Chapter 1

Introduction

1.1 Aim of this book

The pervasive use of wireless communications is more and more conditioning lifestyle and working habits in many developed countries. Examples of this trend are the ever increasing number of users that demand Internet connection when they are traveling, the use of cellular phones to check bank accounts and make remote payments, or the possibility of sharing moments in our lives with distant friends by sending them images and video clips. In the last few years, the proliferation of laptop computers has led to the development of wireless local area networks (WLANs), which are rapidly supplanting wired systems in many residential homes and business offices. More recently, wireless metropolitan area networks (WMANs) have been standardized to provide rural locations with broadband Internet access without the costly infrastructure required for deploying cables. A new generation of wireless systems wherein multimedia services like speech, audio, video and data will converge into a common and integrated platform is currently under study and is expected to become a reality in the near future.

The promise of portability is clearly one of the main advantages of the wireless technology over cabled networks. Nevertheless, the design of a wireless communication system that may reliably support emerging multimedia applications must deal with several technological challenges that have motivated an intense research in the field. One of this challenge is the harsh nature of the communication channel. In wireless applications, the radiated electromagnetic wave arrives at the receiving antenna after being scattered, reflected and diffracted by surrounding objects. As a result, the receiver observes the superposition of several differently attenuated and delayed copies of the transmitted signal. The constructive or destructive combination of these copies induces large fluctuations in the received signal strength with a corresponding degradation of the link quality. In addition, the characteristics of the channel may randomly change in time due to unpredictable variations of the propagation environment or as a consequence of the relative motion between the transmitter and receiver. A second challenge is represented by the limited amount of available radio spectrum, which is a very scarce and expensive resource. It suffices to recall that European telecommunication companies spent over 100 billion dollars to get licenses for third-generation cellular services. To obtain a reasonable return from this investment, the purchased spectrum must be used as efficiently as possible. A further impairment of wireless transmissions is the relatively high level of interference arising from channel reuse. Although advanced signal processing techniques based on multiuser detection have recently been devised for interference mitigation, it is a fact that mobile wireless communications will never be able to approach the high degree of stability, security and reliability afforded by cabled systems. Nevertheless, it seems that customers are ready to pay the price of a lower data throughput and worse link quality in order to get rid of wires.

The interest of the communication industry in wireless technology is witnessed by the multitude of heterogeneous standards and applications that have emerged in the last decade. In the meantime, the research community has worked (and is still working) toward the development of new broadband wireless systems that are expected to deliver much higher data rates and much richer multimedia contents than up-to-date commercial products. The ability to provide users with a broad range of applications with different constraints in terms of admissible delay (latency), quality of service and data throughput, demands future systems to exhibit high robustness against interference and channel impairments, as well as large flexibility in radio resource management. The selection of a proper air-interface reveals crucial for achieving all these features. The multicarrier technology in the form of orthogonal frequency-division multiplexing (OFDM) is widely recognized as one of the most promising access scheme for next generation wireless networks. This technique is already being adopted in many applications, including the terrestrial digital video broadcasting (DVB-T) and some commercial wireless LANs. The main idea behind OFDM is to split a high-rate data stream into a number of substreams with lower rate. These substreams are then transmitted in parallel over orthogonal subchannels characterized by partially overlapping spectra. Compared to single-carrier transmissions, this approach provides the system with increased resistance against narrowband interference and channel distortions. Furthermore, it ensures a high level of flexibility since modulation parameters like constellation size and coding rate can independently be selected over each subchannel. OFDM can also be combined with conventional multiple-access techniques for operation in a multiuser scenario. The most prominent scheme in this area is represented by orthogonal frequency-division multiple-access (OFDMA), which has become part of the emerging standards for wireless MANs.

Even though the concept of multicarrier transmission is simple in its basic principle, the design of practical OFDM and OFDMA systems is far from being a trivial task. Synchronization, channel estimation and radio resource management are only a few examples of the numerous challenges related to multicarrier technology. As a result of continuous efforts of many researchers, most of these challenging issues have been studied and several solutions are currently available in the open literature. Nevertheless, they are scattered around in form of various conference and journal publications, often concentrating on specific performance and implementation issues. As a consequence, they are hardly useful to give a unified view of an otherwise seemingly heterogeneous field. The task of this book is to provide the reader with a harmonized and comprehensive overview of new results in the rapidly growing field of multicarrier broadband wireless communications. Our main goal is to discuss in some detail several problems related to the physical layer design of OFDM and OFDMA systems. In doing so we shall pay close attention to different trade-offs that can be achieved in terms of performance and complexity.

1.2 Evolution of wireless communications

Before proceeding to a systematic study of OFDM and OFDMA, we think it useful to review some basic applications of such schemes and highlight the historical reasons that led to their development. The current section is devoted to this purpose, and illustrates the evolution of wireless communication systems starting from the theoretical works of Maxwell in the nineteenth century till the most recent studies on broadband wireless networks. Some historical notes on multicarrier transmissions are next provided in the last section of this introductory chapter.

1.2.1 *Pioneering era of wireless communications*

The modern era of wireless communications began with the mathematical theory of electromagnetic waves formulated by James Clerk Maxwell in 1873. The existence of these waves was later demonstrated by Heinrich Hertz in 1887, when for the first time a radio transmitter generated a spark in a receiver placed several meters away. Although Nikola Tesla was the first researcher who showed the ability of electromagnetic waves to convey information, Guglielmo Marconi is widely recognized as the inventor of wireless transmissions. His first publicized radio experiment took place in 1898 from a boat in the English Channel to the Isle of Wight, while in 1901 his radio telegraph system sent the first radio signal across the Atlantic Ocean from Cornwall to Newfoundland. Since then, the wireless communication idea was constantly investigated for practical implementation, but until the 1920s mobile radio systems only made use of the Morse code. In 1918 Edwin Armstrong invented the superheterodyne receiver, thereby opening the way to the first broadcast radio transmission that took place at Pittsburgh in 1920. In the subsequent years the radio became widespread all over the world, but in the meantime the research community was studying the possibility of transmitting real-time moving images through the air. These efforts culminated in 1929 with the first experiment of TV transmission made by Vladimir Zworykin. Seven years later the British Broadcasting Corporation (BBC) started its TV services.

Although radio and TV broadcasting were the first widespread wireless services, an intense research activity was devoted to develop practical schemes for bi-directional mobile communications, which were clearly appealing for military applications and for police and fire departments. The first mobile radio telephones were employed in 1921 by the Detroit Police Department's radio bureau, that began experimentation for vehicular mobile services. In subsequent years, these early experiments were followed by many others. In the 1940s, radio equipments called "carphones" occupied most of the police cars. These systems were powered by car batteries and allowed communications among closed group of users due to lack of interconnection with the public switched telephone network (PSTN). In 1946, mobile telephone networks interconnected with the PSTN made their first appearance in several cities across the United States. The main shortcoming of these systems was the use of a single access point to serve an entire metropolitan area, which limited the number of active users to the number of allocated frequency channels. This drawback motivated investigations as how to enlarge the number of users for a given allocated frequency band. A solution was found in 1947 by the AT&T's Bell Labs with the advent of the cellular concept [131], which represented a fundamental contribution in the development of wireless communications. In cellular communication systems, the served area is divided into smaller regions called *cells*. Due to its reduced dimension, each cell requires a relatively low power to be covered. Since the power of the transmitted signal falls off with distance, users belonging to adequately distant cells can operate over the same frequency band with minimal interference. This means that the same frequency band can be reused in other (most often non adjacent) cells, thereby leading to a more efficient use of the radio spectrum.

In 1957, the Union Soviet launched its first satellite Sputnik I and the United States soon followed in 1958 with Explorer I. The era of space exploration and satellite communications had begun. Besides being used for TV services, modern satellite networks provide radio coverage to wide sparsely populated areas where a landline infrastructure is absent. Typical applications are communications from ships, offshore oil drilling platforms and war or disaster areas.

1.2.2 *First generation (1G) cellular systems*

Despite its theoretical relevance, the cellular concept was not widely adopted during the 1960s and 1970s. To make an example, in 1976 the Bell Mobile Phone had only 543 paying customers in the New York City area, and mobile communications were mainly supported by heavy terminals mounted on cars. Although the first patent describing a portable mobile telephone was granted to Motorola in 1975 [25], mobile cellular systems were not introduced for commercial use until the early 1980s, when the so-called first generation (1G) of cellular networks were deployed in most developed countries. The common feature of 1G systems was the adoption of an analog transmission technology. Frequency modulation (FM) was used for speech transmission over the 800-900 MHz band and frequency-division multiple-access (FDMA) was adopted to separate users' signals in the frequency domain. In practice, a fraction of the available spectrum (subchannel) was exclusively allocated to a given user during the call set-up and retained for the entire call.

In the early 1980s, 1G cellular networks experienced a rapid growth in Europe, particularly in Scandinavia where the Nordic Mobile Telephony (NMT) appeared in 1981, and in United Kingdom where the Total Access

Communication System (TACS) started service in 1985. The Advanced Mobile Phone Service (AMPS) was deployed in Japan in 1979, while in the United States it appeared later in 1983. These analog systems created a critical mass of customers. Their main limitations were the large dimensions of cellphones and the reduced traffic capacity due to a highly inefficient use of the radio spectrum.

At the end of the 1980s, progress in semiconductor technology and device miniaturization allowed the production of small and light-weight handheld phones with good speech quality and acceptable battery lifetime. This marked the beginning of the wireless cellular revolution that took almost everyone by surprise since in the meantime many important companies had stopped business activities in cellular communications, convinced that mobile telephony would have been limited to rich people and would have never attracted a significant number of subscribers.

1.2.3 *Second generation (2G) cellular systems*

The limitations of analog radio technology in terms of traffic capacity became evident in the late 1980s, when 1G systems saturated in many big cities due to the rapid growth of the cellular market. Network operators realized that time was ripe for a second generation (2G) of cellular systems that would have marked the transition from analog to digital radio technology. This transition was not only motivated by the need for higher network capacity, but also by the lower cost and improved performance of digital hardware as compared to analog circuitry.

Driven by the success of NMT, in 1982 the Conference of European Posts and Telecommunications (CEPT) formed the Group Spècial Mobile (GSM) in order to develop a pan-European standard for mobile cellular radio services with good speech quality, high spectral efficiency and the ability for secure communications. The specifications of the new standard were approved in 1989 while its commercial use began in 1993. Unlike 1G systems, the GSM was developed as a digital standard where users' analog signals are converted into sequences of bits and transmitted on a frame-by-frame basis. Within each frame, users transmit their bits only during specified time intervals (slots) that are exclusively assigned at the call setup according to a time-division multiple-access (TDMA) approach. Actually, the GSM is based on a hybrid combination of FDMA and TDMA, where FDMA is employed to divide the available spectrum into 200 kHz-wide subchannels while TDMA is used to separate up to a maximum of eight users allocated over the same subchannel. In Europe the operating frequency band is 900 MHz, even though in many big cities the 1800 MHz band is also being adopted to accommodate a larger number of users. Many modern European GSM phones operate in a "dual-band" mode by selecting either of the two recommended frequencies. In the United States, the 1900 MHz frequency band is reserved to the GSM service.

In addition to circuit-switched applications like voice, the adoption of a digital technology enabled 2G cellular systems to offer low-rate data services including e.mail and short messaging up to 14.4 kbps. The success of GSM was such that by June 2001 there were more than 500 millions GSM subscribers all over the world while in 2004 the market penetration exceeded 80% in Western Europe. The reasons for this success can be found in the larger capacity and many more services that the new digital standard offered as compared to previous 1G analog systems. Unfortunately, the explosive market of digital cellphones led to a proliferation of incompatible 2G standards that sometimes prevent the possibility of roaming among different countries. Examples of this proliferation are the Digital Advanced Mobile Phone Services (D-AMPS) which was introduced in the United States in 1991 and the Japanese Pacific Digital Cellular (PDS) [67]. The Interim Standard 95 (IS-95) became operative in the United States starting from 1995 and was the first commercial system to employ the code-division multiple-access (CDMA) technology as an air interface.

1.2.4 *Third generation (3G) cellular systems*

At the end of the 1990s it became clear that GSM was not sufficient to indefinitely support the explosive number of users and the ever-increasing data rates requested by emerging multimedia services. There was the need for a new generation of cellular systems capable of supporting higher transmission rates with improved quality of service as compared to GSM. After long deliberations, two prominent standards emerged: the Japanese-European Universal Mobile Telecommunication System (UMTS) [160] and the American CDMA-2000 [161]. Both systems operate around the 2 GHz frequency band and adopt a hybrid FDMA/CDMA approach. In practice, groups of users are allocated over disjoint frequency subbands, with users sharing a common subband being distinguished by quasi-orthogonal spreading codes. The CDMA technology has several advantages over TDMA and FDMA, including higher spectral efficiency and increased flexibility in radio resource management. In practical applications, however, channel distortions may destroy orthogonality among users' codes, thereby resulting in multiple-access interference (MAI). In the early 1990s, problems related to MAI mitigation spurred an intense research activity on CDMA and other spread-spectrum techniques. This led to the development of a large number of multiuser detection (MUD) techniques [164], where the inherent structure of interfering signals is exploited to assist the data detection process.

The introduction of 3G systems offered a wide range of new multimedia applications with the possibility of speech, audio, images and video transmissions at data rates of 144-384 kbps for fast moving users up to 2 Mbps for stationary or slowly moving terminals. In addition to the increased data rate, other advantages over 2G systems are the improved spectral efficiency, the ability to multiplex several applications with different quality of service requirements, the use of variable bit rates to offer bandwidth on demand and the possibility of supporting asymmetric services in the uplink and downlink directions, which is particularly useful for web browsing and high-speed downloading operations. Unfortunately, the impressive costs paid by telecom providers to get 3G cellular licenses slackened the deployment of the 3G infrastructure all over the world and led to a spectacular crash of the telecom stock market during the years 2000/2001. As a result, many startup companies went bankrupt while others decreased or stopped at all their investments in the wireless communication area. This also produced a significant reduction of public funding for academic research.

1.2.5 *Wireless local and personal area networks*

In the first years of the new millennium, the development of personal area networks (PANs) and wireless local area networks (WLANs) has suscitated a renewed interest in the wireless technology. These products provide wireless connectivity among portable devices like laptop computers, cordless phones, personal digital assistants (PDAs) and computer peripherals. Compared to wired networks they promise portability, allow simple and fast installation and save the costs for deploying cables. Because of their relatively limited coverage range, both technologies are mainly intended for indoor applications.

Several standards for PAN products have been developed by the IEEE 802.15 working group [62]. Among them, Bluetooth is perhaps the most popular scheme. The first release of Bluetooth appeared in 1999 while the first headset was produced by Ericsson in the year 2000. This technology enables low-powered transmissions with short operating ranges up to 10 meters. It provides wireless connection among closely spaced portable devices with limited battery power and must primarily be considered as a substitute for data transfer cables. Typical applications are the interconnection between a hands-free headset and a cellular phone, a DVD player and a television set, a desktop computer and some peripheral devices like a printer, keyboard or mouse. Bluetooth operates over the unlicensed Industrial, Scientific and Medical (ISM) frequency band, which is centered around 2.4 GHz. The allocated spectrum is divided into 79 adjacent subchannels which are accessed by means of a frequency-hopping spread-spectrum (FH-SS) technique. Each subchannel has a bandwidth of 1 MHz for a data rate approaching 1 Mbps [44].

WLANs have a wider coverage area as compared to PANs and are mainly used to distribute the Internet access to a bunch of portable devices (typically laptop computers) dislocated in private homes or office buildings. A typical application is represented by a user who needs to be able to carry out a laptop into a conference room without losing network connection. WLANs are also being used in hotels, airports or coffee shops to create “hotspots” for public access to the Internet. The number of users that can simultaneously be served is usually limited to about 10, even though in principle more users could be supported by lowering the individual data rates. The typical network topology of commercial WLANs is based on a cellular architecture with cell radii up to 100 meters. In this case, several user terminals (UTs) establish a wireless link with a fixed access point (AP) which is connected to the backbone network as illustrated in Fig. 1.1. An alternative configuration is represented in Fig. 1.2, where an ad-hoc network is set up for peer-to-peer communications without involving any AP.

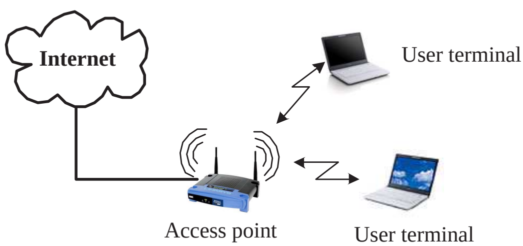

Fig. 1.1 Illustration of a WLAN with fixed access point.

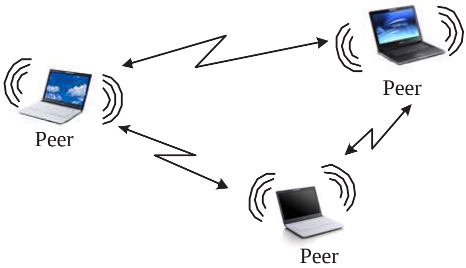

Fig. 1.2 Illustration of a WLAN for peer-to-peer communications.

The most successful class of WLAN products is based on the IEEE 802.11 family of standards. The first 802.11 release appeared in 1997 [58] and was intended to provide data rates of 1 and 2 Mbps. Three different physical layer architectures were recommended. The first two operate over the 2.4 GHz band and employ either a direct-sequence spread-spectrum or frequency-hopping technology. The third operational mode is based on infrared light and has rarely been used in commercial products. A first amendment called 802.11b was ratified in 1999 to improve the data rate up to 11 Mbps [60]. This product was adopted by an industry group called WiFi (Wireless Fidelity) and became soon very popular. In the same year a new amendment called 802.11a recommended the use of OFDM to further increase the data rate up to 54 Mbps [59]. This standard operates over the 5 GHz band, which is unlicensed in the US but not in most other countries. A TDMA approach is used to distinguish users within a cell while FDMA is employed for cell separation. A further evolution of the 802.11 family was approved in 2003 and is called 802.11g [61]. This standard is similar to 802.11a, except that it operates over the ISM band, which is license-exempt in Europe, United States and Japan.

Other examples of WLAN standards include the Japanese multimedia mobile access communication (MMAC) and the European high performance LAN (HiperLAN2) [41]. The physical layers of these systems are based on OFDM and only present minor modifications with respect to IEEE 802.11a. The major differences lie in the MAC layer protocols. Actually, HiperLAN2 employs a reservation based access scheme where each UT sends a request to the AP before transmitting a data packet, while 802.11 adopts Carrier-Sense Multiple-Access with Collision Avoidance (CSMA-CA), where each

UT determines whether the channel is currently available and only in that case it starts transmitting data. As for MMAC, it supports both of the aforementioned protocols.

The current generation of WLANs offers data rates of tens of Mbps and is characterized by low mobility and relatively limited coverage areas. The challenge for future WLANs is to extend the radio coverage and support new services like real-time video applications that are highly demanding in terms of data rate and latency.

1.2.6 *Wireless metropolitan area networks*

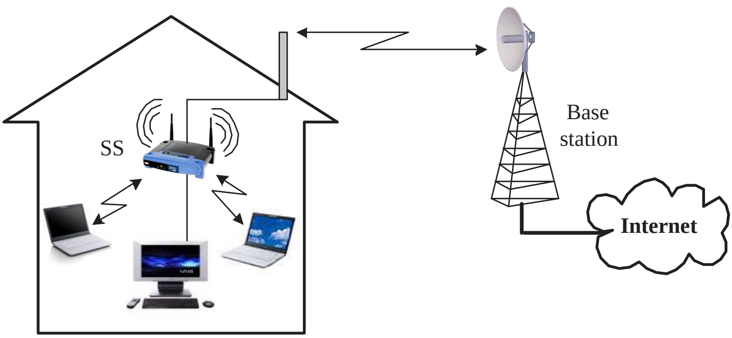

Fig. 1.3 Illustration of a WMAN providing wireless Internet access to a remote SS.

Wireless metropolitan area networks (WMANs) represent the natural evolution of WLANs. The purpose of these systems is to provide network access to residential or enterprise buildings through roof-top antennas communicating with a central radio base station, thereby replacing the wired "last mile" connection by a wireless link. This offers an appealing alternative to cabled access networks or digital subscriber line (DSL) links, and promises ubiquitous broadband access to rural or developing areas where broadband is currently unavailable for lack of a cabled infrastructure. Figure 1.3 depicts a typical scenario where the WMAN provides wireless Internet access to a Subscriber Station (SS) placed within a building. A WLAN or a backbone local network is used inside the building to connect the SS to the user terminals. In a more challenging application, the SS is mounted on a moving vehicle like a car or a train to provide passengers with continuous

Internet connectivity.

Several options for the WMAN air interface and MAC protocols are specified by the IEEE 802.16 Working Group, who started its activity in 1998. The goal was to deliver high data rates up to 50 Mbps over metropolitan areas with cell radii up to 50 kilometers. At the beginning, the interest of the Group focused on the 10-66 GHz band where a large amount of unlicensed spectrum is available worldwide. The first 802.16 release appeared in 2002 [63] and was specifically intended for line-of-sight (LOS) applications due to the severe attenuations experienced by short wavelengths when passing through walls or other obstructions. This standard adopts single-carrier (SC) modulation in conjunction with a TDMA access scheme. Transmission parameters like modulation and coding rates are adaptively adjusted on a frame-by-frame basis depending on the actual interference level and channel quality. The LOS requirement was the main limitation of this first release since rooftop antennas mounted on residential buildings are typically too low for a clear sight line to the base station antenna. For this reason, in the same year 2002 a first amendment called 802.16a was approved to support non line-of-sight (NLOS) operations over the 2-11 GHz band [112]. This novel standard defines three different air interfaces and a common MAC protocol with a reservation based access. The first air interface relies on SC transmission, the second employs OFDM-TDMA while the third operates according to the OFDMA principle in which users' separation is achieved at subcarrier level. Among the three recommended air interfaces, those based on OFDM and OFDMA seem to be favored by the vendor community due to their superior performance in NLOS applications. The last evolution of the 802.16 family is represented by the 802.16e specifications, whose standardization process began in the year 2004 [113]. This emerging standard adopts a scalable OFDMA physical layer and promises mobility at speeds up to 120 km/h by using adaptive antenna arrays and improved inter-cell handover. Its main objective is to provide continuous Internet connection to mobile users moving at vehicular speed.

In order to ensure interoperability among all 802.16-based devices and rapidly converge to a worldwide WMAN standard, an industry consortium called WiMax (Worldwide Interoperability for Microwave Access) Forum has been created. However, due to the large variety of data rates, coverage ranges and potential options specified in the standards, it is currently difficult to predict what type of performance WiMax-certified devices will reasonably provide in the near future.

1.2.7 *Next generation wireless broadband systems*

The demand for novel high-rate wireless communication services is growing today at an extremely rapid pace and is expected to further increase in the next years. This trend has motivated a significant number of research and development projects all over the world to define a fourth generation (4G) of wireless broadband systems that may offer increased data rates and better quality of service than current 3G products. The new wireless technology will support multimedia applications with extremely different requirements in terms of reliability, bit rates and latency. The integration of the existing multitude of standards into a common platform represents one of the major goals of 4G systems, which can only be achieved through the adoption of a flexible air interface with high scalability and interoperability [57, 138].

Software Defined Radio (SDR) represents a viable solution to provide 4G systems with the necessary level of flexibility and reconfigurability [4, 159, 170]. The main concept behind SDR is that different transceiver functions are executed as software programs running on suitable processors. Once the software corresponding to existing standards has been pre-loaded on the system, the SDR platform guarantees full compatibility among different wireless technologies. In addition, SDR can easily incorporate new standards and protocols by simply loading the specific application software.

A second challenge for next generation systems is the conflict between the increasing demand for higher data rates and the scarcity of the radio spectrum. This calls for an air interface characterized by an extremely high spectral efficiency. Recent advances in information theory has shown that large gains in terms of capacity and coverage range are promised by multiple-input multiple-output (MIMO) systems, where multiple antennas are deployed at both ends of the wireless link [46]. Based on these results, it is likely that the MIMO technology will be widely adopted in 4G networks. An alternative way for improving the spectral efficiency is the use of flexible modulation and coding schemes, where system resources are adaptively assigned to users according to their requested data rates and channel quality. As mentioned previously, the multicarrier technique is recognized as a potential candidate for next generation broadband wireless systems thanks to its attractive features in terms of robustness against channel distortions and narrowband interference, high spectral efficiency, high flexibility in resource management and ability to support adaptive modulation schemes. Furthermore, multicarrier transmissions can easily be combined with MIMO technology as witnessed by recent advances on

MIMO-OFDM [149] and MIMO-OFDMA.

1.3 Historical notes on multicarrier transmissions

The first examples of multicarrier (MC) modems operating in the High-Frequency (HF) band date back to the 1950s. In these early experiments, the signal bandwidth was divided into several non-overlapping frequency subchannels, each modulated by a distinct stream of data coming from a common source. On one hand, the absence of any spectral overlap between adjacent subchannels helped to eliminate interference among different data streams (interchannel interference). On the other, it resulted into a very inefficient use of the available spectrum. The idea of orthogonal MC transmission with partially overlapping spectra was introduced by Chang in 1966 with his pioneering paper on parallel data transmission over dispersive channels [15]. In the late 1960s, the MC concept was adopted in some military applications such as KATHRYN [184] and ANDEFT [120]. These systems involved a large hardware complexity since parallel data transmission was essentially implemented through a bank of oscillators, each tuned on a specific subcarrier. As a consequence, in that period much of the research effort was devoted to find efficient modulation and demodulation schemes for MC digital communications [121, 139]. A breakthrough in this sense came in 1971, when Weinstein and Ebert eliminated the need for a bank of oscillators and proposed the use of the Fast Fourier Transform (FFT) for baseband processing. They also introduced the *guard band* concept to eliminate interference among adjacent blocks of data. The new FFT-based technique was called orthogonal frequency-division multiplexing (OFDM). Despite its reduced complexity with respect to previously developed MC schemes, practical implementation of OFDM was still difficult at that time because of the limited signal processing capabilities of the electronic hardware. For this reason, OFDM did not attract much attention until 1985, when was suggested by Cimini for high-speed wireless applications [21].

Advances in digital and hardware technology in the early 1990s enabled the practical implementation of FFTs of large size, thereby making OFDM a realistic option for both wired and wireless transmissions. The ability to support adaptive modulation and to mitigate channel distortions without the need for adaptive time-domain equalizers made OFDM the selected access scheme for asymmetric digital subscriber loop (ADSL) applications in the USA [19]. In Europe, Digital Audio Broadcasting (DAB) standardized by ETSI was the first commercial wireless system to use OFDM as an air interface in 1995 [39]. This success continued in 1997 with the adoption of OFDM for terrestrial Digital Video Broadcasting (DVB-T) [40] and in 1999 with the release of the WLAN standards HiperLAN2 [41] and IEEE 802.11a [59], both based on OFDM-TDMA. More recently, OFDM has been used in the interactive terrestrial return channel (DVB-RCT) [129] and in the IEEE 802.11g WLAN products [61]. In 1998 a combination of OFDM and FDMA called orthogonal frequency-division multiple-access (OFDMA) was proposed by Sari and Karam for cable TV (CATV) networks [140]. The main advantages of this scheme over OFDM-TDMA are the increased flexibility in resource management and the ability for dynamic channel assignment. Compared to ordinary FDMA, OFDMA offers higher spectral efficiency by avoiding the need for large guard bands between users' signals. A hybrid combination of OFDMA and TDMA has been adopted in the uplink of the DVB-RCT system while both OFDM-TDMA and OFDMA are recommended by the IEEE 802.16a standard for WMANs [112]. An intense research activity is currently devoted to study MIMO-OFDM and MIMO-OFDMA as promising candidates for 4G wireless broadband systems.

1.4 Outline of this book

The remaining chapters of this book are organized in the following way.

Chapter 2 lays the groundwork material for further developments and is divided into three parts. The first is concerned with the statistical characterization of the wireless channel. Here, some relevant parameters are introduced ranging from the channel coherence bandwidth and Doppler spread to the concept of frequency-selective and time-selective fading. The second part illustrates the basic idea of OFDM and how this kind of modulation can be implemented by means of FFT-based signal processing. The OFDMA principle is described in the third part of the chapter, along with some other popular multiple-access schemes based on OFDM.

Chapter 3 provides a comprehensive overview of synchronization methods for OFDMA applications. A distinction is made between downlink and uplink transmissions, with a special attention to the uplink situation which is particularly challenging due to the presence of many unknown synchronization parameters. Several timing and frequency recovery schemes are presented, and comparisons are made in terms of system complexity and estimation accuracy. Some methods for compensating the synchronization errors in an uplink scenario are illustrated in the last part of this chapter.

Chapter 4 deals with channel estimation and equalization in OFDM systems. After illustrating how channel distortions can be compensated for through a bank of one-tap complex-valued multipliers, we present a large variety of methods for estimating the channel frequency response over each subcarrier. A number of these schemes are based on suitable interpolation of pilot symbols which are inserted in the transmitted frame following some specified grid patterns. Other methods exploit the inherent redundancy introduced in the OFDM waveform by the use of the cyclic prefix and/or virtual carriers. The chapter concludes by illustrating recent advances in the context of joint channel estimation and data detection based on the expectation-maximization (EM) algorithm.

Chapter 5 extends the discussions of the previous two chapters and presents a sophisticated receiver structure for uplink OFDMA transmissions where the tasks of synchronization, channel estimation and data detection are jointly performed by means of advanced iterative signal processing techniques. At each iteration, tentative data decisions are exploited to improve the synchronization and channel estimation accuracy which, in turn, produces more reliable data decisions in the next iteration. Numerical results demonstrate the effectiveness of this iterative architecture.

Chapter 6 covers the topic of dynamic resource allocation in multicarrier systems, where power levels and/or data rates are adaptively adjusted over each subcarrier according to the corresponding channel quality. We begin by reviewing the rate-maximization and margin-maximization concepts and discuss several bit and power loading techniques for single-user OFDM. The second part of the chapter presents a survey of state-of-the-art allocation techniques for OFDMA applications. In this case, the dynamic assignment of subcarriers to the active users provides the system with some form of multiuser diversity which can be exploited to improve the overall data throughput.

Finally, Chapter 7 provides a thorough discussion of the peak-to-average power ratio (PAPR) problem, which is considered as one of the main obstacles to the practical implementation of OFDM/OFDMA. After providing a detailed statistical characterization of the PAPR, a large number of PAPR reduction schemes are presented, starting from the conventional clipping technique till some sophisticated encoding approaches based on Reed-Muller codes and Golay complementary sequences.