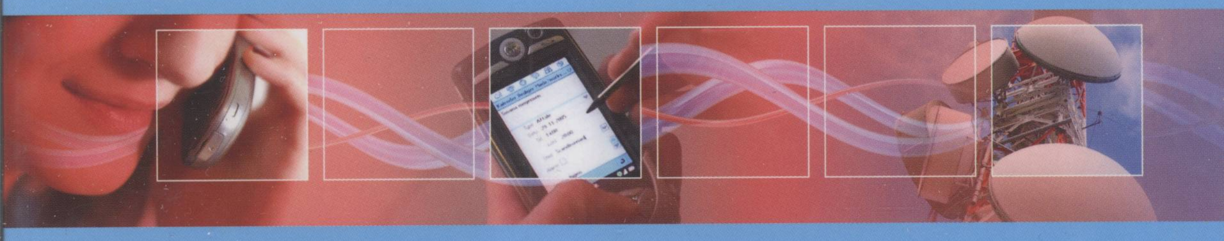
Hyung G. Myung and David J. Goodman

# Single Carrier FDMA

## A New Air Interface for Long Term Evolution



Wiley Series on
Wireless Communications
and Mobile Computing

WILEY

# SINGLE CARRIER FDMA

## A NEW AIR INTERFACE FOR LONG TERM EVOLUTION

**Hyung G. Myung**

*Qualcomm/Flarion Technologies, USA*

**David J. Goodman**

*Polytechnic University, USA*



WILEY

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

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.



*Library of Congress Cataloging-in-Publication Data*

Myung, Hyung G.
Single carrier FDMA : a new air interface for long term evolution / Hyung G. Myung, David J. Goodman.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-72449-1 (cloth)
1. Wireless communication systems. 2. Mobile communication systems. I. Goodman, David J., 1939– II. Title.
TK5103.2.H983 2008
621.384–dc22

2008027441

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

ISBN 978-0-470-72449-1 (HB)

Typeset in 11/13pt Times by Aptara Inc., New Delhi, India.
Printed in Singapore by Markono Print Media Pte Ltd

# SINGLE CARRIER FDMA

## Wiley Series on Wireless Communications and Mobile Computing

*Series Editors:* Dr Xuemin (Sherman) Shen, *University of Waterloo, Canada*
Dr Yi Pan, *Georgia State University, USA*

The 'Wiley Series on Wireless Communications and Mobile Computing' is a series of comprehensive, practical and timely books on wireless communication and network systems. The series focuses on topics ranging from wireless communication and coding theory to wireless applications and pervasive computing. The books offer engineers and other technical professional, researchers, educators, and advanced students in these fields invaluable insight into the latest developments and cutting-edge research.

**Other titles in this series**

Mišić and Mišić: *Wireless Personal Area Networks: Performance, Interconnections and Security with IEEE 802.15.4,* January 2008 987-0-470-51847-2

Takagi and Walke: *Spectrum Requirement Planning in Wireless Communications: Model and Methodology for IMT-Advanced,* April 2008 987-0-470-98647-9

Pérez-Fontán and Mariño Espiñeira: *Modeling the Wireless Propagation Channel: A Simulation Approach with MATLAB®,* August 2008 987-0-470-72785-0

Ippolito: *Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance,* September 2008 978-0-470-72527-6

Lin and Sou: *Charging for Mobile All-IP Telecommunications,* September 2008 987-0-470-77565-3

Hart, Tao, Zhou: *IEEE 802.16j Multi-hop Relay,* March 2009 978-0-470-99399-6

Qian, Muller, Chen: *Security in Wireless Networks and Systems,* May 2009 978-0-470-51212-8

Wang, Kondi, Luthra, Ci: *4G Wireless Video Communications,* May 2009 978-0-470-77307-9

Shen, Cai, Mark: *Multimedia for Wireless Internet — Modeling and Analysis,* May 2009 978-0-470-77065-8

Stojmenovic: *Wireless Sensor and Actuator Networks: Algorithms and Protocols for Scalable Coordination and Data Communication,* August 2009 978-0-470-17082-3

# Preface

Commercial cellular telecommunications date from the early 1980s when the first car telephone arrived on the market. Public acceptance grew rapidly and the technology progressed through a sequence of "generations" that begin with each new decade. The first generation systems in 1980 used *frequency* division multiple access (FDMA) to create physical channels. Digital transmission arrived in the early 1990s with the most popular systems employing *time* division multiple access (TDMA) and others relying on *code* division (CDMA). Third generation technology dating from 2000 uses *code* division whereas the next generation promises a return to *frequency* division. As the preferred form of multiple access migrates through the time-frequency-code space, the bandwidth of the transmission channels steadily increases. The first systems transmitted signals in 25 or 30 kHz bands. Second generation Global System for Mobile (GSM) uses 200 kHz and the CDMA channels occupy 1.25 MHz. The channel spacing of third generation wideband CDMA is 5 MHz and the next generation of cellular systems will transmit signals in bandwidths up to 20 MHz.

In 2008, two FDMA technologies are competing for future adoption by cellular operating companies. WiMAX, standardized by the IEEE (Institute of Electrical and Electronic Engineers), was first developed to provide broadband Internet access to stationary terminals and later enhanced for transmission to and from mobile devices. The other emerging technology, referred to as "long term evolution" (LTE), is standardized by 3GPP (Third Generation Partnership Project). WiMAX and LTE both use Orthogonal FDMA for transmission from base stations to mobile terminals and WiMAX also uses OFDMA for uplink transmission. On the other hand, the LTE standard for uplink transmission is based on Single Carrier FDMA (SC-FDMA), the principal subject of this book.

We aim to introduce SC-FDMA to an audience of industry engineers and academic researchers. The book begins with an overview of cellular technology evolution that can be appreciated by novices to the subject and non-technical readers. Subsequent chapters become increasingly specialized.

The first half of the book is a tutorial that introduces SC-FDMA and compares it with related techniques including single carrier modulation with frequency domain equalization, orthogonal frequency division modulation (used for example in wireless LANs and digital video broadcasting), and orthogonal FDMA.

The second chapter describes the wireless channel characteristics with the strongest impact on the performance of FDMA. The third chapter presents the signal processing operations of SC-FDMA and the time-domain and frequency-domain properties of SC-FDMA signals. Chapter 4 covers the physical layer of the LTE uplink, providing details of the SC-FDMA implementation standardized by 3GPP. The purpose of the standard is to ensure compatibility between conforming base stations and terminal equipment. However, the standard also allows for considerable operational flexibility in practical equipment and networks. Many of the implementation decisions fall in the category of "scheduling", the subject of Chapter 5. Scheduling, also an important aspect of OFDMA, involves apportioning the channel bandwidth among terminals by means of subcarrier mapping, adaptive modulation, and power control. In addition to a general description of scheduling issues, Chapter 5 presents research results obtained by the authors and our colleagues at Polytechnic University, comparing the effects of various scheduling techniques on system performance.

The final three chapters are also derived from our research. The subject of Chapter 6 is the application of multiple input multiple output (MIMO) transmission and reception to SC-FDMA systems, and Chapter 7 presents the peak power characteristics of SC-FDMA signals. A salient motivation for employing SC-FDMA in a cellular uplink is the fact that its peak-to-average power ratio (PAPR) is lower than that of OFDMA. Chapter 7 uses mathematical derivations and computer simulation to derive the probability model of instantaneous power for a wide variety of SC-FDMA system configurations. It also examines the possibility of clipping the transmitted signal amplitude to reduce the PAPR at the expense of increased binary error rate and increased out-of-band emissions. Finally, Chapter 8 describes the use of MATLAB® to perform link-level and PAPR simulations of SC-FDMA and related techniques.

We are pleased to acknowledge the contribution of Dr Junsung Lim, now at Samsung Corporation, who introduced us to the subject of SC-FDMA. In the course of his Ph.D. studies, Dr Lim collaborated with us in a large portion of the research described in the second half of this book. We were joined in this effort by Kyungjin Oh, who wrote an M.S. dissertation at Polytechnic University on the impact of imperfect channel state information on SC-FDMA. We are also grateful for the encouragement and advice we received from the staff of John Wiley & Sons, Ltd, publisher of this book. We convey special thanks to Sarah Hinton and Emily Dungey, our main contacts at Wiley as we wrote the book. Our special thanks also go to Mark Hammond who was instrumental in the initial process of this book's writing. We are also grateful to Katharine Unwin and Alex King at Wiley who contributed to the quality of this book.

The material in this book is partially based upon work supported by the National Science Foundation under Grant No. 0430145.

# Contents

# 1

# Introduction

In less than three decades, the status of cellular telephones has moved from laboratory breadboard via curious luxury item to the world's most pervasive consumer electronics product. Cellular phones have incorporated an ever-growing array of other products including pagers, cameras, camcorders, music players, game machines, organizers, and web browsers. Even though wired telephony is 100 years older and the beneficiary of "universal service" policies in developed countries, the number of cellular phones has exceeded wired phones for a few years and the difference keeps growing. For hundreds of millions of people in developing countries, cellular communications is the only form of telephony they have experienced.

First conceived as a marriage of mature telephony and mature radio communications, cellular communications is now widely recognized as its own technical area and a driver of innovation in a wide range of technical fields including – in addition to telephony and radio – computing, electronics, cryptography, and signal processing.

## 1.1 Generations

The subject of this book, Single Carrier Frequency Division Multiple Access (SC-FDMA), is a novel method of radio transmission under consideration for deployment in future cellular systems. The development of SC-FDMA represents one step in the rapid evolution of cellular technology. Although technical progress is continuous and commercial systems frequently adopt new improvements, certain major advances mark the transition from one generation of technology to another. First generation systems, introduced in the early 1980s, were characterized by analog

*Single Carrier FDMA: A New Air Interface for Long Term Evolution* Hyung G. Myung and David J. Goodman

speech transmission. Second generation technology, deployed in the 1990s, transmits speech in digital format. Equally important, second generation systems introduced advanced security and networking technologies that make it possible for a subscriber to initiate and receive phone calls throughout the world.

Even before the earliest second generation systems arrived on the market, the cellular community turned its attention to third generation (3G) technology with the focus on higher bit rates, greater spectrum efficiency, and information services in addition to voice telephony. In 1985, the International Telecommunication Union (ITU) initiated studies of Future Public Land Telecommunication Systems [1]. Fifteen years later, under the heading IMT-2000 (International Mobile Telecommunications-2000), the ITU issued a set of recommendations, endorsing five technologies as the basis of 3G mobile communications systems. In 2008, cellular operating companies are deploying two of these technologies, referred to as WCDMA (wideband code division multiple access) and CDMA2000, where and when they are justified by commercial considerations. Meanwhile, the industry is looking beyond 3G and considering SC-FDMA as a leading candidate for the "long term evolution" (LTE) of radio transmissions from cellular phones to base stations. It is anticipated that LTE technology will be deployed commercially around 2010 [2].

With respect to radio technology, successive cellular generations have migrated to signals transmitted in wider and wider radio frequency bands. The radio signals of first generation systems occupied bandwidths of 25 and 30 kHz, using a variety of incompatible frequency modulation formats. Although some second generation systems occupied equally narrow bands, the two that are most widely deployed, GSM and CDMA, occupy bandwidths of 200 kHz and 1.25 MHz, respectively. The third generation WCDMA system transmits signals in a 5 MHz band. This is the approximate bandwidth of the version of CDMA2000 referred as 3X-RTT (radio transmission technology at three times the bandwidth of the second generation CDMA system). The version of CDMA2000 with a large commercial market is 1X-RTT. Its signals occupy the same 1.25 MHz bandwidth as second generation CDMA, and in fact it represents a graceful upgrade of the original CDMA technology. For this reason, some observers refer to 1X-RTT as a 2.5G technology [3]. Planners anticipate even wider signal bands for the long term evolution of cellular systems. Orthogonal Frequency Division Multiplexing (OFDM) and SC-FDMA are attractive technologies for the 20 MHz signal bands under consideration for the next generation of cellular systems.

## 1.2 Standards

The technologies employed in cellular systems are defined formally in documents referred to as "compatibility specifications". A compatibility specification is one type of technical standard. Its purpose is to ensure that two different network elements interact properly. In the context of cellular communications, the two most obvious examples of interacting equipment types are cellular phones and base stations. As readers of this book are aware, standards organizations define a large number of other network elements necessary for the operation of today's complex cellular networks.

In addition to cellular phones and base stations, the most familiar cellular network elements are mobile switching centers, home location registers, and visitor location registers. In referring to standards documents, it is helpful to keep in mind that the network elements defined in the documents are "functional" elements, rather than discrete pieces of equipment. Thus, two different network elements, such as a visitor location register and a mobile switching center, can appear in the same equipment and the functions of a single network element (such as a base transceiver station) can be distributed among dispersed devices.

Figure 1.1 shows the network elements and interfaces in one 3G system [4]. The network elements (referred to in the standards as "entities") are contained in four major groups enclosed by dotted boxes. The core network (CN) is at the top of the figure. Below the core network is the radio access network with three sets of elements; a Base Station System (BSS) exchanges radio signals with mobile stations (MS) to deliver circuit switched services, and a corresponding Radio Network System (RNS) exchanges radio signals with mobile stations to deliver packet switched services. This book focuses on the radio signals traveling across the air interfaces. The Um interface applies to circuit switched services carrying signals between mobile stations and Base Transceiver Stations (BTS). Uu applies to packet switched services carrying signals between a mobile station and a base station system.

## 1.3 Cellular Standards Organizations 3GPP and 3GPP2

Two Third Generation Partnership Projects publish 3GPP cellular standards. The original Partnership Project, 3GPP, is concerned with descendents of the Global System for Mobile (GSM). The 3G technologies standardized by 3GPP are often referred to collectively as WCDMA (wideband code division multiple access). 3GPP uses two other acronyms

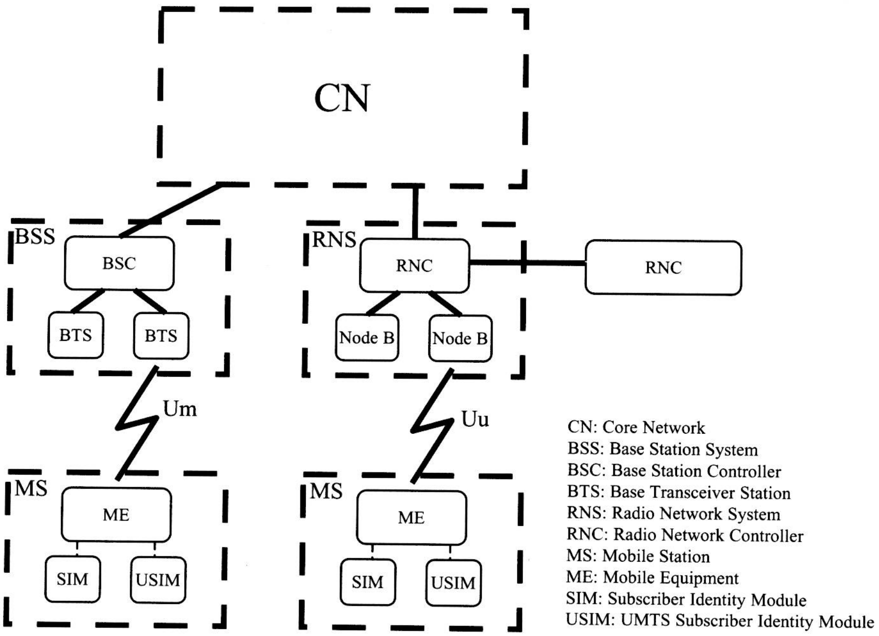



**Figure 1.1** Basic configuration of a public land mobile network (PLMN) supporting circuit switched (CS) and packet switched (PS) services and interfaces [4]. *Source:* ETSI (European Telecommunications Standards Institute) © 2007. 3GPP™ TSs and TRs are the property of ARIB, ATIS, CCSA, ETSI, TTA and TTC who jointly own the copyright in them. They are subject to further modifications and are therefore provided to you "as is" for information purposes only. Further use is strictly prohibited.

to describe its specifications: UMTS (Universal Mobile Telecommunications System) applies to the entire cellular network contained in hundreds of 3GPP specifications; and UTRAN (Universal Terrestrial Radio Access Network) refers to the collection of network elements, and their interfaces, used for transmission between mobile terminals and the network infrastructure. The other project, 3GPP2, is concerned with advanced versions of the original CDMA cellular system. The technologies standardized by 3GPP2 are often referred to collectively as CDMA2000.

The Partnership Projects consist of "organizational partners", "market representation partners", and "individual members". The organizational partners are the regional and national standards organizations, listed in Table 1.1, based in North America, Europe, and Asia. The market representation partners are industry associations that promote deployment of specific technologies. The individual members are companies associated with one

**Table 1.1** Organizational members of the Partnership Projects

| Organizational member | Nationality | Affiliation |
|---|---|---|
| Association of Radio Industries and Businesses | Japan | 3GPP and 3GPP2 |
| Alliance for Telecommunication Industry Solutions | United States | 3GPP |
| China Communications Standards Association | China | 3GPP and 3GPP2 |
| European Telecommunication Standards Institute | Europe | 3GPP |
| Telecommunications Industry Association | North America | 3GPP2 |
| Telecommunications Technology Association | Korea | 3GPP and 3GPP2 |
| Telecommunication Technology Committee | Japan | 3GPP and 3GPP2 |

or more of the organizational partners. In October 2006 there were 297 individual members of 3GPP and 82 individual members of 3GPP2.

The technologies embodied in WCDMA and CDMA2000 appear in hundreds of technical specifications covering all aspects of a cellular network. In both Partnership Projects, responsibility for producing the specifications is delegated to Technical Specification Groups (TSG), each covering one category of technologies. In 3GPP, the TSGs are further subdivided into Work Groups (WG). The publication policies of the two Partnership Projects are different. 3GPP periodically "freezes" a complete set of standards, including many new specifications. Each set is referred to as a "Release". Each Release is complete in that it incorporates all unchanged sections of previous standards that are still in effect as well as any new and changed sections. 3GPP also publishes preliminary specifications that will form part of a future Release. By contrast, each TSG in 3GPP2 publishes a new or updated specification whenever the specification obtains necessary approvals.

Release 5 of WCDMA was frozen in 2002, Release 6 in 2005, and Release 7 in 2007 [5]. In 2008, LTE specifications are being finalized as Release 8. Two of the innovations in Release 5 are High Speed Downlink Packet Access (HSDPA) and the IP Multimedia Subsystem (IMS). In Release 6, the innovations are High Speed Uplink Packet Access (HSUPA), the Multimedia Broadcast/Multicast Service (MBMS), and Wireless LAN/cellular interaction, and in Release 7, Multiple Input