless channels and the frequency selective fading will be discussed in Chapter 2.

1.1 Historical introduction

Wireless mobile communications was born in 1897 when Guglielmo Marconi demonstrated the first radio transmission with a ship sailing across the English Channel. In 1899, Marconi carried out another ship-based mobile communication test in New York Harbor. From 1921 to 1940, one way and two ways analogy mobile systems based on Amplitude Modulation (AM) or Frequency Modulation (FM) were tested and used in police departments in the U. S. In 1946, Domestic Public Land Mobile Radio

Service(DPLMRS) with 3 channels near 150 MHz was inaugurated in St. Louis. Early mobile services in police systems or in public mobile telephone communications are non-cellular. Capacities of these systems are limited by the assigned bandwidth of spectrum.

During the 1950s and 1960s, Bell laboratories developed the cellular theory. Frequencies can be reused within the same service area by using a cellular system to support more communication users. AT&T sent a request of spectra and a suggestion of the cellular service to the U. S. Federal Communications Commission(FCC) in 1947 and in 1968, respectively. In 1978, field tests of cellular systems were carried out —Advanced Mobile Phone Service(AMPS) in Chicago and American Radio Telephone Service(ARTS) in Washington DC. Design of the cellular system was implemented to the end of the 1960s[8]. In 1982, FCC finally allocated a 40 MHz spectrum with 666 duplex channels in the 800-900 MHz range for AMPS. AMPS was the fist U. S. cellular system deployed in 1983 by Ameritech in Chicago. In Japan, the first cellular system became operational in 1979 by Nippon Telephone and Telegraph(NTT). In 1981, Nordic Mobile Telephone System(NMTS) developed by Ericssion entered public service in Sweden. AMPS and NMTS exhibit *the first generation* (1G) technology for mobile communications. The first generation mobile systems are based on digital signaling transmissions and analog voice transmissions. Multiple users can simultaneously communicate with the Base Station(BS) by the Frequency Division Multiple Access(FDMA) approach.

The second generation (2G) of cellular mobile systems is based on digital communications. Compared to the analog systems, digital mobile systems in 2G can offer higher capacity and security, improved cost and power efficiency. In addition, they can support for international roaming and new services. In the early 1980s, analog cellular systems experienced rapid growth in Europe. Many countries developed their own systems. Each system of a country was incompatible with everyone else's in equipments and operations. The inter-operation of a mobile phone in European countries was impossible, and market for each type of equipment was limited. In 1982, the Conference of European Posts and Telegraphs (CEPT) assembled a study group called the Groupe Spécial Mobile (GSM) to develop a pan-European public mobile phone system. In 1989, work done by the GSM group was transferred to the European Telecommunication Standard Institute(ETSI), and the name was changed to Global System for Mobile Communications. Commercial service of GSM, with spectrum allocated at the 900 MHz(890-915 MHz for uplink and 935-960 MHz for downlink) band, was started in 1991. GSM is a digital system and is based on the Time Division Multiple Access(TDMA) approach. Interim Standard-54(IS-54) is the first digital North American standard for mobile communications. It was standardized by Electronic Industries Alliance (EIA) and Telecommunication Industry Association (TIA) in 1990. The spectrum used in IS-54 is the same as that in AMPS. In fact, IS-54 was designed to work in a dual mode way to maintain compatibility with the existing analog AMPS networks. By 1993, American cellular networks were again running out of capacity, and a new digital cellular standard, IS-136, was launched in American. IS-136 utilized TDMA in both voice channels and control channels, and added a number of features to the original IS-54 specifications, including text messaging, circuit switched data, and an improved compression protocol. IS-54 and IS-136 are usually called as Digital AMPS(D-AMPS). Both the IS-54 networks and the IS-136 networks are based on TDMA. In 1995, another digital cellular standard, IS-95, was commercially launched by Qualcomm. It could provide roughly ten times more capacity than analog networks by using a new multiple access approach, namely, Code Division Multiple Access(CDMA).

To develop a new generation of cellular systems to facilitate global roaming and multimedia services, the International Telecommunication Union (ITU) started *the third generation* (3G) standardization process in 1985. From 1995 to 1997, the 3G is called Future Public Land Mobile Telecommunications Systems (FPLMTS). In March 1997, ITU changed the name of 3G to International Mobile Telecommunications 2000(IMT-2000). The "2000" was used to identify not only the spectrum in which the systems were intended to operate but also the year in which the systems were likely to come to market. Between 1996 and 1998, many companies and Regional Standards Development Organizations(RSDO) proposed a total of 17 competing proposals for IMT-2000 to ITU. The evaluation of proposals was completed in 1998, and three CDMA standards combined from proposals were finally assembled, namely, WCDMA, cdma2000, and TD-SCDMA. The Wideband CDMA(WCDMA) and cdma2000 were the successor to the GSM and the successor to the IS-95, respectively, while the TD-SCDMA was a scheme developed in China. The "TD" in TD-SCDMA was used to identify the Time Division Duplex(TDD), while SCDMA to mean a synchronized CDMA scheme. In 1998, the various regional telecommunication associations interested in developing WCDMA networks banded together to conduct the 3rd Generation Partnership Project(3GPP). The initial scope of the 3GPP organization is to introduce the technical specifications and reports for a 3G system based on evolved GSM core networks. 3GPP2 is another collaboration established also in 1998 with scope for promoting cdma2000. In 2001, NTT DoCoMo launched the first commercial 3G network. In 2009, TD-SCDMA got commercial applications started in China. The maximum data rate of 3G systems can reach 2 Mbps(in doors). In mid 2000s, an enhanced 3G protocol introduced in 3GPP Release 5, namely, the High Speed Downlink Package Access(HSDPA), was begun to be implemented. It can offer a peak data rate as high as 42 Mbps. The 3GPP organization also released another protocol, HSUPA, in 3GPP Release 6 for increasing the uplink data rate of WCDMA. According to reports, the peak data rate of HSUPA can approach 7.2 Mbps. A further enhanced system, HSPA+, was released by 3GPP in 2008. HSPA+ can provide a data rate up to 84 Mbps in the downlink and 10.8 Mbps in the uplink. In 3GPP, WCDMA is a generic protocol based on the standard called Universal Mobile Telecommunications Systems (UMTS). TD-SCDMA and HSPA techniques series are extended protocols based on UMTS.

3GPP *Long Term Evolution*(LTE) is a standard for wireless data communications technology and an evolution of GSM/UMTS standards. One goal of LTE was to increase the capacity and speed of wireless data networks, and another goal was to redesign and simplify the 3G network architecture to develop an IP-based system with significantly reduced transfer latency (10 ms even less round-trip delays). Standardization work for LTE started in late 2004. By 2007, all LTE features related to its functionality were defined, and by 2008, most protocol and performance specifications were finished and included in 3GPP Release 8. LTE systems based on Release 8 should support peak data rates of 100 Mbps in the downlink and 50 Mbps in the uplink, within a 20 MHz bandwidth. It also supports mobility up to 350 km/h. LTE systems can offer great spectrum flexibility. With an overall system bandwidth that extends from 1.4 MHz to 20 MHz, LTE can operate in various frequency bands. Furthermore, LTE can operate in either paired or unpaired spectrum by working in the FDD mode or the TDD mode. In addition, adaptive coding and modulation techniques are also supported in LTE systems.

1.2 Cellular concepts

This section is to introduce the basic concepts about the cellular systems, including the cellular structure, frequency reuse, interference and signal to interference ratio, channel assignment strategies and power control, multiple access approaches, roaming and handoff.

1.2.1 Cellular structure and frequency reuse

In December 1947, Douglas H. Ring and W. Rae Young, Bell Labs engineers, recommended hexagonal cells for mobile phones in vehicles. In a cellular system, a communication area is divided into many small regions called cells. To develop the cellular communication theory, a hexagon is usually used to denote the coverage of a cell, and a Base Station (BS) is built in each cell to communicate with all the subscribers located in the cell. In a cellular system, a hand-set or a Mobile Station (MS) located in a cell cannot directly communicate with another MS by wireless channels, not to mention a fixed telephone. Signals transmitted from a mobile user, or to arrive at a user, have to pass through a BS located at the center of the cell or at a corner of the hexagon. When the BSs are located at the center of cells, the antennas of BSs should be omni-directional. If the BSs are located at the corners of hexagons rather than the centers, then directional antennas can be used to transmit/receive in three directions each towards an adjacent hexagon cell. All the base stations of a cellular system are controlled by a central switching station called Mobile Switching Center (MSC) or Mobile Telephone Switching Office (MTSO). The MSC is responsible for all kinds of network management functions such as channel allocations, handovers, billing, power control etc. The MSC is also connected to the Public Subscriber Telephone Network (PSTN) or Public Land Mobile Network (PLMN) as shown in Fig. 1.1[173] so as to allow the MS to talk to a land line telephone or vice versa.

The core principle of cellular systems is the use of multiple BSs with lower powers, each covering a small cell-region, instead of using single BS with a higher power to complete coverage of a communication area. All the cells are classified into several groups. Each group called a cluster contains several neighboring cells and is assigned the whole spectrum. Let us assume that the whole available spectrum contains $N = MK$ frequency channels, and each cluster contains K cells, where K is usually called the cluster size with typical values 4, 7 and 12. Each cell or BS will use $M = N/K$

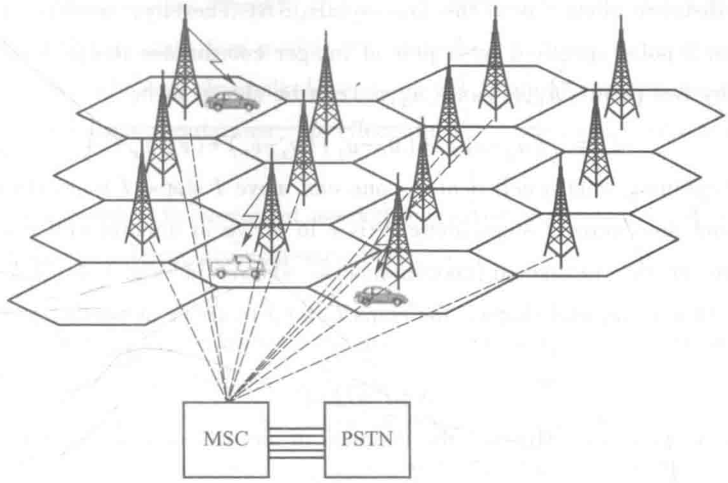

Fig. 1.1 A cellular system[173]

frequency channels. As a result, the total N channels can be reused in every cluster. Fig. 1.2 demonstrates a cellular scheme. In this scheme, three clusters each with 7 cells are assumed for frequency reuse. The total N available frequency channels are divided into $K = 7$ groups and each cell occupies $M = N/7$ channels. That is, each cell will use one seventh the total available spectrum. Therefore, 1/7 ($1/K$) is usually called the frequency reuse factor. In a cellular system, the cells with the same channel group are allocated at the same site in every cluster. For example, all the cells denoted by Cell 1 in Fig. 1.2 and allocated at the centers of clusters will use the same frequency channels. In a cellular system, the use of same frequency channels in more than one cell will introduce the Co-channel Interference (CCI) to the system if the interspacing between a pair cells is not far enough. Fortunately, we can choose the cell size, the cluster size and the transmit power of each BS to maintain the CCI lower than a desired level. This is attributed to the fact that the power of signals will fall when increasing the propagation distance. Under a power lever, any radio link will not cause significant interference to another radio link with the same communication spectrum.

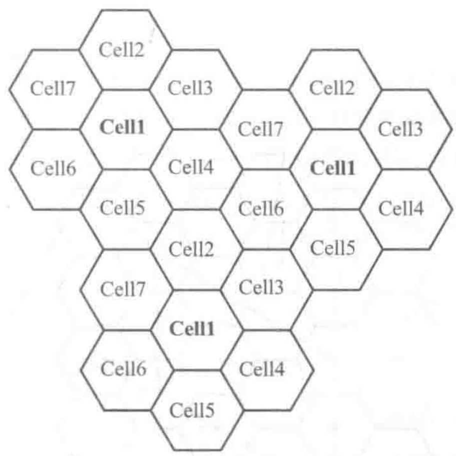

Fig. 1.2 A frequency reuse scheme

To explore the geometrical relationship of adjacent co-channel cells, let us use d, D, and R to denote the interspacing between any two neighboring cells, the distance between any two adjacent co-channel cells, and the cell radius, respectively, as shown in Figs. 1.3 and 1.4. The radius is defined as the distance from the center of a cell to any of its vertices. Fig. 1.3 shows the most convenient set of coordinates for hexagonal geometry. The positive halves of the two axes intersect at a