SIGNAL PROCESSING FOR 5G

ALGORITHMS AND IMPLEMENTATIONS

EDITED BY

FA-LONG LUO

CHARLIE (JIANZHONG) ZHANG

IEEE PRESS

WILEY

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This edition first published 2016

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

Names: Luo, Fa-Long, editor. | Zhang, Charlie, editor.
Title: Signal processing for 5G : algorithms and implementations / edited by Fa-Long Luo, Charlie Zhang.
Description: Chichester, West Sussex, United Kingdom : John Wiley & Sons Inc., [2016] | Includes bibliographical references and index.
Identifiers: LCCN 2016010334| ISBN 9781119116462 (cloth) | ISBN 9781119116486 (epub) | ISBN 9781119116479 (Adobe PDF)
Subjects: LCSH: Signal processing–Digital techniques–Mathematics. | Mobile communication systems–Standards. | Wireless communication systems–Standards. | Computer algorithms.
Classification: LCC TK5102.9 .S5423 2016 | DDC 621.3845/6–dc23 LC record available at https://lccn.loc.gov/2016010334

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

Set in 10/12pt, TimesLTStd by SPi Global, Chennai, India.

Printed and bound in Malaysia by Vivar Printing Sdn Bhd

1 2016

Preface

5G wireless technology is developing at an explosive rate and is one of the biggest areas of research within academia and industry. In this rapid development, signal processing techniques are playing the most important role. In 2G, 3G and 4G, the peak service rate was the dominant metric for performance. Each of these previous generations was defined by a standout signal processing technology that represented the most important advance made. In 2G, this technology was time-division multiple access (TDMA); in 3G, it was code-division multiple access (CDMA); and in 4G, it was orthogonal frequency-division multiple access (OFDMA). However, this will not be the case for 5G systems – there will be no dominant performance metric that defines requirements for 5G technologies. Instead, a number of new signal processing techniques will be used to continuously increase peak service rates, and there will be a new emphasis on greatly increasing capacity, coverage, efficiency (power, spectrum, and other resources), flexibility, compatibility, reliability and convergence. In this way, 5G systems will be able to handle the explosion in demand arising from emerging applications such as big data, cloud services, and machine-to-machine communication.

A number of new signal processing techniques have been proposed for 5G systems and are being considered for international standards development and deployment. These new signal processing techniques for 5G can be categorized into four groups:

1. new modulation and coding schemes
2. new spatial processing techniques
3. new spectrum opportunities
4. new system-level enabling techniques.

The successful development and implementation of these technologies for 5G will be challenging and will require huge effort from industry, academia, standardization organizations and regulatory authorities.

From an algorithm and implementation perspective, this book aims to be the first single volume to provide a comprehensive and highly coherent treatment of all the signal processing techniques that enable 5G, covering system architecture, physical (PHY)-layer (down link and up link), protocols, air interface, cell acquisition, scheduling and rate adaption, access procedures, relaying and spectrum allocation. This book is organized into twenty-three chapters in five parts.

Part 1: Modulation, Coding and Waveform for 5G

The first part, consisting of eight chapters, will present and compare the detailed algorithms and implementations of all major candidate modulation and coding schemes for 5G, including generalized frequency division multiplexing (GFDM), filter-bank multi-carrier (FBMC) transmission, universal filtered multi-carrier (UFMC) transmission, bi-orthogonal frequency division multiplexing (BFDM), spectrally efficient frequency division multiplexing (SEFDM), the faster-than-Nyquist signaling (FTN) based time-frequency packing (TFP), sparse code multiple access (SCMA), multi-user shared access (MUSA) and non-orthogonal multiple access (NOMA).

With a focus on FBMC, GFDM, UFMC, BFDM and TFP, Chapter 1 presents a comprehensive introduction to these waveform generation and modulation schemes by covering the basic principles, mathematical models, step-by-step algorithms, implementation complexities, schematic processing flows and the corresponding application scenarios involved.

Chapter 2 is devoted to the FTN data transmission method, with the emphasis on applications that are important for future 5G systems. What is explored in this chapter mainly includes time-FTN methods with non-binary modulation and multi-subcarrier methods that are similar in structure to OFDM. In either, there is an acceleration processing in time or compacting in frequency that makes signal streams no longer orthogonal. FTN can be combined with error-correcting coding structures to form true waveform coding schemes that work at high-bit rates per Hertz and second. As a matter of fact, FTN based systems can potentially double data transmission rates.

The technical evolution from OFDM to FBMC is addressed in Chapter 3, covering the principles, algorithms, designs and implementations of these two schemes. This chapter first presents the details of OFDM-based schemes and the major shortcomings that prevent them from being employed in 5G. Through introduction of synthesis and analysis filter banks, prototype filter design and the corresponding polyphase implementation, Chapter 3 then extensively deals with the working principles of FBMC and compares it with OFDM in terms of performance – power spectral density and out of band power radiation – and complexity – number of fast Fourier transforms and filter banks. One can also see from this chapter that OFDM is a special case of FBMC.

Easy and effective integration with massive multiple-input and multiple-output (MIMO) technology is a key requirement for a modulation and waveform generation scheme in 5G. Chapter 4 demonstrates that FBMC can serve as a viable candidate waveform in the application of massive MIMO. The chapter outlines the system model, algorithm formulation, self-equalization property and pilot contamination of FBMC for massive MIMO channels, and also shows that while FBMC offers the same processing gain as OFDM, it offers the advantages of: more flexible carrier aggregation (CA), higher bandwidth efficiency – because of the absence of cyclic prefix (CP) – blind channel equalization and larger subcarrier spacing, and hence less sensitivity to carrier frequency offset and lower peak-to-average power ratio (PAPR).

Chapter 5 presents a non-orthogonal multicarrier system, namely, spectrally efficient frequency division multiplexing (SEFDM), which packs subcarriers at a frequency separation less than the symbol rate while maintaining the same transmission rate per individual subcarrier. Thus spectral efficiency is improved in comparison with the OFDM system. By transmitting the same amount of data, the SEFDM system can conceptually save up to 45% bandwidth.

This chapter also describes a practical experiment in which the SEFDM concept is evaluated in a CA scenario considering a realistic fading channel. On the other hand, SEFDM involves higher computation complexity and longer processing delays, mainly due to the requirement for complex signal detection. This suggests that advanced hardware implementation is still highly desirable, so as to make SEFDM a better fit to 5G.

As pointed out in Chapter 6, non-orthogonal multi-user superposition and shared access is a promising technology that can increase the system throughput and simultaneously serve massive connections. Non-orthogonal access allows multiple users to share time and frequency resources in the same spatial layer via simple linear superposition or code-domain multiplexing. This chapter overviews all major non-orthogonal access schemes, categorizing them into two groups:

- the non-spreading methods, where modulation symbols are one-to-one mapped to the time/frequency resource elements
- the spreading methods, where symbols are first spread and then mapped to time/frequency resources.

Their design principles, key features, advantages and disadvantages are extensively discussed in this chapter.

Chapter 7 is devoted to a new multiple access scheme, termed NOMA, which introduces power-domain user multiplexing and exploits channel differences among users to improve spectrum efficiency. This chapter also explains the interface design aspects of NOMA, for example multi-user scheduling and multi-user power control, and its combination with MIMO. The performance evaluation and ongoing experimental trials of downlink and uplink NOMA are reported. The simulation results and the measurements obtained from the testbed show that under multiple configurations the cell throughput achieved by NOMA is 30% higher than that of OFDMA.

With a tutorial style, Chapter 8 presents an overview of all the major multicarrier modulation (MCM) candidates for 5G, categorizing them into three groups:

- subcarrier filtered MCM using linear convolution
- subcarrier filtered MCM using circular convolution
- subband windowed MCM.

General comparisons of these candidate algorithms are made in this chapter, covering PAPR, OOB emission, processing and implementation complexity, spectrum efficiency, the requirement of CP, intercarrier interference, intersymbol interference, multipath distortion, orthogonality and the related effects of frequency offset and phase noise, synchronization requirements in both the time domain and the frequency domain, latency, mobility, compatibility and integration with other processing such as massive MIMO.

Part 2: New Spatial Signal Processing for 5G

The five chapters in Part 2 focus on new spatial signal processing technologies for 5G, mainly addressing massive MIMO, full-dimensional MIMO (FD-MIMO), three-dimensional MIMO

(3D-MIMO), adaptive 3D beamforming and diversity, continuous aperture phased MIMO (CAP-MIMO) and orbital angular momentum (OAM) based multiplexing. Chapter 9 mainly deals with the principle, theory, algorithm, design, testing, implementation and prototyping on advanced computing and processing platforms for the massive MIMO technique, which will certainly be employed in 5G standards. Core processing blocks, such as downlink precoding, uplink detection and channel estimation, are reviewed first, after which the emphasis is put on the various hardware implementation issues of massive MIMO, covering radio frequency (RF) front-end calibration, baseband processing, synchronization analyses, testbed design and system prototyping, as well as the corresponding deployment scenarios.

Design and implementation of massive MIMO transmission and reception, which uses millimeter wave (mmWave) bands, is presented in Chapter 10. More specifically, this chapter proposes a framework for the design, analysis, testing and practical implementation of a new MIMO transceiver architecture: CAP-MIMO. Using the concept of beam-space MIMO communication – multiplexing data into multiple orthogonal spatial beams in order to optimally exploit the spatial antenna dimension – CAP-MIMO combines the directivity gains of traditional antennas, the beam-steering capability of phased arrays, and the spatial multiplexing gains of MIMO systems to realize the multi-GBps capacity potential of mmWave technology, as well as the unprecedented operational functionality of dynamic multibeam steering and data multiplexing.

Chapter 11 mainly deals with the modeling and measurement of 3D propagation channels, which play very important roles in designing and implementing an FD-MIMO and 3D-beamforming system. This chapter first presents the fundamental channel descriptions and then provides advanced measurement and modeling techniques for 3D propagation channels. The related measurement results and theoretical analyses for those propagation effects that significantly influence 3D channel behaviors are also outlined. This chapter can serve as a good start for modeling and measuring many other propagation channels arising in application scenarios such as the outdoor-to-indoor scenario and high-density-user scenario.

From theory to practice, all technical aspects of the massive-antenna-based 3D-MIMO techniques are addressed in Chapter 12, with the emphasis on performance evaluation. More specifically, this chapter evaluates the performance of 3D-MIMO with massive antennas by system-level simulation, using practical assumptions and a channel model, and by field trials, with a commercial terminal and networks. In addition, extensive comparisons and analyses of the system-level simulation results and the field-trial test measurements are provided. It is shown that an active antenna system (AAS) can make a good compromise between cost and performance by integrating the active transceivers and the passive antenna array into one unit. This suggests that the AAS can be considered key to commercialization of 3D-MIMO with massive antennas in future 5G systems.

Chapter 13 presents a comprehensive introduction to the basic concept of the OAM of electromagnetic (EM) waves and its applications in wireless communication. It covers the generation, detection of multiplexing and demultiplexing of OAM beams, as well as analyses of the propagation effects in OAM channels. As reported in this chapter, OAM-based multiplexing can increase the system capacity and spectral efficiency of wireless communication links by transmitting multiple coaxial data streams. Moreover, OAM multiplexing can also be combined with the polarization multiplexing and the traditional spatial multiplexing to further improve system performance in terms of the capacity and spectral efficiency.

Part 3: New Spectrum Opportunities for 5G

Organized into four chapters, Part 3 is devoted to signal processing algorithms and their implementation for 5G, taking advantage of new spectrum opportunities, such as the mmWave band and full-duplex (FD) transmission. Chapter 14 provides an overview of the building of a mmWave proof of concept (PoC) system for 5G, covering the RF front end, real-time control, analog-to-digital and digital-to-analog converters, distributed multiprocessor control and baseband processing implementation. Some important requirements of a flexible prototyping platform are discussed in this chapter, along with the software and hardware system architecture needed to enable high-throughput, high-bandwidth applications such as mmWave radio access technology for 5G. For the purpose of showing how to handle design and implementation challenges, a case study of the design of a mmWave PoC system on the basis of a commercial off-the-shelf platform is provided in this chapter as well.

Chapter 15 focuses on mmWave channel modeling and also discusses other signal processing problems for mmWave communication in 5G. Two approaches to meet the requirements of the 5G mmWave channel model are presented in this chapter, namely:

- an enhanced 3GPP-spatial channel model
- a ray-propagation-based statistical model.

Using understanding and analyses of the mmWave channel characteristics, this chapter provides system-design considerations for 5G mmWave band radio access technology and key signal processing technologies related to 5G mmWave communications, including beam acquisition, channel estimation and interference handling.

The general principles and basic algorithms of FD transmission are given in Chapter 16, which explains FD system requirements, self-interference cancellation (SIC) techniques, implementation challenges, impairment mitigation and hardware integration with MIMO. FD operation offers not only the potential to double spectral efficiency (bits/second/Hz) but also improvement of the reliability and flexibility of dynamic spectrum allocation. Meanwhile, SIC is the key to making FD a reality. With the emphasis on signal processing aspects of SIC, this chapter outlines four SIC techniques:

- passive self-interference (SI) suppression in the propagation domain
- active SIC in the analog domain
- active SIC in the digital domain
- auxiliary chain SIC.

Chapter 17 provides an overview of state-of-the-art SI mitigation and cancellation techniques for multi-antenna in-band FD communication, including bidirectional and relay transmission. Design and implementation of FD transceivers is described through concrete examples, notably passive isolation, RF cancellation and nonlinear and adaptive digital cancellation. In the final part of Chapter 17, a demonstration of the in-band full-duplex transceiver is given. The demonstration combines the antenna design with RF and digital cancellation in a relay case, showing that overall SI suppression of nearly 100-dB – down to the noise level – can be achieved, even when using regular low-cost components.

Part 4: New System-level Enabling Technologies for 5G

Part 4 consists of four chapters, which address all the new system-level enabling technologies for 5G, including cloud radio access network (C-RAN), device-to-device (D2D) communication and ultradense networks (UDN). In Chapter 18, major signal processing issues for C-RAN are first reviewed and then the emphasis is moved to two key baseband signal processing steps, namely channel estimation in the uplink and channel encoding/linear precoding in the downlink. Together with theoretical analyses and numerical simulations, the chapter outlines the corresponding algorithms for joint optimization of baseband fronthaul compression and baseband signal processing under different PHY functional splits, whereby uplink channel estimation and downlink channel encoding/linear precoding are carried out either at remote radio heads or at the baseband unit.

Motivated by the consideration that energy efficiency is one of the drivers of 5G networks, Chapter 19 addresses the problem of power allocation for energy efficiency in wireless interference networks. This is formulated as the maximization of the network global energy efficiency with respect to all of the user equipment's transmit power, and a solution to the problem using sequential fractional programming algorithms is outlined. As pointed out at the beginning of this chapter, D2D communication is being considered as one of the key ingredients of 5G wireless networks. Therefore, the use of the sequential fractional programming algorithms in a 5G cellular system with D2D communication is described, including algorithm details, theoretical analyses and numerical simulations.

Chapter 20 is devoted to ultradense networks (UDNs), which are considered to be one of the paramount and dominant approaches to meet the ultra-high traffic volume, density and capacity required for 5G. All of the major technology challenges for deployment and operation of UDN are addressed in this chapter, including site acquisition and expenditure, network operation and management, interference management, mobility management and backhaul resources. Key technologies presented include network coordination, interference mitigation or cancellation-based receivers, dual connectivity, virtual cell, virtual layer, mobility anchor and handover command diversity, as well as joint time and frequency synchronization.

The scope of Chapter 21 is to provide a thorough analysis and discussion of the radio resources management (RRM) aspects of UDNs, with the emphasis on centralized optimization problem modeling and solving. By first presenting a series of mathematical models and programming algorithms for optimal RRM decisions and then applying these algorithms to potential UDN system setups, the chapter explores rate-performance trends as a function of infrastructure densification, as well as the impact of individual RRM dimension optimization on overall performance. It is shown that optimal RRM serves as a key enabler for getting the most of the resource reuse and proximity benefits offered by UDNs.

Part 5: Reference Design and 5G Standard Development

Serving as a practical implementation reference design example and a proof of concept, the real-time prototyping of an FD communication system for 5G is described in Chapter 22, which first reviews major self-interference cancellation schemes and then presents the details of prototyping in hardware architectures, processing flows, programming tools and testing setups. The prototyping system presented in this chapter consists of four main components:

- a dual-polarized antenna
- controller
- field-programmable gate array modules
- the corresponding RF front ends.

All of the key technology issues in converging FD concepts to real silicon are extensively addressed in this chapter: analog and digital SIC, synchronization, reference symbol allocation and channel estimation, cancellation measurement and throughput testing.

Chapter 23 is the last chapter of this book. The standards roadmap from 4G to 5G is first reviewed, and then the major enabling technologies and a more detailed roadmap of the 5G standard development are discussed. As summarized in this chapter, the technologies to be employed in 5G standards should not only enable efficient support of enhanced mobile broadband, which has been a major focus of all the previous generations, but should also enable new services, such as massive-machine-type communications, ultra-reliable communications and ultralow-latency communications. From a standards development and a regulatory-authority point of view, this chapter also shows that new frequency bands above 6 GHz (up to 100 GHz) are expected to play a very important role in 5G networks.

For whom is this book written?

It is hoped that this book will serve not only as a complete and invaluable reference for professional engineers, researchers, manufacturers, network operators, software developers, content providers, service providers, broadcasters, and regulatory bodies aiming at development, standardization, deployment and applications development of 5G systems and beyond, but also as a textbook for graduate students in circuits, signal processing, wireless communications, microwave technology, information theory, antennas and propagation, and system-on-chip implementation.

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Contents

Preface xvii

List of Contributors xxv

Part I MODULATION, CODING AND WAVEFORM FOR 5G

1 An Introduction to Modulations and Waveforms for 5G Networks **3**
Stefano Buzzi, Alessandro Ugolini, Alessio Zappone and Giulio Colavolpe

1.1 Motivation and Background 3
1.1.1 The LTE Solution: OFDM and SC-FDMA 6
1.2 New Modulation Formats: FBMC, GFDM, BFDM, UFMC and TFP 7
1.2.1 Filter-bank Multicarrier 7
1.2.2 Generalized Frequency Division Multiplexing 10
1.2.3 Bi-orthogonal Frequency Division Multiplexing 13
1.2.4 Universal Filtered Multicarrier 14
1.2.5 Time-frequency Packing 15
1.2.6 Single-carrier Schemes 18
1.3 Waveform Choice 19
1.4 Discussion and Concluding Remarks 20
References 22

2 Faster-than-Nyquist Signaling for 5G Communication **24**
John B. Anderson

2.1 Introduction to FTN Signaling 25
2.1.1 Definition of FTN: FTN from Detection Theory 26
2.1.2 The Shannon Limit for FTN 31
2.1.3 Summary 32
2.2 Time FTN: Receivers and Performance 32
2.2.1 The BCJR Algorithm and Iterative Decoding 33
2.2.2 Binary Coded FTN Performance 36
2.2.3 Four-level Coded FTN 38
2.2.4 Summary 41

2.3 Frequency FTN Signaling 41
2.3.1 Definition of Frequency FTN 41
2.3.2 Implementation of Frequency FTN 44
2.3.3 Summary 44
2.4 Summary of the Chapter 45
References 46

3 From OFDM to FBMC: Principles and Comparisons **47**
Wei Jiang and Thomas Kaiser
3.1 Introduction 47
3.2 The Filter Bank 49
3.2.1 The Synthesis Filters 49
3.2.2 The Analysis Filters 51
3.3 Polyphase Implementation 53
3.4 OFDM 55
3.4.1 Cyclic Prefix 56
3.4.2 Guard Band 60
3.5 FBMC 61
3.6 Comparison of FBMC and Filtered OFDM 62
3.6.1 Classical Approaches to Sidelobe Suppression 63
3.6.2 Performance 64
3.6.3 Complexity 65
3.7 Conclusion 65
References 66

4 Filter Bank Multicarrier for Massive MIMO **67**
Arman Farhang, Nicola Marchetti and Behrouz Farhang-Boroujeny
4.1 System Model and FBMC Formulation in Massive MIMO 69
4.1.1 Polyphase-based CMT in Massive MIMO 69
4.1.2 FS-based CMT in Massive MIMO 72
4.2 Self-equalization Property of FBMC in Massive MIMO 74
4.2.1 Numerical Study of Polyphase-based CMT in a Massive MIMO Channel 75
4.2.2 Numerical Study of FS-based CMT in a Massive MIMO Channel 79
4.3 Comparison with OFDM 80
4.4 Blind Equalization and Pilot Decontamination 82
4.4.1 Simulation Results 85
4.5 Conclusion 87
References 88

5 Bandwidth-compressed Multicarrier Communication: SEFDM **90**
Izzat Darwazeh, Tongyang Xu and Ryan C Grammenos
5.1 Introduction 91
5.2 SEFDM Fundamentals 93
5.2.1 The Principle of SEFDM 93
5.2.2 Generation of SEFDM Signals 95
5.2.3 Detection of SEFDM Signals 97

5.3 Block-SEFDM 97
5.3.1 Principle of Block-SEFDM 97
5.3.2 Two-stage Signal Detection 98
5.4 Turbo-SEFDM 102
5.4.1 Principle of Turbo-SEFDM 102
5.4.2 Soft Detection 103
5.5 Practical Considerations and Experimental Demonstration 106
5.5.1 Channel Estimation 106
5.5.2 Experimental Demonstration 109
5.6 Summary 112
References 112

6 Non-orthogonal Multi-User Superposition and Shared Access 115
Yifei Yuan

6.1 Introduction 115
6.2 Basic Principles and Features of Non-orthogonal Multi-user Access 116
6.2.1 Non-orthogonal Multi-user Superposition for Improved Spectral Efficiency 117
6.2.2 Non-orthogonal Multi-user Access for Massive Connectivity 119
6.3 Downlink Non-orthogonal Multi-user Transmission 121
6.3.1 Direct Superposition without Gray Mapping 121
6.3.2 Superposition with Gray Mapping 121
6.4 Uplink Non-orthogonal Multi-user Access 129
6.4.1 LDS-CDMA/OFDM 129
6.4.2 SCMA 131
6.4.3 MUSA 132
6.4.4 PDMA 138
6.5 Summary and Future Work 140
References 142

7 Non-Orthogonal Multiple Access (NOMA): Concept and Design 143
Anass Benjebbour, Keisuke Saito, Anxin Li, Yoshihisa Kishiyama and Takehiro Nakamura

7.1 Introduction 143
7.2 Concept 145
7.2.1 Downlink NOMA 145
7.2.2 Uplink NOMA 147
7.3 Benefits and Motivations 148
7.4 Interface Design 150
7.4.1 Downlink NOMA 150
7.4.2 Uplink NOMA 151
7.5 MIMO Support 153
7.5.1 Downlink NOMA 153
7.5.2 Uplink NOMA 156
7.6 Performance Evaluations 157