Multi-Carrier and Spread Spectrum Systems

K. Fazel

Marconi Communications GmbH
Germany

and

S. Kaiser

German Aerospace Center (DLR)
Germany

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West Sussex PO19 8SQ, England

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John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

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Library of Congress Cataloging-in-Publication Data

Fazel, Khaled.
Multi-carrier and spread spectrum systems / K. Fazel, S. Kaiser.
p. cm.
Includes bibliographical references and index.
ISBN 0-470-84899-5
1. Spread spectrum communications. 2. Multiplexing. I. Kaiser, Stefan, 1960– II. Title.

TK5103.45.F39 2003
621.382 – dc22

2003057595

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-470-84899-5

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

to

my parents, my wife Miriam,
my daughters Sarah, Sophia, and Susanna
(K.F.)

my wife Susanna,
my sons Lukas and Philipp and my daughter Anna
(S.K.)

Contents

Foreword

This book discusses multi-carrier modulation and spread spectrum techniques, recognized as the most promising candidate modulation methods for the 4th generation (4G) of mobile communications systems. The authors of this book were the first to propose MC-CDMA for the next generation of mobile communications, and are still continuing their contribution towards beyond 3G. Considering the requirements of 4G systems, multi-carrier and spread spectrum systems appear to be the most suitable as they provide higher flexibility, higher transmission rates and frequency usage efficiency. This is the first book on these methods, providing the reader with the fundamentals of the technologies involved and the related applications.

The book deals with the principles through definitions of basic technologies and the multipath channel over which the signals are transmitted. It defines MC-CDMA as a frequency PN pattern and MC-DS-CDMA as a straight extension of DS-CDMA; and argues that these twin asymmetric technologies are most suitable for 4G since MC-CDMA is suitable for the downlink and MC-DS-CDMA is suitable for the uplink in the cellular systems. Although MC-CDMA performs better than MC-DS-CDMA, it needs chip synchronization between users, and is therefore difficult to deploy in the uplink. Thus, for this asymmetric structure it is very important to understand the multi-carrier spread spectrum methods. Hybrid multiple access schemes like Multi-Carrier FDMA, Multi-Carrier TDMA, and Ultra Wide Band systems are discussed as more extended systems. Implementation issues, including synchronization, channel estimation, and RF issues, are also discussed in depth. Wireless local area networks, broadcasting transmission, and cellular mobile radio are shown to realize seamless networking for 4G. Although cellular systems have not yet been combined with other wireless networks, different wireless systems should be seamlessly combined. The last part of this book discusses capacity and flexibility enhancement technologies like diversity techniques, space–time/frequency coding, and SDR (Software Defined Radio).

This book greatly assists not only theoretical researchers, but also practicing engineers of the next generation of mobile communications systems.

March 2003

Prof. Masao Nakagawa
Department of Information and Computer Science
Keio University, Japan

Preface

Nowadays, multi-carrier transmission is considered to be an old concept. Its basic idea goes back to the mid-1960s. Nevertheless, behind any old technique there are always many simple and exciting ideas, the terrain for further developments of new efficient schemes.

Our first experience with the simple and exciting idea of OFDM started in early 1991 with *digital audio broadcasting (DAB)*. From 1992, our active participation in several research programmes on *digital terrestrial TV broadcasting (DVB-T)* gave us further opportunities to look at several aspects of the OFDM technique with its new advanced digital implementation possibilities. The experience gained from the joined specification of several OFDM-based demonstrators within the German HDTV-T and the EU-RACE dTTb research projects served as a basis for our commitment in 1995 to the final specifications of the DVB-T standard, relaying on the multi-carrier transmission technique.

Parallel to the HDTV-T and the dTTb projects, our further involvement from 1993 in the EU-RACE CODIT project, with the scope of building a first European 3G testbed, following the DS-CDMA scheme, inspired our interest in another old technique, *spread spectrum*, being as impressive as multi-carrier transmission. Although the final choice of the specification of the CODIT testbed was based on wideband CDMA, an alternative multiple-access scheme exploiting the new idea of combining OFDM with spread spectrum, i.e., *multi-carrier spread spectrum* (MC-SS), was considered as a potential candidate and discussed widely during the definition phase of the first testbed.

Our strong belief in the efficiency and flexibility of multi-carrier spread spectrum compared to W-CDMA for applications such as beyond 3G motivated us, from the introduction of this new multiple access scheme at PIMRC '93, to further contribute to it, and to investigate different corresponding system level aspects.

Due to the recognition of the merits of this combination by well-known international experts, since the PIMRC '93 conference, MC-SS has rapidly become one of the most widespread independent research topics in the field of mobile radio communications. The growing success of our organized series of international workshops on MC-SS since 1997, the large number of technical sessions devoted in international conferences to multi-carrier transmission, and the several special editions of the *European Transactions on Telecommunications (ETT)* on MC-SS highlight the importance of this combination for future wireless communications.

Several MC-CDMA demonstrators, e.g., one of the first built within DLR and its live demonstration during the 3rd international MC-SS workshop, a multitude of recent international research programmes like the research collaboration between DoCoMo-Eurolabs

and DLR on the design of a future broadband air interface or the EU-IST MATRICE, 4MORE and WINNER projects, and especially the NTT-DoCoMo research initiative to build a demonstrator for beyond 3G systems based on the multi-carrier spread spectrum technique, emphasize the commitment of the international research community to this new topic.

Our experience gained during the above-mentioned research programmes, our current involvement in the ETSI-BRAN project, our yearly seminars organized within Carl Granz Gesellschaft (CCG) on digital TV broadcasting and on WLAN/WLL have given us sufficient background knowledge and material to take this initiative to collect in this book most important aspects on multi-carrier, spread spectrum and multi-carrier spread spectrum systems.

We hope that this book will contribute to a better understanding of the principles of multi-carrier and spread spectrum and may motivate further investigation into and development of this new technology.

K. Fazel, S. Kasier

Acknowledgements

The authors would like to express their sincere thanks to Prof. M. Nakagawa from Keio University, Japan, for writing the foreword. Many thanks go to Dr. H. Attarachi, Dr. N. Maeda, Dr. S. Abeta, and Dr. M. Sawahashi from NTT-DoCoMo for providing us with material regarding their multi-carrier spread spectrum activities. Many thanks also for the support of Dr. E. Auer from Marconi Communications and for helpful technical discussions with members of the Mobile Radio Transmission Group from DLR. Further thanks also go to I. Cosovic from DLR who provided us with results for the uplink, especially with pre-equalization.

K. Fazel, S. Kasier

Introduction

The common feature of the next generation wireless technologies will be the convergence of multimedia services such as speech, audio, video, image, and data. This implies that a future wireless terminal, by guaranteeing high-speed data, will be able to connect to different networks in order to support various services: switched traffic, IP data packets and broadband streaming services such as video. The development of wireless terminals with generic protocols and multiple-physical layers or software-defined radio interfaces is expected to allow users to seamlessly switch access between existing and future standards.

The rapid increase in the number of wireless mobile terminal subscribers, which currently exceeds 1 billion users, highlights the importance of wireless communications in this new millennium. This revolution in the information society has been happening, especially in Europe, through a continuous evolution of emerging standards and products by keeping a seamless strategy for the choice of solutions and parameters. The adaptation of wireless technologies to the user's rapidly changing demands has been one of the main drivers of this revolution. Therefore, the worldwide wireless access system is and will continue to be characterized by a heterogeneous multitude of standards and systems. This plethora of wireless communication systems is not limited to cellular mobile telecommunication systems such as GSM, IS-95, D-AMPS, PDC, UMTS or cdma2000, but also includes wireless local area networks (WLANs), e.g., HIPERLAN/2, IEEE 802.11a/b and Bluetooth, and wireless local loops (WLL), e.g., HIPERMAN, HIPERACCESS, and IEEE 802.16 as well as broadcast systems such as digital audio broadcasting (DAB) and digital video broadcasting (DVB).

These trends have accelerated since the beginning of the 1990s with the replacement of the first generation analog mobile networks by the current 2nd generation (2G) systems (GSM, IS-95, D-AMPS and PDC), which opened the door for a fully digitized network. This evolution is still continuing today with the introduction of the deployment of the 3rd generation (3G) systems (UMTS, IMT-2000 and cdma2000). In the meantime, the research community is focusing its activity towards the next generation beyond 3G, i.e. *fourth generation (4G)* systems, with more ambitious technological challenges.

The primary goal of next-generation wireless systems (4G) will not only be the introduction of new technologies to cover the need for higher data rates and new services, but also the *integration* of existing technologies in a common platform. Hence, the selection of a *generic* air-interface for future generation wireless systems will be of great importance. Although the exact requirements for 4G have not yet been commonly defined, its new air interface shall fulfill at least the following requirements:

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 ISBN: 0-470-84899-5

— *generic architecture*, enabling the integration of existing technologies,
— *high spectral efficiency*, offering higher data rates in a given scarce spectrum,
— *high scalability*, designing different cell configurations (hot spot, ad hoc), hence better coverage,
— *high adaptability and reconfigurability*, supporting different standards and technologies,
— *low cost*, enabling a rapid market introduction, and
— *future proof*, opening the door for new technologies.

From Second- to Third-Generation Multiple Access Schemes

2G wireless systems are mainly characterized by the transition of analog towards a fully digitized technology and comprise the GSM, IS-95, PDC and D-AMPS standards.

Work on the pan-European digital cellular standard *Global System for Mobile* communications (GSM) started in 1982 [14][37], where now it accounts for about two-thirds of the world mobile market. In 1989, the technical specifications of GSM were approved by the European Telecommunication Standard Institute (ETSI), where its commercial success began in 1993. Although GSM is optimized for circuit-switched services such as voice, it offers low-rate data services up to 14.4 kbit/s. High speed data services up to 115.2 kbit/s are possible with the enhancement of the GSM standard towards the *General Packet Radio Service* (GPRS) by using a higher number of time slots. GPRS uses the same modulation, frequency band and frame structure as GSM. However, the *Enhanced Data rate for Global Evolution* (EDGE) [3] system which further improves the data rate up to 384 kbit/s introduces a new modulation scheme. The final evolution from GSM is the transition from EDGE to 3G.

Parallel to GSM, the American IS-95 standard [43] (recently renamed *cdmaOne*) was approved by the Telecommunication Industry Association (TIA) in 1993, where its first commercial application started in 1995. Like GSM, the first version of this standard (IS-95A) offers data services up to 14.4 kbit/s. In its second version, IS-95B, up to 64 kbit/s data services are possible.

Meanwhile, two other 2G mobile radio systems have been introduced: *Digital Advanced Mobile Phone Services* (D-AMPS/IS-136), called TDMA in the USA and the *Personal Digital Cellular* (PDC) in Japan [28]. Currently PDC hosts the most convincing example of high-speed internet services to mobile, called *i-mode*. The high amount of congestion in the PDC system will urge the Japanese towards 3G and even 4G systems.

Trends towards more capacity for mobile receivers, new multimedia services, new frequencies and new technologies have motivated the idea of 3G systems. A unique international standard was targeted: *Universal/International Mobile Telecommunication System* (UMTS/IMT-2000) with realization of a new generation of mobile communications technology for a world in which personal communication services will dominate. The objectives of the third generation standards, namely UMTS [17] and cdma2000 [44] went far beyond the second-generation systems, especially with respect to:

— the wide range of multimedia services (speech, audio, image, video, data) and bit rates (up to 2 Mbit/s for indoor and hot spot applications),

— the high quality of service requirements (better speech/image quality, lower bit error rate (BER), higher number of active users),
— operation in mixed cell scenarios (macro, micro, pico),
— operation in different environments (indoor/outdoor, business/domestic, cellular/cordless),
— and finally flexibility in frequency (variable bandwidth), data rate (variable) and radio resource management (variable power/channel allocation).

The commonly used multiple access schemes for second and third generation wireless mobile communication systems are based on either *Time Division Multiple Access* (TDMA), *Code Division Multiple Access* (CDMA) or the combined access schemes in conjunction with an additional *Frequency Division Multiple Access* (FDMA) component:

— The GSM standard, employed in the 900 MHz and 1800 MHz bands, first divides the allocated bandwidth into 200 kHz FDMA sub-channels. Then, in each sub-channel, up to 8 users share the 8 time slots in a TDMA manner [37].
— In the IS-95 standard up to 64 users share the 1.25 MHz channel by CDMA [43]. The system is used in the 850 MHz and 1900 MHz bands.
— The aim of D-AMPS (TDMA IS-136) is to coexist with the analog AMPS, where the 30 kHz channel of AMPS is divided into three channels, allowing three users to share a single radio channel by allocating unique time slots to each user [27].
— The recent ITU adopted standards for 3G (UMTS and cdma2000) are both based on CDMA [17][44]. For UMTS, the CDMA-FDD mode, which is known as wideband CDMA, employs separate 5 MHz channels for both the uplink and downlink directions. Within the 5 MHz bandwidth, each user is separated by a specific code, resulting in an end-user data rate of up to 2 Mbit/s per carrier.

Table 1 summarizes the key characteristics of 2G and 3G mobile communication systems.

Beside tremendous developments in mobile communication systems, in public and private environments, operators are offering wireless services using WLANs in selected

Table 1 Main parameters of 2G and 3G mobile radio systems

Parameter	2G systems		3G systems
	GSM	IS-95	IMT-2000/UMTS (WARC'92 [39])
Carrier frequencies	900 MHz 1800 MHz	850 MHz 1900 MHz	1900–1980 MHz 2010–2025 MHz 2110–2170 MHz
Peak data rate	64 kbit/s	64 kbit/s	2 Mbit/s
Multiple access	TDMA	CDMA	CDMA
Services	Voice, low rate data	Voice, low rate data	Voice, data, video

Table 2 Main parameters of WLAN communication systems

Parameter	Bluetooth	IEEE 802.11b	IEEE 802.11a	HIPERLAN/2
Carrier frequency	2.4 GHz (ISM)	2.4 GHz (ISM)	5 GHz	5 GHz
Peak data rate	1 Mbit/s	5.5 Mbit/s	54 Mbit/s	54 Mbit/s
Multiple access	FH-CDMA	DS-CDMA with carrier sensing	TDMA	TDMA
Services	Ethernet	Ethernet	Ethernet	Ethernet, ATM

spots such as hotels, train stations, airports and conference rooms. As Table 2 shows, there is a similar objective to go higher in data rates with WLANs, where multiple access schemes TDMA or CDMA are employed [15][30].

FDMA, TDMA and CDMA are obtained if the transmission bandwidth, the transmission time or the spreading code are related to the different users, respectively [2].

FDMA is a multiple access technology widely used in satellite, cable and terrestrial radio networks. FDMA subdivides the total bandwidth into N_c narrowband sub-channels which are available during the whole transmission time (see Figure 1). This requires band-pass filters with sufficient stop band attenuation. Furthermore, a sufficient guard band is left between two adjacent spectra in order to cope with frequency deviations of local oscillators and to minimize interference from adjacent channels. The main advantages of FDMA are in its low required transmit power and in channel equalization that is either not needed or much simpler than with other multiple access techniques. However, its drawback in a cellular system might be the implementation of N_c modulators and demodulators at the base station (BS).

TDMA is a popular multiple access technique, which is used in several international standards. In a TDMA system all users employ the same band and are separated by allocating short and distinct time slots, one or several assigned to a user (see Figure 2).

In TDMA, neglecting the overhead due to framing and burst formatting, the multiplexed signal bandwidth will be approximately N_c times higher than in an FDMA system, hence,

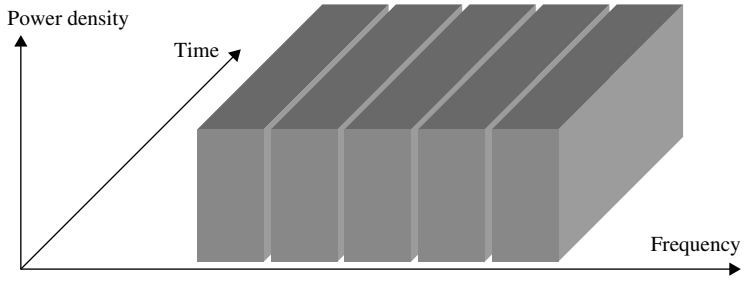

Figure 1 Principle of FDMA (with $N_c = 5$ sub-channels)

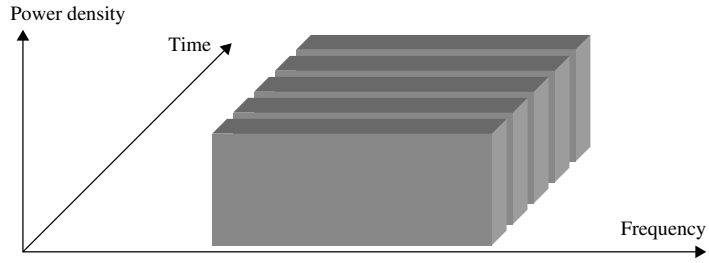

Figure 2 Principle of TDMA (with 5 time slots)

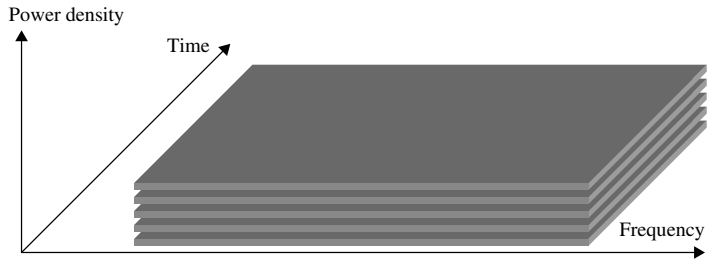

Figure 3 Principle of CDMA (with 5 spreading codes)

Table 3 Advantages and drawbacks of different multiple access schemes

Multiple access scheme	Advantages	Drawbacks
FDMA	– Low transmit power – Robust to multipath – Easy frequency planning – Low delay	– Low peak data rate – Loss due to guard bands – Sensitive to narrow band interference
TDMA	– High peak data rate – High multiplexing gain in case of bursty traffic	– High transmit power – Sensitive to multipath – Difficult frequency planning
CDMA	– Low transmit power – Robust to multipath – Easy frequency planning – High scalability – Low delay	– Low peak data rate – Limited capacity per sector due to multiple access interference

leading to quite complex equalization, especially for high-data rate applications. The channel separation of TDMA and FDMA is based on the orthogonality of signals. Therefore, in a cellular system, the co-channel interference is only present from the reuse of frequency.

On the contrary, in CDMA systems all users transmit at the same time on the same carrier using a wider bandwidth than in a TDMA system (see Figure 3). The signals of

users are distinguished by assigning different spreading codes with low cross-correlation properties. Advantages of the spread spectrum technique are immunity against multipath distortion, simple frequency planning, high flexibility, variable rate transmission and resistance to interference.

In Table 3, the main advantages and drawbacks of FDMA, TDMA and CDMA are summarized.

From Third- to Fourth-Generation Multiple Access Schemes

Besides offering new services and applications, the success of the next generation of wireless systems (4G) will strongly depend on the choice of the concept and technology innovations in architecture, spectrum allocation, spectrum utilization and exploitation [38][39]. Therefore, new high-performance physical layer and multiple access technologies are needed to provide high speed data rates with flexible bandwidth allocation. A low-cost *generic radio interface*, being operational in mixed-cell and in different environments with scalable bandwidth and data rates, is expected to have better acceptance.

The technique of *spread spectrum* may allow the above requirements to be at least partially fulfilled. As explained earlier, a multiple access scheme based on direct sequence code division multiple access (DS-CDMA) relies on spreading the data stream using an assigned spreading code for each user in the time domain [40][45][47][48]. The capability of minimizing multiple access interference (MAI) is given by the cross-correlation properties of the spreading codes. In the case of severe multipath propagation in mobile communications, the capability of distinguishing one component from others in the composite received signal is offered by the autocorrelation properties of the spreading codes [45]. The so-called rake receiver should contain multiple correlators, each matched to a different resolvable path in the received composite signal [40]. Therefore, the performance of a DS-CDMA system will strongly depend on the number of active users, the channel characteristics, and the number of arms employed in the rake. Hence, the system capacity is limited by self-interference and MAI, which results from the imperfect auto- and cross-correlation properties of spreading codes. Therefore, it will be difficult for a DS-CDMA receiver to make full use of the received signal energy scattered in the time domain and hence to handle full load conditions [40].

The technique of *multi-carrier transmission* has recently been receiving wide interest, especially for high data-rate broadcast applications. The history of orthogonal multi-carrier transmission dates back to the mid-1960s, when Chang published his paper on the synthesis of band-limited signals for multichannel transmission [5][6]. He introduced the basic principle of transmitting data simultaneously through a band-limited channel without interference between sub-channels (without *inter-channel interference*, ICI) and without interference between consecutive transmitted symbols (without *inter-symbol interference*, ISI) in time domain. Later, Saltzberg performed further analyses [41]. However, a major contribution to multi-carrier transmission was presented in 1971 by Weinstein and Ebert [49] who used Fourier transform for base-band processing instead of a bank of sub-carrier oscillators. To combat ICI and ISI, they introduced the well-known *guard time* between the transmitted symbols with raised cosine windowing.

The main advantages of multi-carrier transmission are its robustness in frequency selective fading channels and, in particular, the reduced signal processing complexity by equalization in the frequency domain.

The basic principle of multi-carrier modulation relies on the transmission of data by dividing a high-rate data stream into several low-rate sub-streams. These sub-streams are modulated on different sub-carriers [1][4][9]. By using a large number of sub-carriers, a high immunity against multipath dispersion can be provided since the useful symbol duration T_s on each sub-stream will be much larger than the channel time dispersion. Hence, the effects of ISI will be minimized. Since the amount of filters and oscillators necessary is considerable for a large number of sub-carriers, an efficient digital implementation of a special form of multi-carrier modulation, called orthogonal frequency division multiplexing (OFDM), with rectangular pulse-shaping and guard time was proposed in [1]. OFDM can be easily realized by using the discrete Fourier transform (DFT). OFDM, having densely spaced sub-carriers with overlapping spectra of the modulated signals, abandons the use of steep band-pass filters to detect each sub-carrier as it is used in FDMA schemes. Therefore, it offers a high spectral efficiency.

Today, progress in digital technology has enabled the realization of a DFT also for large numbers of sub-carriers (up to several thousand), through which OFDM has gained much importance. The breakthrough of OFDM came in the 1990s as it was the modulation chosen for ADSL in the USA [8], and it was selected for the European DAB standard [11]. This success continued with the choice of OFDM for the European DVB-T standard [13] in 1995 and later for the WLAN standards HIPERLAN/2 and IEEE802.11a [15][30] and recently in the interactive terrestrial return channel (DVB-RCT) [12]. It is also a potential candidate for the future fixed wireless access standards HIPERMAN and IEEE802.16a [16][31]. Table 4 summarizes the main characteristics of several standards employing OFDM.

The advantages of multi-carrier modulation on one hand and the flexibility offered by the spread spectrum technique on the other hand have motivated many researchers to investigate the combination of both techniques, known as *Multi-Carrier Spread Spectrum* (MC-SS). This combination, published in 1993 by several authors independently [7][10][18][25][35][46][50], has introduced new multiple access schemes called MC-CDMA and MC-DS-CDMA. It allows one to benefit from several advantages of both multi-carrier modulation and spread spectrum systems by offering, for instance, high flexibility, high

Table 4 Examples of wireless transmission systems employing OFDM

Parameter	DAB	DVB-T	IEEE 802.11a	HIPERLAN/2
Carrier frequency	VHF	VHF and UHF	5 GHz	5 GHz
Bandwidth	1.54 MHz	8 MHz (7 MHz)	20 MHz	20 MHz
Max. data rate	1.7 Mbit/s	31.7 Mbit/s	54 Mbit/s	54 Mbit/s
Number of sub-carriers (FFT size)	192 up to 1536 (256 up to 2048)	1705 and 6817 (2048 and 8196)	52 (64)	52 (64)

spectral efficiency, simple and robust detection techniques and narrow band interference rejection capability.

Multi-carrier modulation and multi-carrier spread spectrum are today considered potential candidates to fulfill the requirements of next generation (4G) high-speed wireless multimedia communications systems, where *spectral efficiency* and *flexibility* will be considered the most important criteria for the choice of the air interface.

Multi-Carrier Spread Spectrum

Since 1993, various combinations of multi-carrier modulation with the spread spectrum technique as multiple access schemes have been introduced. It has been shown that multi-carrier spread spectrum (MC-SS) offers high spectral efficiency, robustness and flexibility [29].

Two different philosophies exist, namely MC-CDMA (or OFDM-CDMA) and MC-DS-CDMA (see Figure 4 and Table 5).

MC-CDMA is based on a serial concatenation of direct sequence (DS) spreading with multi-carrier modulation [7][18][25][50]. The high-rate DS spread data stream of processing gain P_G is multi-carrier modulated in the way that the chips of a spread data symbol are transmitted in parallel and the assigned data symbol is simultaneously transmitted on each sub-carrier (see Figure 4). As for DS-CDMA, a user may occupy the total bandwidth for the transmission of a single data symbol. Separation of the user's signal is performed in the code domain. Each data symbol is copied on the sub-streams before multiplying it with a chip of the spreading code assigned to the specific user. This reflects that an MC-CDMA system performs the spreading in frequency direction and, thus, has an additional degree of freedom compared to a DS-CDMA system. Mapping of the chips

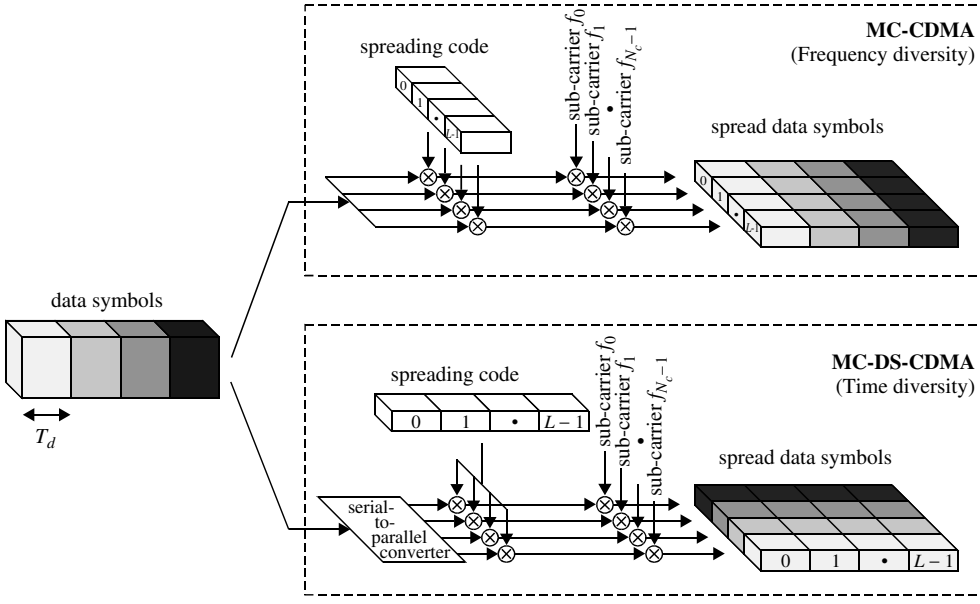

Figure 4 General principle of MC-CDMA and MC-DS-CDMA systems

Table 5 Main characteristics of different MC-SS concepts

Parameter	MC-CDMA	MC-DS-CDMA
Spreading	Frequency direction	Time direction
Sub-carrier spacing	$F_S = \frac{P_G}{N_c T_d}$	$F_S \geqslant \frac{P_G}{N_c T_d}$
Detection algorithm	MRC, EGC, ZF, MMSE equalization, IC, MLD	Correlation detector (coherent rake)
Specific characteristics	Very efficient for the synchronous downlink by using orthogonal codes	Designed especially for an asynchronous uplink
Applications	Synchronous uplink and downlink	Asynchronous uplink and downlink

in the frequency direction allows for simple methods of signal detection. This concept was proposed with OFDM for optimum use of the available bandwidth. The realization of this concept implies a guard time between adjacent OFDM symbols to prevent ISI or to assume that the symbol duration is significantly larger than the time dispersion of the channel. The number of sub-carriers N_c has to be chosen sufficiently large to guarantee frequency nonselective fading on each sub-channel. The application of orthogonal codes, such as Walsh–Hadamard codes for a synchronous system, e.g., the downlink of a cellular system, guarantees the absence of MAI in an ideal channel and a minimum MAI in a real channel. For signal detection, single-user detection techniques such as maximum ratio combining (MRC), equal gain combining (EGC), zero forcing (ZF) or minimum mean square error (MMSE) equalization, as well as multiuser detection techniques like interference cancellation (IC) or maximum likelihood detection (MLD), can be applied.

As depicted in Figure 4, MC-DS-CDMA modulates sub-streams on sub-carriers with a carrier spacing proportional to the inverse of the chip rate. This will guarantee orthogonality between the spectra of the sub-streams [42]. If the spreading code length is smaller or equal to the number of sub-carriers N_c, a single data symbol is not spread in the frequency direction, instead it is spread in the time direction. Spread spectrum is obtained by modulating N_c time spread data symbols on parallel sub-carriers. By using high numbers of sub-carriers, this concept benefits from time diversity. However, due to the frequency nonselective fading per sub-channel, frequency diversity can only be exploited if channel coding with interleaving or sub-carrier hopping is employed or if the same information is transmitted on several sub-carriers in parallel. Furthermore, higher frequency diversity could be achieved if the sub-carrier spacing is chosen larger than the chip rate. This concept was investigated for an asynchronous uplink scenario. For data detection, N_c coherent receivers can be used.

It can be noted that both schemes have a generic architecture. In the case where the number of sub-carriers $N_c = 1$, the classical DS-CDMA transmission scheme is obtained, whereas without spreading ($P_G = 1$) it results in a pure OFDM system.

By using a variable spreading factor in frequency and/or time and a variable sub-carrier allocation, the system can easily be adapted to different environments such as *multicell* and *single cell* topologies, each with different coverage areas.

Today, the field of multi-carrier spread spectrum communications is considered to be an independent and important research topic; see [19] to [23], [26], [36]. Several deep system analysis and comparisons of MC-CDMA and MC-DS-CDMA with DS-CDMA have been performed that show the superiority of MC-SS [24][29][32][33][34]. In addition, new application fields have been proposed such as high-rate cellular mobile (4G), high-rate wireless indoor and fixed wireless access (FWA). In addition to system-level analysis, a multitude of research activities have been addressed to develop appropriate strategies for detection, interference cancellation, channel coding, modulation, synchronization (especially uplink) and low-cost implementation design.

The Aim of this Book

The interest in multi-carrier transmission, especially in multi-carrier spread spectrum, is still growing. Many researchers and system designers are involved in system aspects and the implementation of these new techniques. However, a comprehensive collection of their work is still missing.

The aim of this book is first to describe and analyze the basic concepts of the combination of multi-carrier transmission with spread spectrum, where the different architectures and the different detection strategies are detailed. Concrete examples of its applications for future cellular mobile communications systems are given. Then, we examine other derivatives of MC-SS (e.g., OFDMA, SS-MC-MA and interleaved FDMA) and other variants of the combination of OFDM with TDMA, which are today part of WLAN, WLL and DVB-RCT standards. Basic OFDM implementation issues, valid for most of these combinations, such as channel coding, modulation, digital I/Q-generation, synchronization, channel estimation, and effects of phase noise and nonlinearity are further analyzed.

Chapter 1 covers the fundamentals of today's wireless communications. First a detailed analysis of the radio channel (outdoor and indoor) and its modeling are presented. Then the principle of OFDM multi-carrier transmission is introduced. In addition, a general overview of the spread spectrum technique, especially of DS-CDMA, is given. Examples of applications of OFDM and DS-CDMA for broadcast, WLAN, and cellular systems (IS-95, UMTS) are briefly presented.

Chapter 2 describes the combinations of multi-carrier transmission with the spread spectrum technique, namely MC-CDMA and MC-DS-CDMA. It includes a detailed description of the different detection strategies (single-user and multiuser) and presents their performance in terms of bit error rate (BER), spectral efficiency and complexity. Here a cellular system with a point- to multi-point topology is considered. Both downlink and uplink architectures are examined.

Hybrid multiple access schemes based on MC-SS, OFDM or spread spectrum are analyzed in Chapter 3. This chapter covers OFDMA, being a derivative of MC-CDMA, OFDM-TDMA, SS-MC-MA, interleaved FDMA and ultra wide band (UWB) schemes. All these multiple access schemes have recently received wide interest. Their concrete application fields are detailed in Chapter 5.

The issues of digital implementation of multi-carrier transmission systems, essential especially for system- and hardware designers, are addressed in Chapter 4. Here, the

different functions such as digital I/Q generation, analog/digital conversion, digital multi-carrier modulation/demodulation, synchronization (time, frequency), channel estimation, coding/decoding and other related RF issues such as nonlinearities, phase noise and narrow band interference rejection are analyzed.

In Chapter 5, concrete application fields of MC-SS, OFDMA and OFDM-TDMA for cellular mobile (4G), wireless indoor (WLAN), fixed wireless access (FWA/WLL) and interactive multimedia communication (DVB-T return channel) are outlined, where for each of these systems, the multi-carrier architecture and their main parameters are described. The capacity advantages of using adaptive channel coding and modulation, adaptive spreading and scalable bandwidth allocation are discussed.

Finally, Chapter 6 covers further techniques that can be used to enhance system capacity or offer more flexibility for the implementation and deployment of the transmission systems examined in Chapter 5. Here, diversity techniques such as space time/frequency coding and Tx/Rx antenna diversity in MIMO concepts and software-defined radio (SDR) are introduced.

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