Multi-Carrier and Spread Spectrum Systems

From OFDM and MC-CDMA to LTE and WiMAX

Second Edition

K. Fazel | S. Kaiser

WILEY

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A John Wiley and Sons, Ltd, Publication

This edition first published 2008

Registered office John Wiley & Sons Ltd, The Atrium,
Southern Gate, Chichester,
West Sussex PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication Data

Fazel, Khaled.
Multi-carrier and spread spectrum systems: from OFDM and MC-CDMA to LTE and WiMAX / K. Fazel, S. Kaiser. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-99821-2
1. Spread spectrum communications. 2. Multiplexing. I. Kaiser, Stefan, 1960–II. Title.
TK5103.45.F39 2008
621.382–dc22

2008031728

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

ISBN 978-0-470-99821-2

Typeset by Laserwords Private Limited, Chennai, India
Printed and bound in Singapore by Markono Print Media Pte Ltd.

Multi-Carrier and Spread Spectrum Systems

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.)

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.

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

Preface (Second Edition)

The demand for high data rate wireless multi-media applications has increased significantly in the past few years. The wireless user's pressure towards faster communications, no matter whether mobile, nomadic, or fixed positioned, without extra cost is nowadays a reality. Finding an optimal solution for this dilemma is challenging, not only for manufacturers but also for network operators. The recent strategy followed within ETSI 3GPP LTE and the WiMAX Forum was an evolutionary concept, especially for mobile applications. Both have adopted a new PHY layer multi-carrier transmission with a MIMO scheme, a promising combination offering a high data rate at low cost.

Since the first edition of our book in 2003, the application field of multi-carrier transmission in mobile communications has been extended in two important areas: *3GPP Long Term Evolution* (LTE) and *WiMAX*. Parallel to that, the topic of MIMO in conjunction with OFDM has taken further steps.

New experiences gained during the above-mentioned standardization activities and the latest research results on MIMO-OFDM gave us sufficient background and material to extend this book towards its Second Edition, i.e. covering new application fields (LTE and WiMAX) and new trends on MIMO-OFDM technology. We hope that the Second Edition of this book will further contribute to a better understanding of the principles of multi-carrier transmission and of its variety of application fields, and, finally, it may motivate research toward new developments.

K. Fazel, S. Kaiser

Preface (First Edition)

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 Euro-Labs 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 of the 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. Kaiser

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. Atarashi, 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 Ericsson GmbH and for helpful technical discussions with members of the DOCOMO Euro-Labs and the Mobile Radio Transmission Group from DLR. Further thanks also go to Dr. I. Cosovic from DOCOMO Euro-Labs who provided us with results for the uplink, especially with pre-equalization.

K. Fazel, S. Kaiser

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Introduction

The main feature of the next-generation wireless systems will be the convergence of mult-media 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 3 billion users, highlights the importance of wireless communications in this new millennium. This revolution in the information society has taken place, especially in Europe and Japan through a continuous evolution of emerging standards and products by keeping a seamless strategy for the choice of solutions and parameters. The continuous adaptation of wireless technologies to the user's rapidly changing demands has been one of the main drivers for the success of this evolution. 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, CDMA-2000, WCDMA/UMTS, HSDPA, HSUPA, or 3GPP LTE, but also includes wireless local area networks (WLANs), e.g. IEEE 802.11a/n and Bluetooth, broadband wireless access (BWA) such as WiMAX systems with their first goal to introduce wireless local loops (WLL) services based on ETSI HIPERMAN and IEEE 802.16x standards and in a future step to support full cellular mobility, as well as broadcast systems such as digital audio broadcasting (DAB) and digital video broadcasting (DVB-T and DVB-H).

These trends have accelerated since the beginning of the 1990s with the replacement of the first-generation analogue mobile networks by the current second-generation (2G) systems (GSM, IS-95, D-AMPS, and PDC), which opened the door for a fully digital network. This evolution is continuing with the deployment of the third-generation (3G) systems namely WCDMA/UMTS, HSDPA, HSUPA, and CDMA-2000, referred to as IMT 2000. The *3GPP Long Term Evolution* (LTE) standard with significantly higher data rates than in 3G systems can be considered as 3G evolution. In the meantime, the research community is focusing its activity towards the next-generation mobile systems beyond 3G (B3G), referred to as *IMT-Advanced* or fourth-generation (4G) systems, with even more ambitious technological challenges. Note that especially within the *WINNER Project* [55], which is a European research project, partly funded by the European Commission, innovative solutions for IMT-Advanced are targeted. The WINNER concept covers data rates that are higher than with LTE. The WINNER concept is described in References [54] and [55].

The primary goal of next-generation wireless systems (IMT-Advanced) 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 into 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 IMT-Advanced have not yet been commonly defined, its new air interface will fulfill at least the following requirements:

- *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) for improved coverage;
- *high adaptability and reconfigurability*, supporting different standards and technologies;
- *low latency*, allowing better service quality;
- *low cost*, enabling a rapid market introduction; and
- *future proof*, opening the door for new technologies.

From 2G to 3G and B3G Multiple Access Schemes

2G wireless systems are mainly characterized by the transition from analogue to a fully digital 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 [18, 39], where now it accounts for about 85 % 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 with up to 171.2 kbit/s are possible with the enhancement of the GSM standard, namely the *General Packet Radio Service* (GPRS), by assigning multiple time slots to one link. GPRS uses the same modulation, frequency band, and frame structure as GSM. The *Enhanced Data Rate for Global Evolution* (EDGE) [6] system, which further improves the data rate up to 384 kbit/s, introduces a new spectrum efficient modulation scheme. Parallel to GSM, the American IS-95 standard [45] (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 are possible.

Two further 2G mobile radio systems were introduced: *Digital Advanced Mobile Phone Services* (D-AMPS/IS-136), called TDMA in the USA, and the *Personal Digital Cellular* (PDC) in Japan [30]. The most convincing example of high speed mobile Internet services, called *i-mode*, was introduced 1999 in Japan in the PDC system. The high increase in customers and traffic in the PDC system urged the Japanese to start the first 3G WCDMA network in 2001 under the name *FOMA*.

Trends toward 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, referred to as *International Mobile Telecommunications 2000* (IMT-2000), realizing 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 WCDMA/UMTS [1], HSDPA [2], HSUPA [3], and CDMA-2000 [46] 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 14.4 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), in data rate (variable), and in 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) or *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. In each sub-channel, up to eight users share eight time slots in a TDMA manner [39].
- In the IS-95 standard up to 64 users share the 1.25 MHz channel by CDMA [45]. 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 analogue 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 [29].
- The 3G standards (WCDMA/UMTS and CDMA-2000) adopted by ITU are both based on CDMA [1, 46]. For UMTS, the CDMA-FDD mode, which is known as wideband CDMA (WCDMA), 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 theoretically up to 2 Mbit/s per carrier. Further evolutions of WCDMA are the extensions towards *high speed downlink packet access* (HSDPA) with data rates of up to 14.4 Mbit/s and of *high speed uplink packet access* (HSUPA) with data rates of up to 5.74 Mbit/s. These improvements are obtained by introducing higher order modulation schemes, channel-dependent scheduling, and hybrid ARQ (HARQ) with soft combining together with multiple code allocation. The downlink additionally supports adaptive coding and modulation. The set of HSDPA and HSUPA is termed *high speed packet access* (HSPA) [2, 3].