OFDM Baseband Receiver Design for Wireless Communications

Tzi-Dar Chiueh
National Taiwan University, Taiwan

Pei-Yun Tsai
National Central University, Taiwan
OFDM Baseband Receiver Design
for Wireless Communications
OFDM Baseband Receiver Design for Wireless Communications

Tzi-Dar Chiueh
National Taiwan University, Taiwan

Pei-Yun Tsai
National Central University, Taiwan
To my Dad Chin-Mu, my wife Jill, my daughter Joanne, and my son Kevin.

–Tzi-Dar Chiueh

To my families for their constant encouragement and support.

–Pei-Yun Tsai
Contents

Preface xi

About the Authors xv

Acknowledgements xvii

1. Introduction 1
   1.1 Wireless Communication Systems 1
       1.1.1 Digital Broadcasting Systems 1
       1.1.2 Mobile Cellular Systems 3
       1.1.3 Wireless Network Systems 5

2. Digital Modulation 9
   2.1 Single-Carrier Modulation 9
       2.1.1 Power Spectral Densities of Modulation Signals 11
       2.1.2 PSK, QAM and ASK 11
       2.1.3 CPFSK and MSK 14
       2.1.4 Pulse Shaping and Windowing 15
   2.2 Multi-Carrier Modulation 17
       2.2.1 Orthogonal Frequency-Division Multiplexing 19
       2.2.2 OFDM-Related Issues 19
       2.2.3 OFDM Transceiver Architecture 24
       2.2.4 OFDM System Examples 26

Bibliography 28
3. Multiple Access and Error-Correcting Codes 31

3.1 Multiple Access 31
   3.1.1 Frequency-Division Multiple Access (FDMA) 31
   3.1.2 Time-Division Multiple Access (TDMA) 31
   3.1.3 Code-Division Multiple Access (CDMA) 33
   3.1.4 Carrier Sense Multiple Access (CSMA) 34

3.2 Spread Spectrum and CDMA 35
   3.2.1 PN Codes 35
   3.2.2 Direct-Sequence Spread Spectrum 38
   3.2.3 Frequency-Hopping Spread Spectrum 40

3.3 Error-Correcting Codes 41
   3.3.1 Block Codes 42
   3.3.2 Reed-Solomon Codes 45
   3.3.3 Convolutional Codes 48
   3.3.4 Low-Density Parity-Check Codes 53

Bibliography 56

4. Signal Propagation and Channel Model 59

4.1 Introduction 59

4.2 Wireless Channel Propagation 59
   4.2.1 Path Loss and Shadowing 60
   4.2.2 Multipath Fading 61
   4.2.3 Multipath Channel Parameters 62

4.3 Front-End Electronics Effects 68
   4.3.1 Carrier Frequency Offset 68
   4.3.2 Sampling Clock Offset 69
   4.3.3 Phase Noise 70
   4.3.4 IQ Imbalance and DC Offset 70
   4.3.5 Power Amplifier Nonlinearity 73

4.4 Channel Model 74
   4.4.1 Model for Front-End Impairments 75
   4.4.2 Multipath Rayleigh Fader Model 77
   4.4.3 Channel Models Used in Standards 78

Bibliography 84

5. Synchronization 85

5.1 Introduction 85

5.2 Synchronization Issues 86
   5.2.1 Synchronization Errors 86
   5.2.2 Effects of Synchronization Errors 86
   5.2.3 Consideration for Estimation and Compensation 90

5.3 Detection/Estimation of Synchronization Errors 91
   5.3.1 Symbol Timing Detection 91
   5.3.2 Carrier Frequency Offset Estimation 100
9. Circuit Techniques

9.1 Introduction

9.2 FFT
  9.2.1 FFT Algorithms
  9.2.2 Architecture
  9.2.3 Comparison

9.3 Delay Buffer
  9.3.1 SRAM/Register File-Based Delay Buffer
  9.3.2 Pointer-Based Delay Buffer
  9.3.3 Gated Clock Strategy
  9.3.4 Comparison

9.4 Circuits for Rectangular-to-Polar Conversion
  9.4.1 Arctangent Function
  9.4.2 Magnitude Function
  9.4.3 Comparison

9.5 Circuits for Polar-to-Rectangular Conversion
  9.5.1 Trigonometric Approximation
  9.5.2 Polynomial Approximation
  9.5.3 Comparison

Bibliography

10. System Examples

10.1 MC-CDMA Downlink Receiver IC
  10.1.1 System Description
  10.1.2 Transmitter and Receiver Design
  10.1.3 Circuit Design
  10.1.4 Experimental Results

10.2 MIMO–OFDM Cognitive Radio Receiver IC
  10.2.1 System Overview
  10.2.2 Architecture and Circuit Design
  10.2.3 Experimental Results

Bibliography

Index
Preface

Orthogonal frequency-division multiplexing (OFDM) has become the favorite modulation technology for wireless communication systems. To address the needs of OFDM receiver design, we have developed this book based on course materials for a class in digital communication IC design. This book is ideal for advanced undergraduate and post-graduate students from either VLSI design or signal processing backgrounds. For engineers working on algorithms or hardware of wireless communications systems, this book provides a comprehensive understanding of the state-of-the-art OFDM design technology and will be a valuable reference.

The topics in this book include theories, algorithms, architectures and circuits of OFDM wireless communication systems. One special feature of this book lies in last three chapters, from which our readers can learn how to develop signal processing algorithms oriented from hardware implementation and how to design ICs for wireless OFDM systems. These techniques are lively illustrated through two design examples dealing with two OFDM systems that currently attract much attention–MC-CDMA for future cellular communications and MIMO–OFDM for next-generation WLAN with cognitive radio capability.

This book is organized into three parts. The first part of the book aims at reviewing background knowledge that includes fundamentals of modulation and communication, signal propagation and channel modeling. In this part, ideas behind formulas, rather than mathematical derivations, are emphasized and several examples are provided to allow easy comprehension of the concepts. In the second part, in-depth treatment of two essential signal processing tasks–synchronization and channel estimation–is offered. Then, MIMO (multiple-input multiple-output) techniques with their application to OFDM systems are also delineated. This part of the book aims to present the readers with modern signal-processing algorithms in OFDM baseband receivers. The third part of the book talks about hardware design, from design methodology to design of essential blocks. Finally, the book ends with a couple of examples that cover the latest OFDM receiver IC developments. The following gives a more detailed description of the content in each chapter.
Chapter 1 reviews several important wireless communication standards, including digital broadcasting systems, mobile cellular systems and wireless data network systems. Without exception, OFDM is the modulation scheme of choice for all standards, exemplifying the importance of OFDM technology in wireless communications.

Chapter 2 discusses digital modulation techniques, including both single-carrier modulation and multi-carrier modulation. The introduction to conventional single-carrier modulation techniques serves as the basis for explaining the multi-carrier OFDM modulation. Basic OFDM processing operations, such as discrete Fourier transform (DFT)/inverse discrete Fourier transform (IDFT), guard interval insertion, guard-band reservation and spectrum shaping, are addressed. The phenomenon of high peak-to-average power ratios in OFDM modulation signals is also illustrated. Then, several standards are described to exemplify OFDM system parameters, such as the fast Fourier transform (FFT) size, guard-interval ratio and guard band ratio with regard to Doppler frequency and channel maximum excess delay.

Multiple access schemes, meaning to support a number of users in the same communication link, are discussed in Chapter 3. In addition, spread spectrum techniques, from which CDMA is derived, are illustrated. In that section, several important codes popularly used in CDMA and spread spectrum systems are also presented. Error-correcting codes, indispensable in digital communication systems, are introduced subsequently. Several prevailing error-correcting codes and their decoding strategies are covered. They include convolutional codes, Reed-Solomon codes and low-density parity check (LDPC) codes.

Wireless receiver design is impossible without a thorough understanding of the impairments to signals during propagation. Chapter 4 discusses propagation mechanisms, fading phenomena and other non-ideal effects in the channel and transceiver front-ends. Passing through a wireless channel, communication signals suffer from path loss and a shading effect, which prominently weaken received signal strength. In addition, delay spread, Doppler spread and angle spread in the signal are possible and they produce signal replicas with different arrival times, distorted spectra and incident angles. Front-end electronic non-ideality must also be taken into consideration when designing wireless receivers. Oscillator mismatch as well as relative motion between the transmitter and the receiver causes carrier frequency offset and sampling clock offset. Unmatched branches in the up-/down-conversion path may result in I–Q imbalance and DC offset. A power amplifier with limited linear region is another source of amplitude and phase distortion. In Chapter 4, details about all of the above will be presented.

Synchronization is one of the critical issues in all communication systems, wired and wireless alike. Algorithms for synchronizing the phase and frequency of the carrier signal as well as the sampling clock signal in OFDM receivers are the main topic of Chapter 5. The chapter starts with descriptions of carrier frequency offset, carrier phase error, sampling clock offset and symbol timing offset and their impacts on the received OFDM signals. For each synchronization error, several estimation algorithms with performance comparison are presented. Then time-domain and frequency-domain compensation approaches are introduced. Their pros and cons are also given to help the designers to make knowledgeable and appropriate decisions for their designs.

Chapter 6 concentrates on the channel estimation tasks in OFDM receivers. To perform channel estimation, a receiver often relies on some reference signals, such as the preamble and the pilot signals. As a result, channel estimation algorithms are categorized according to the available reference signal pattern. Channel statistics and characteristics of channel
power-delay profiles can also be exploited to obtain better estimation results. Although one prominent advantage of OFDM lies in its simple yet effective one-tap equalization, this chapter will discuss multiple-tap equalizers in OFDM receivers, as they are needed more and more due to inter-carrier interference caused by mobile channels.

As multiple-input multiple-output (MIMO) techniques continue to show promising results in enhancing communication performance in regard to transmission efficiency and quality of service, MIMO has become a very important topic. In Chapter 7, the multiple antenna configurations are first discussed, and then MIMO–OFDM systems are described. New pilot patterns and modified synchronization and channel estimation for MIMO–OFDM systems are presented. Then, the chapter goes on to discuss several MIMO techniques, such as space–time block codes, spatial multiplexing, spatial decorrelation/beam-forming and their detection methods.

Chapter 8 presents the hardware design methodology for communication receiver design. Systematic approaches to map the system-level and the algorithm-level design to the architecture-level and the circuit-level description are first delineated. The effects of finite precision and clipping in analog-to-digital converters (ADC) and limited word-lengths of data path signals are discussed. Specifically, word-length optimization for hardware functional blocks is illustrated. The propagation of quantization errors and the change in signal dynamic range after several common fixed-point arithmetic operations in communication circuits are illustrated. The chapter ends with the introduction of techniques for converting a design in floating-point arithmetic to a corresponding fixed-point design.

Chapter 9 illustrates architectures and circuits that are widely used in OFDM systems, including fast Fourier transform (FFT) processors, delay buffers, circuits for rectangular-to-polar conversion and polar-to-rectangular conversion. A couple of hardware-oriented FFT algorithms are first introduced, followed by several FFT architectures. Pipelined architectures can perform FFT at sample rate, though consuming more hardware resources. On the other hand, memory-based architectures are area-efficient, but may require higher clock rate and complicated control in memory addressing. A delay buffer can be efficiently implemented in shift registers or SRAMs, depending on its length. The chapter also presents several circuits for rectangular-to-polar conversion, which are needed when the phase or magnitude of a complex value is desired. Furthermore, circuits for polar-to-rectangular conversion, needed to generate sinusoidal waveforms, are also introduced at the end of this chapter.

Finally, in the tenth chapter of the book, two OFDM receiver designs are reported. First, a downlink MC-CDMA baseband receiver for future mobile cellular communications is introduced in detail. Then, the design of a cognitive-radio receiver using MIMO–OFDM technology is given. With these two examples, the readers can comprehend firsthand how the algorithms and circuits introduced in the book can be applied in real-life designs.

T. D. Chiueh and P. Y. Tsai
Taipei, Taiwan
About the Authors

The authors and their groups at the National Taiwan University, Taipei, Taiwan, and the National Central University, Taoyuan, Taiwan, have been doing research in wireless communication baseband IC design for more than a decade, focusing especially on OFDM (orthogonal frequency-division multiplexing) systems recently. The research results have been published in important international journals and conferences, and are recognized by domestic and international awards.

**Tzi-Dar Chiueh** received his Ph.D. in electrical engineering from the California Institute of Technology in 1989 and he is now a Professor of Electrical Engineering at the National Taiwan University (NTU). Since August 2004, he has also served as the Director of the Graduate Institute of Electronics Engineering at the same university. He has held visiting positions at ETH Zurich Switzerland and at the State University of New York at Stony Brook. Professor Chiueh has received the Acer Longtern Award 11 times and the MXIC Golden Silicon Award in 2002 and 2005. His teaching efforts were recognized four times by the Teaching Excellence Award from the NTU. Professor Chiueh was the recipient of the Distinguished Research Achievements Award from the National Science Council, Taiwan, in 2004, and was awarded the Himax Chair Professorship at the NTU in 2006. He is the author of more than 140 technical papers, many of which are on algorithm, architecture and integrated circuits for baseband communication systems.

**Pei-Yun Tsai** received her Ph.D. in electrical engineering from the National Taiwan University in 2005 and she is now an Assistant Professor of Electrical Engineering at the National Central University, Taoyuan, Taiwan. Professor Tsai has received the Acer Longtern Award, MXIC Golden Silicon Award and 1st Asian Solid-State Circuit Conference Student Design Contest Outstanding Award in 2005. Her research interests include signal-processing algorithms and architectures for baseband communication systems.
Acknowledgements

First of all, the authors would like to thank the contribution of Dr Ming-Luen Liu from Mediatek, Inc., Hsinchu, Taiwan, for writing an important part of this book: Chapter 8, and the contribution of Mr. Po-An Chen for the second example in Chapter 10. We would also like to thank the reviewers: Professor Yuan-Hao Huang and Professor Hsin-Pin Ma of the National Tsing Hua University, Hsinchu, Taiwan; Chun-Hao Liao, Yen-Shuo Chang, Jun-Wei Lin, Jin-Hao Yu, Chun-Hao Liu, Yu-Yen Chen, Chien-Yi Wang, Jing-Yeu Yang, all of the Graduate Institute of Electronics Engineering, National Taiwan University. Their valuable comments have greatly improved the content of this book.

Tzi-Dar Chiueh also wishes to thank all former and current students of his MicroSystem Research Laboratory (MSRL) at the National Taiwan University for their tremendous research work. Last, but not least, the constant encouragement from Professor Liang-Gee Chen from the NTU for the development of this book’s materials is appreciated.
1
Introduction

All wireless communication standards, existing and under development, adopt or consider adopting orthogonal frequency-division multiplexing (OFDM) as the modulation technique. It is clear that OFDM has become the definitive modulation scheme in current and future wireless communication systems.

1.1 Wireless Communication Systems

Pursuance for better ways of living has been instrumental in advancing human civilization. Communication services available at any time and place free people from the limitation of being attached to fixed devices. Nowadays, thanks to the remarkable progress in wireless technology, affordable wireless communication service has become a reality. Mobile phones hook people up whenever and wherever they want. Digital audio and video broadcasting offers consumers high-resolution, better-quality and even interactive programmes. The devices are now thin, light, small and inexpensive. Furthermore, smart mobile phones capable of multimedia and broadband internet access are showing up on the shelves.

Several projects studying wireless networks with different extents of coverage are under way. They will enable wireless access to internet backbone everywhere, either indoors or outdoors and in rural or metropolitan areas. In the following, their evolution and future developments will be introduced. The essential role that the orthogonal frequency-division multiplexing (OFDM) technique plays in wireless communication systems will also become very clear.

1.1.1 Digital Broadcasting Systems

In the modern world, most people fill the need for information and entertainment through audio and video broadcasting. The inauguration of AM radio can be traced back to the early twentieth century, whilst analog TV programmes were first broadcast before the Second World War. Around the middle of twentieth century, FM radio programmes became available. These technologies, based on analog communication, brought news, music, drama, movies and much more into our daily lives. To provide more and better programmes, digital broadcasting techniques, such as digital audio broadcasting (DAB) and digital video broadcasting (DVB), began to replace the analog broadcasting technologies in the past several years.
Digital Audio Broadcasting (DAB)

DAB is among the first standards that use the OFDM technique. The DAB project started in mid-1980 [1]. Based on OFDM, DAB has one distinct benefit: a single-frequency network (SFN). In a single frequency broadcasting network, one carrier frequency can be used for all transmitters to broadcast the same radio programme in the entire country without suffering from co-channel interference. On the other hand, in the FM system, only one out of approximately 15 possible frequencies can be used, resulting in a very inefficient frequency re-use factor of 15. A single-frequency network and a multi-frequency network are illustrated in Figure 1.1.

In the DAB system, it is not necessary to search for radio stations as is necessary with AM/FM radios. The programmes of all radio stations are integrated in so-called multiplexes. Multiplexes save on the maintenance cost of individual radio stations. In addition, variable bandwidths can be assigned to each programme, fulfilling their respective demands for sound quality. Music radio multiplexes can transmit at a rate up to the highest-quality 192 Kbps, while mono talk and news programmes may use only 80 Kbps. Furthermore, the DAB system features better mobile reception quality thanks to the OFDM technique.

Digital Video Broadcasting (DVB)

DVB is the European standard for digital television broadcasting [2]. The DVB standards include DVB-S for satellites, DVB-C for cables, DVB-T for terrestrial transmission and DVB-H for low-power handheld terminals. Among them, DVB-T and DVB-H utilize OFDM as the modulation scheme. DVB-T receivers started shipping in late-1990 and now digital DVB-T programmes are available in many countries. As the DAB system, DVB-T/H technology also supports countrywide single-frequency networks. In addition, DVB-T/H standards offer several modes of operation that are tailored for large-scale SFN and high-mobility reception.
The basic digital stream in DVB-T is the MPEG-2 transport stream that contains one or more programme streams. Each stream multiplexes compressed video, audio and data signals. The DVB-T standard can support a data rate of MPEG-2 high-definition TV (HDTV), which is up to 31 Mbps. In DVB-H, high-speed IP services as an enhancement of mobile telecommunication networks are offered. Moreover, DVB standard has allowed for integration with bi-direction data connections through other access technology, thus enabling interactive applications between the viewers and the TV stations.

1.1.2 Mobile Cellular Systems

Mobile phones are now a necessity to several billions of people in the world. Their functionalities range from voice service to picture, video and broadband data services. Figure 1.2 shows the migration from the second-generation (2G) to the third-generation (3G), and then onward to the fourth-generation (4G) mobile cellular communication systems. In 2G, the GSM system is used as the European standard and CDMAOne 1X is adopted in North America. Both of them offer digital voice services at around 10 Kbps. Afterwards, General Packet Radio Service (GPRS) and Enhanced Data rate for Global Evolution (EDGE) systems provide transmission rates of up to several hundreds of Kbps as an enhancement of the GSM standard. Similarly, CDMA2000 1X upgraded the data transmission to 300 Kbps in North America.

Currently, 3G standards provide data services with a data rate of up to 2 Mbps to accommodate multimedia applications. Two main-stream 3G standards are CDMA2000 1X and wideband-CDMA (W-CDMA). The enhanced version of W-CDMA has been standardized as High Speed Downlink Packet Access (HSDPA), which is regarded as 3.5G and can achieve about a 10-Mbps transmission rate. The third-Generation Partnership Project (3GPP) long-term evolution (LTE) has started to plan possible solutions to future mobile communication technology. The main features include [3]:

![Evolution of major mobile cellular communication systems](image-url)
• spectral efficiency up to 10 b/s/Hz;
• provision of a flexible radio resource management to enlarge cell coverage and improve system efficiency;
• supporting internet protocol version 6 (IPv6) multimedia services with low power consumption and high performance; and
• supporting mobility up to 250 Km/hr.

In order to satisfy high spectral efficiency, low power consumption and excellent performance requirements, advanced techniques are necessary in any future 4G system.

Modulation

In the downlink 3GPP-LTE evolved universal terrestrial radio access (E-UTRA) project, OFDM is considered as the modulation scheme [4]. OFDM has the distinct advantage that it can combat frequency-selective fading channels, which is quite a challenge for receivers of wideband systems. Additionally, OFDM can achieve efficient spectrum utilization, flexible subcarrier allocation and adaptable subcarrier modulation [3].

MIMO

Multiple antennas can be used at the transmitter and at the receiver of a communication system. Such systems are called multiple input and multiple output (MIMO) systems. MIMO systems may be implemented in several different ways and can be categorized into three types. The first type of MIMO system provides spatial diversity and enhances power efficiency. It includes space–time/frequency block code (STBC/SFBC), space–time trellis code (STTC) and delay diversity systems. The second type of MIMO system implements spatial multiplexing to increase its transmission rate. Independent data streams are transmitted over a group of antennas. At the receiver, signals from several antennas are detected and the transmitted information recovered. In the third type of MIMO system, some capacity gain can be achieved over non-MIMO systems by pre-processing the signals to be transmitted according to the channel characteristics and then decoding the received signals accordingly.

Link Adaptation

Link adaptation algorithms, composed of adaptive modulation and coding (AMC), are also regarded as one prominent technique for future communication systems. Its basic concept is to adapt transmission parameters according to channel conditions. Modulation schemes and rates for forward-error-correction codes are the fundamental adaptable parameters. Other parameters, such as power levels, signal bandwidth and spreading factor in spread spectrum and CDMA systems, are also settings that can be adjusted [5].

Radio Resource Management

Flexible radio resource management (RRM) policies become indispensable in future wireless systems as users with various multimedia applications require different quality of service (QoS). Three major topics include scheduling, power control and interference
mitigation. Scheduling is very crucial in that a large number of different applications need to be supported. Priority-based management of different queues must be supported to satisfy all sorts of QoS requirements and cope with a variety of traffic flows [5]. Power-control algorithms, on the other hand, are designed to minimize overall power consumption. The benefits brought about by power control are lower interference level and longer battery life. Finally, the interference mitigation methods include interference randomization, interference cancellation and interference avoidance.

### 1.1.3 Wireless Network Systems

Bluetooth and IEEE 802.11 wireless local area network are two famous wireless networks. Actually, the Institute of Electrical and Electronics Engineers (IEEE) has already defined several wireless data network standards, from small-area to large-area, as depicted in Figure 1.3. The smallest one is the wireless personal area network (PAN), which covers only several meters around a user. Operating in a bigger environment than wireless PAN, the IEEE 802.11 wireless local area network (LAN) is by far the most successful and prevalent wireless computer network standard. In wireless LAN, short-distance communications within several tens of meters and up to 100 meters are provided. The metropolitan area network (MAN) extends its coverage to several kilometers—the range of typical cells in urban areas. The wide-area network (WAN) is the standard with the largest coverage and it supports communications over up to tens of kilometers, including hilly terrains and rural areas. With all these networks, uninterrupted internet access can be made available whenever and wherever the users desire.

**Personal Area Network (PAN)**

The IEEE 802.15 working group is responsible for the standardization of wireless PAN [6]. Portable and mobile infotainment products such as cameras, personal digital assistants (PDAs) and handsets can benefit greatly from incorporating the function of wireless PAN connection. Several projects are coordinated by the IEEE 802.15 working group. IEEE 802.15.1 was developed based on the Bluetooth standard. In the enhanced data rate (EDR)
standard of Bluetooth 2.0, scatter ad hoc connections (shown in Figure 1.4(a)) with a peak data rate of 2.178 Mbps is achieved. The frequency band used is the industrial, scientific and medical (ISM) band at 2.4 GHz.

The IEEE 802.15.3 task group works on high-rate, low-cost and low-power solutions. The standard was released in 2003. It adopts ad hoc peer-to-peer networking and supports data rates from 11 to 55 Mbps. In 2002, a project authorization request (PAR) initiated the development of a high-data-rate ultra wide-band (UWB) standard as the IEEE 802.15.3a standard, which was regarded as an enhanced amendment for high-speed multimedia and imaging applications to the IEEE 802.15.3 standard. UWB communications are defined as systems whose emitted signal bandwidths exceed 500 MHz or 25% of the carrier frequency. Two proposals were presented: multi-band orthogonal frequency-division multiplexing (MB-OFDM) and direct-sequence UWB (DS-UWB). Formed in 2005, the IEEE 802.15.3c group endeavoured to develop alternative physical layer solutions exploiting millimeter waves—the band around 57–64 GHz, to be specific. This standard is geared towards short-range applications that require very high data rates of up to 2 Gbps, such as real-time high-definition video streaming.

On the other hand, the IEEE 802.15.4 standard aims to provide a wireless solution with a low data rate but low power consumption and longer battery life. The target applications include house automation, remote control and toy interaction. This standard operates in the ISM radio bands: 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz in most countries. Data rates of 250, 40 and 20 Kbps are supported with very low-complexity devices to allow years of operation.

**Local Area Network (LAN)**

The working group of IEEE 802.11, also known as WiFi, defines a series of wireless LAN standards [7]. Unlike the scatter ad hoc network of wireless PAN, the 802.11 wireless LAN standard...
adopts cellular radio architecture using base stations, called access points (AP), to control the traffic to/from the subscriber station (SS) within their respective cells, as shown in Figure 1.4(b). The access points are usually connected to a wireline backbone to set up links to the internet.

The first IEEE 802.11 standard was released in 1997 using either frequency hopping spread spectrum (2.4 GHz), direct sequence spread spectrum (2.4 GHz) or infrared (IR) as the transmission technology. The supported data rates were 1 and 2 Mbps. Two years later, IEEE 802.11b, which uses a complementary code keying (CCK) modulation scheme, was ratified as an amendment. It extends the transmission rate to 5.5 and 11 Mbps. With a data rate that was five times higher than the previous generation, IEEE 802.11b products suddenly became very popular in the market. Simultaneously, in 1999, another OFDM wireless LAN standard (IEEE 802.11a) was proposed and it increased the maximum data rate to 54 Mbps. Because the 2.4 GHz ISM band is very crowded, IEEE 802.11a uses another band at around 5 GHz with a low level of interference. Unfortunately, a higher carrier frequency incurs more penetration loss and also increases the cost of radio-frequency components. As a result, IEEE 802.11g was approved in 2003 to transmit at 2.4 GHz using the same OFDM technique as in IEEE 802.11a and yet achieving a data rate of up to 54 Mbps. In addition, IEEE 802.11g is backward compatible to IEEE 802.11b. It has so many conveniences and advantages that IEEE 802.11g or dual-band (2.4/5 GHz), tri-mode (11a/b/g) products are now very well received in the market.

In 2004, a new task group (IEEE 802.11n) was formed to increase the wireless LAN data rate further. A very aggressive spectral efficiency higher than 15 bps/Hz is proposed and it needs to offer interoperability with existing 802.11a/b/g networks. Wireless technologies including OFDM modulation and MIMO techniques with up to four antennas are adopted. Other measures put forward in the 802.11n proposals are higher code rate, low-density parity check code (LDPC), 20/40MHz channelization and reduction in guard interval overhead.

**Metropolitan Area Network (MAN)**

The 802.16 is the IEEE standard for a wireless MAN, sometimes also dubbed WiMAX [8]. It specifies an air interface for fixed and broadband wireless access systems and aims to provide a solution to the so-called ‘last-mile’ internet connection problem. In the countryside, deployment of wired digital subscriber loop (DSL), cable or optical fibre can be very expensive. On the contrary, with the wireless IEEE 802.16 networks, residents in rural areas can connect to the internet effortlessly.

Originally, the 802.16 and 16c defined a single-carrier system operating at frequencies ranging from 10 to 66 GHz. Later, the 802.16a defined several modes, such as single-carrier, OFDM and orthogonal frequency-division multiple access (OFDMA), in licensed and unlicensed bands from 2 to 11 GHz. The 802.16-2004, originally known as the 802.16d, includes the standards defined in the 802.16/16c and 16a. One year later, the 802.16e-2005 proposed a revision with more enhanced mobility than the 802.16d and it was thus called mobile WiMAX. The major revision is a scalable OFDM scheme in the OFDMA mode to restrict the Doppler effect regardless of the bandwidth used. In addition, the highest carrier frequency was reduced from 11 to 6 GHz. The new standard also incorporated several MIMO techniques to enhance its performance in terms of coverage, frequency re-use and bandwidth efficiency.
Wide Area Network (WAN)

The wireless network with maximum coverage is the WAN, also called mobile broadband wireless access (MBWA) [9]. The working group was established in 2002 with a scope to provide IP services with full mobility of up to 250 Km/hr in cells with a radius of tens of kilometers. 802.22 networks operate with a carrier frequency below 3.5 GHz. In the draft, a combination of the OFDM scheme and MIMO techniques was considered.

In Figure 1.5, the mobility and data rate of several wireless data communication network standards are illustrated. The IEEE 802.11n wireless LAN provides the highest transmission rate but can only be used in fixed reception. On the other hand, IEEE 802.20 and 3GPP-LTE E-UTRA support the highest mobility of 250 Km/hr with a data rate possibly approaching 100 Mbps. Note that all these advanced standards have one feature in common, namely they all use OFDM. This illustrates the fact that OFDM is and will be the modulation technology of choice in wireless communications.

Bibliography