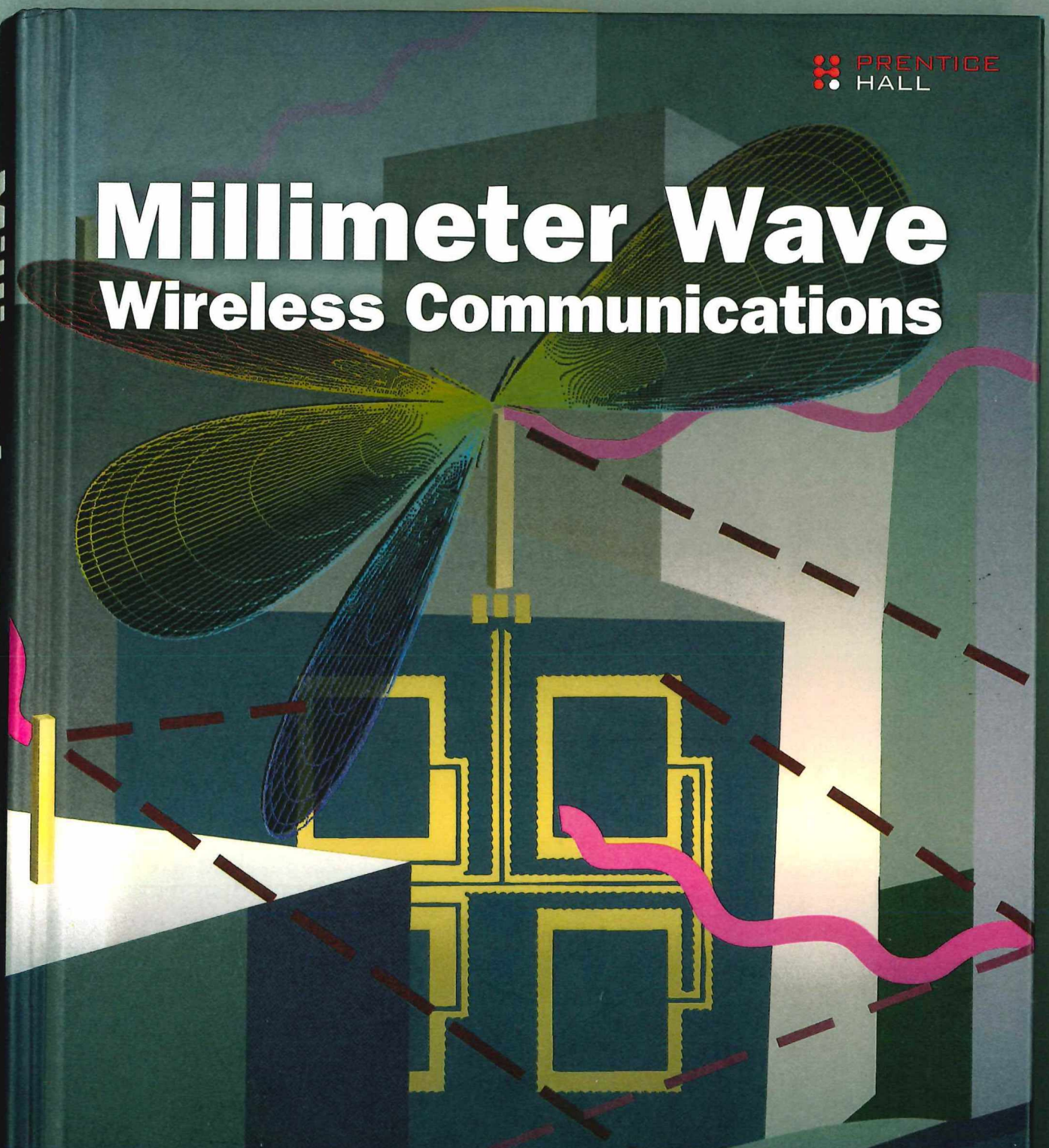
PRENTICE HALL

# Millimeter Wave Wireless Communications



Theodore S. Rappaport • Robert W. Heath Jr.
Robert C. Daniels • James N. Murdock

Prentice Hall Communications Engineering and Emerging Technologies Series | **Theodore S. Rappaport, Series Editor**

# Praise for *Millimeter Wave Wireless Communications*

"This is a great book on mmWave systems that covers many aspects of the technology targeted for beginners all the way to the advanced users. The authors are some of the most credible scholars I know of who are well respected by the industry. I highly recommend studying this book in detail."

—Ali Sadri, PhD, Sr. Director, Intel Corporation, MCG mmWave Standards and Advanced Technologies

"The most comprehensive book covering all aspects of 60 GHz/mm-Wave communication, from digital bits and signal processing all the way to devices, circuits, and electromagnetic waves. A great reference for engineers and students of mm-Wave communication."

—Ali Niknejad, Berkeley Wireless Research Center (BWRC)

"Due to the huge availability of spectrum in 30-100 GHz bands, millimeter wave communication will be the next frontier in wireless technology. This book is the first in-depth coverage addressing essential aspects of millimeter wave communication including channel characteristics and measurements at millimeter wave bands, antenna technology, circuits, and physical layer and medium access control design. It also has an interesting chapter on 60 GHz unlicensed band wireless standards. I found the book extremely useful and recommend it to researchers and practicing engineers who are keen on shaping the future of wireless communication. Thank you Rappaport, Heath, Daniels, and Murdock for giving us *Millimeter Wave Wireless Communications*."

—Amitabha (Amitava) Ghosh, Head, North America Radio Systems, Nokia

"I highly recommend *Millimeter Wave Wireless Communications* to anyone looking to broaden their knowledge in mmWave communication technology. The authors have introduced the key technologies relevant to the rapidly evolving world of wireless access communications while providing an excellent bibliography for anyone seeking to learn about specific topics in greater depth."

—Bob Cutler, Principal Solutions Architect, Agilent Technologies Inc.

"This timely, ambitious, and well-written book is the first to cover all aspects of millimeter wave wireless communications. The authors' interdisciplinary approach illustrates how the unique characteristics of millimeter wave hardware and signal propagation affect and can be mitigated or exploited in the physical, multiple access, and network layers of the overall system design. The authors are renowned wireless communication experts uniquely qualified to write a comprehensive book on this emerging field, which strikes the perfect balance of breadth and depth. This book is likely to become an immediate classic, as well as required reading for students, researchers, and practitioners."

—Andrea Goldsmith, Stephen Harris Chair Professor, Department of Electrical Engineering, Stanford University

"Mm-wave communications systems promise to alleviate the spectrum crunch and be a major part of future WLAN as well as cellular systems. The authors, leading experts in the field, have admirably succeeded in illuminating all the diverse aspects — ranging from semiconductor technology to wave propagation to MAC layer and standards — that impact the design and deployment. The book is a must-read for anybody working on this important emerging class of systems."

—Professor Andy Molisch, University of Southern California, FIEEE, FAAAS, FIET, MAuAcSc

"This is the first book that addresses the technologies of millimeter wave design needed to implement multi-gigabit communication links. It provides in one place the communication theory background as well as the unique characteristics of millimeter wave communication systems."

—Bob Brodersen, Berkeley Wireless Research Center, Department of Electrical Engineering and Computer Science, University of California, Berkeley

"With the advent of broadly addressing the millimeter wave spectrum from 30 GHz-300 GHz, new groundbreaking advances in communications are to be expected. This book provides a fantastic overview as well as in-depth background material for millimeter wave communications. It is a must-buy to be in the hands of any wireless communications engineer active in advancing technology beyond its current boundaries."

—Gerhard P. Fettweis, cfAED Coordinator, HAEC Coordinator, Vodafone Chair Professor, Technische Universität, Dresden

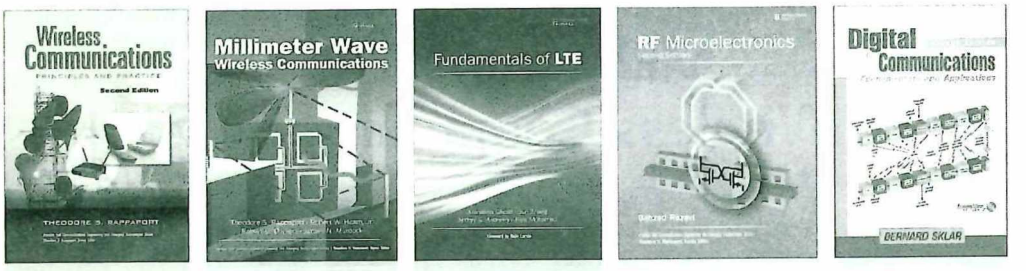
"This timely monograph is expected to play an influential role in the definition of future generations of wireless systems by formulating a future-proof road-map. . . ."

—Professor Lajos Hanzo, FREng, FIEEE, DSc, Head of Communications, Signal Processing and Control, University of Southampton

# Millimeter Wave Wireless Communications

# Prentice Hall Communications Engineering and Emerging Technologies Series

Theodore S. Rappaport, Series Editor




PRENTICE HALL

Visit **informit.com/communicationengineering**
for a complete list of available publications

---

**Prentice Hall Professional's Communications Engineering and Emerging Technologies Series** provides leading-edge learning and information about wireless and other innovative technologies that are revolutionizing communications around the world. This series reveals to readers the minds of leading experts in these fields, often as the technologies are being developed and implemented.

Make sure to connect with us!
informit.com/socialconnect

informIT.com the trusted technology learning source | PRENTICE HALL | Safari Books Online

ALWAYS LEARNING

PEARSON

# Millimeter Wave Wireless Communications

Theodore S. Rappaport
Robert W. Heath Jr.
Robert C. Daniels
James N. Murdock

PRENTICE HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 6 of 24

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed with initial capital letters or in all capitals.

The authors and publisher have taken care in the preparation of this book, but make no expressed or implied warranty of any kind and assume no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information or programs contained herein.

For information about buying this title in bulk quantities, or for special sales opportunities (which may include electronic versions; custom cover designs; and content particular to your business, training goals, marketing focus, or branding interests), please contact our corporate sales department at corpsales@pearsoned.com or (800) 382-3419.

For government sales inquiries, please contact governmentsales@pearsoned.com.

For questions about sales outside the United States, please contact international@pearsoned.com.

Visit us on the Web: informit.com/ph

*Library of Congress Cataloging-in-Publication Data*
Rappaport, Theodore S., 1960- author.
Millimeter wave wireless communications / Theodore S. Rappaport, Robert W. Heath, Robert C. Daniels, James N. Murdock.
pages cm
Includes bibliographical references and index.
ISBN 978-0-13-217228-8 (hardcover : alk. paper)
1. Millimeter wave communication systems. 2. Wireless communication systems. I. Heath, Robert W. (Robert William), 1931- II. Daniels, Robert C. (Robert Clark), 1980- III. Murdock, James N. (James Nelson), 1986- IV. Title.
TK5103.4835.R37 2014
621.384—dc23

2014014143

Copyright © 2015 Pearson Education, Inc.

Cover illustration by Jennifer Rappaport, www.jennyrap.com.

All rights reserved. Printed in the United States of America. This publication is protected by copyright, and permission must be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458, or you may fax your request to (201) 236-3290.

ISBN-13: 978-0-13-217228-8
ISBN-10: 0-13-217228-3
Text printed in the United States on recycled paper at Courier in Westford, Massachusetts.
First printing, September 2014

To my wife, Brenda, and our children, Matthew, Natalie, and Jennifer. Their love is a gift from God that I am thankful for every day.

—TSR

To my family, Garima, Pia, and Rohan, for their love and support;
to my parents, Bob and Judy Heath, for their encouragement;
and to Dr. Mary Bosworth for her passion in the pursuit of higher education.

—RWH

To my parents, Richard and Lynn Daniels, for their steadfast support.

—RCD

To my family, Peter, Bonnie, and Thomas Murdock.

—JNM

# Contents

**Preface** xvii
**Acknowledgments** xxi
**About the Authors** xxiii

**Part I Prerequisites** 1

**1 Introduction** 3
1.1 The Frontier: Millimeter Wave Wireless 3
1.2 A Preview of MmWave Implementation Challenges 17
1.3 Emerging Applications of MmWave Communications 19
1.3.1 Data Centers 19
1.3.2 Replacing Wired Interconnects on Chips 21
1.3.3 Information Showers 22
1.3.4 The Home and Office of the Future 23
1.3.5 Vehicular Applications 24
1.3.6 Cellular and Personal Mobile Communications 25
1.3.7 Aerospace Applications 26
1.4 Contributions of This Textbook 27
1.5 Outline of This Textbook 28
1.5.1 Illustrations for this Textbook 30
1.6 Symbols and Common Definitions 31
1.7 Chapter Summary 32

**2 Wireless Communication Background** 33
2.1 Introduction 33
2.2 Complex Baseband Representation 34



MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 9 of 24

2.3 Digital Modulation 39
2.3.1 Symbols 40
2.3.2 Symbol Detection 41
2.3.3 Binary Phase Shift Keying and Variants 43
2.3.4 Amplitude Shift Keying and Variants 45
2.3.5 Quadrature Phase Shift Keying and Variants 45
2.3.6 Phase Shift Keying 47
2.3.7 Quadrature Amplitude Modulation 48
2.4 Equalization in the Time Domain 49
2.4.1 Linear Equalization 51
2.4.2 Decision Feedback Equalization 53
2.4.3 Maximum Likelihood Sequence Estimation 55
2.5 Equalization in the Frequency Domain 56
2.5.1 Single Carrier Frequency Domain Equalization 57
2.5.2 OFDM Modulation 60
2.6 Error Control Coding 62
2.6.1 Block Codes for Error Detection 63
2.6.2 Reed-Solomon Code 64
2.6.3 Low Density Parity Check Codes 65
2.6.4 Convolutional Codes 67
2.6.5 Trellis Coded Modulation 69
2.6.6 Time Domain Spreading 70
2.6.7 Unequal Error Protection 71
2.7 Estimation and Synchronization 72
2.7.1 Structure to Facilitate Communication 73
2.7.2 Frequency Offset Synchronization 75
2.7.3 Frame Synchronization 78
2.7.4 Channel Estimation 79
2.8 Multiple Input Multiple Output (MIMO) Communication 81
2.8.1 Spatial Multiplexing 82
2.8.2 Spatial Diversity 84
2.8.3 Beamforming in MIMO Systems 85
2.8.4 Hybrid Precoding 87
2.9 Hardware Architectures 88
2.10 System Architecture 91
2.11 Chapter Summary 95

**Part II Fundamentals** 97

**3 Radio Wave Propagation for MmWave** 99
3.1 Introduction 99
3.2 Large-Scale Propagation Channel Effects 101
3.2.1 Log-Distance Path Loss Models 105
3.2.2 Atmospheric Effects 106
3.2.3 Weather Effects on MmWave Propagation 108
3.2.4 Diffraction 111
3.2.5 Reflection and Penetration 111
3.2.6 Scattering and Radar Cross Section Modeling 117
3.2.7 Influence of Surrounding Objects, Humans, and Foliage 119
3.2.8 Ray Tracing and Site-Specific Propagation Prediction 122
3.3 Small-Scale Channel Effects 126
3.3.1 Delay Spread Characteristics 129
3.3.2 Doppler Effects 130
3.4 Spatial Characterization of Multipath and Beam Combining 132
3.4.1 Beam-Combining Procedure 132
3.4.2 Beam-Combining Results 133
3.5 Angle Spread and Multipath Angle of Arrival 135
3.6 Antenna Polarization 138
3.7 Outdoor Channel Models 139
3.7.1 3GPP-Style Outdoor Propagation Models 149
3.7.2 Vehicle-to-Vehicle Models 165
3.8 Indoor Channel Models 166
3.8.1 Ray-Tracing Models for Indoor Channels 169
3.8.2 Rayleigh, Rician, and Multiwave Fading Models 169
3.8.3 IEEE 802.15.3c and IEEE 802.11ad Channel Models 171
3.8.4 IEEE 802.15.3c 177
3.8.5 IEEE 802.11ad 178
3.9 Chapter Summary 184

**4 Antennas and Arrays for MmWave Applications** 187
4.1 Introduction 187
4.2 Fundamentals of On-Chip and In-Package MmWave Antennas 189
4.2.1 Antenna Fundamentals 191
4.2.2 Fundamentals of Antenna Arrays 194

4.3 The On-Chip Antenna Environment 198
4.3.1 Complementary Metal Oxide Semiconductor Technology (CMOS) 200
4.4 In-Package Antennas 209
4.5 Antenna Topologies for MmWave Communications 211
4.6 Techniques to Improve Gain of On-Chip Antennas 225
4.6.1 Integrated Lens Antennas 231
4.7 Adaptive Antenna Arrays — Implementations for MmWave Communications 235
4.7.1 Beam Steering for MmWave Adaptive Antenna Arrays 237
4.7.2 Antenna Array Beamforming Algorithms 242
4.7.3 Specific Beamforming Algorithms — ESPRIT and MUSIC 249
4.7.4 Case Studies of Adaptive Arrays for MmWave Communications 251
4.8 Characterization of On-Chip Antenna Performance 252
4.8.1 Case Studies of MmWave On-Chip Antenna Characterization 253
4.8.2 Improving Probe Station Characterizations of On-Chip or In-Package Antennas 255
4.9 Chapter Summary 257

**5 MmWave RF and Analog Devices and Circuits 259**
5.1 Introduction 259
5.2 Basic Concepts for MmWave Transistors and Devices 260
5.3 S-Parameters, Z-Parameters, Y-Parameters, and ABCD-Parameters 263
5.4 Simulation, Layout, and CMOS Production of MmWave Circuits 267
5.5 Transistors and Transistor Models 273
5.6 More Advanced Models for MmWave Transistors 279
5.6.1 BSIM Model 286
5.6.2 MmWave Transistor Model Evolution — EKV Model 287
5.7 Introduction to Transmission Lines and Passives 288
5.7.1 Transmission Lines 292
5.7.2 Differential versus Single-Ended Transmission Lines 298
5.7.3 Inductors 298
5.7.4 Parasitic Inductances from Bond Wire Packaging 304
5.7.5 Transformers 304
5.7.6 Interconnects 308
5.8 Basic Transistor Configurations 308
5.8.1 Conjugate Matching 309
5.8.2 Miller Capacitance 310

5.8.3 Poles and Feedback 311
5.8.4 Frequency Tuning 313
5.9 Sensitivity and Link Budget Analysis for MmWave Radios 314
5.10 Important Metrics for Analog MmWave Devices 317
5.10.1 Non-Linear Intercept Points 317
5.10.2 Noise Figure and Noise Factor 322
5.11 Analog MmWave Components 323
5.11.1 Power Amplifiers 323
5.11.2 Low Noise Amplifiers 334
5.11.3 Mixers 342
5.11.4 Voltage-Controlled Oscillators (VCOs) 350
5.11.5 Phase-Locked Loops 364
5.12 Consumption Factor Theory 370
5.12.1 Numerical Example of Power-Efficiency Factor 374
5.12.2 Consumption Factor Definition 376
5.13 Chapter Summary 382

**6 Multi-Gbps Digital Baseband Circuits 383**
6.1 Introduction 383
6.2 Review of Sampling and Conversion for ADCs and DACs 384
6.3 Device Mismatches: An Inhibitor to ADCs and DACs 393
6.4 Basic Analog-to-Digital Conversion Circuitry: Comparators 394
6.4.1 Basic ADC Components: Track-and-Hold Amplifiers 397
6.5 Goals and Challenges in ADC Design 403
6.5.1 Integral and Differential Non-Linearity 406
6.6 Encoders 407
6.7 Trends and Architectures for MmWave Wireless ADCs 409
6.7.1 Pipeline ADC 409
6.7.2 Successive Approximation ADCs 410
6.7.3 Time-Interleaved ADC 411
6.7.4 Flash and Folding-Flash ADC 413
6.7.5 ADC Case Studies 420
6.8 Digital-to-Analog Converters (DACs) 421
6.8.1 Basic Digital-to-Analog Converter Circuitry: The Current DAC 422
6.8.2 Case Studies of DAC Circuit Designs 429
6.9 Chapter Summary 431

**Part III MmWave Design and Applications** **433**

**7 MmWave Physical Layer Design and Algorithms** **435**
7.1 Introduction 435
7.2 Practical Transceivers 436
7.2.1 Signal Clipping and Quantization 436
7.2.2 Power Amplifier Non-linearity 439
7.2.3 Phase Noise 441
7.3 High-Throughput PHYs 444
7.3.1 Modulation, Coding, and Equalization 445
7.3.2 A Practical Comparison of OFDM and SC-FDE 447
7.3.3 Synchronization and Channel Estimation 459
7.4 PHYs for Low Complexity, High Efficiency 461
7.4.1 Frequency Shift Keying (FSK) 462
7.4.2 On-Off, Amplitude Shift Keying (OOK, ASK) 463
7.4.3 Continuous Phase Modulation 463
7.5 Future PHY Considerations 464
7.5.1 Ultra-Low ADC Resolution 464
7.5.2 Spatial Multiplexing 466
7.6 Chapter Summary 469

**8 Higher Layer Design Considerations for MmWave** **471**
8.1 Introduction 471
8.2 Challenges when Networking MmWave Devices 472
8.2.1 Directional Antennas at the PHY 472
8.2.2 Device Discovery 475
8.2.3 Collision Detection and Collision Avoidance 476
8.2.4 Channel Reliability Due to Human Blockage 478
8.2.5 Channel Utilization and Spatial Reuse 480
8.3 Beam Adaptation Protocols 481
8.3.1 Beam Adaptation in IEEE 802.15.3c 482
8.3.2 Beam Adaptation in IEEE 802.11ad 483
8.3.3 Beam Adaptation for Backhaul 484
8.3.4 Beam Adaptation through Channel Estimation 484
8.4 Relaying for Coverage Extension 487
8.5 Support for Multimedia Transmission 493
8.6 Multiband Considerations 497
8.7 Performance of Cellular Networks 500
8.8 Chapter Summary 504

**9 MmWave Standardization** **507**
9.1 Introduction 507
9.2 60 GHz Spectrum Regulation 509
9.2.1 International Recommendations 509
9.2.2 Regulations in North America 509
9.2.3 Regulations in Europe 510
9.2.4 Regulations in Japan 510
9.2.5 Regulations in Korea 511
9.2.6 Regulations in Australia 511
9.2.7 Regulations in China 511
9.2.8 Comments 511
9.3 IEEE 802.15.3c 512
9.3.1 IEEE 802.15.3 MAC 512
9.3.2 IEEE 802.15.3c MmWave PHY 520
9.4 WirelessHD 550
9.4.1 Application Focus 550
9.4.2 WirelessHD Technical Specification 551
9.4.3 The Next Generation of WirelessHD 554
9.5 ECMA-387 555
9.5.1 Device Classes in ECMA-387 555
9.5.2 Channelization in ECMA-387 556
9.5.3 MAC and PHY Overview for ECMA-387 557
9.5.4 Type A PHY in ECMA-387 559
9.5.5 Type B PHY in ECMA-387 560
9.5.6 Type C PHY in ECMA-387 561
9.5.7 The Second Edition of ECMA-387 561
9.6 IEEE 802.11ad 562
9.6.1 IEEE 802.11 Background 562
9.6.2 Important IEEE 802.11ad MAC Features 564
9.6.3 Directional Multi-Gigabit PHY Overview for IEEE 802.11ad 572
9.7 WiGig 582
9.8 Chapter Summary 583

**Bibliography** **585**
**List of Abbreviations** **653**
**Index** **657**

# Preface

When the cellular telephone revolution began in the 1970s, it was hard to imagine how wireless communication would become such a fundamental part of today's world. Indeed, the Internet had not yet been invented, personal computers did not exist, and long-distance data communication was carried out over landline phones using analog audio modems with data rates no greater than 300 bits per second. The launch of the commercial cellular telephone industry gave birth to unprecedented freedom and functionality, the wireless age was born, and tetherless communications captured the hearts and minds of a new generation of engineers and technologists, and most importantly, the public. As the computer and Internet revolutions sprang forward in the 1990s and into the 21st century, the wireless industry followed. Despite its remarkable growth, however, wireless has failed to reach its full potential.

Wireless technologies are pervasive, with over 5 billion cellphones on planet Earth. Today's fourth-generation (4G) Long Term Evolution (LTE) cellular technology and the IEEE 802.11n wireless Internet standards provide enormous data rates — transfer rates of hundreds of megabits per second between users. The wireless industry is estimated to be a 1 trillion USD global business, approaching the size of the global construction industry. It is remarkable to consider, however, that in one important dimension, wireless is still in its infancy with enormous room to expand.

Consider this astonishing fact: Since the first cellphone call was made 40 years ago, computer clock speeds have increased from less than 1 MHz to today's clock rates of 5 GHz, more than three orders of magnitude. The memory and storage sizes of computers have exploded from a few kilobytes to today's terabyte-sized hard drives, an expansion of seven orders of magnitude. Yet, during their 40-year lifetime, the mobile communications and personal area network industries have been range-bound in operating carrier frequency, stuck between approximately 500 MHz (used by the early analog mobile phone systems and the recently allocated 700 MHz cellular spectrum) and 5.8 GHz (used by modern WiFi enterprise systems on the IEEE 802.11a standard). Remarkably, in 40 years, the wireless industry has seen little movement in its operating frequency. While all other technological evolutions have exploited Moore's law to gain an increase in scale of many orders of magnitude, the operating carrier frequencies of practically all mobile and portable wireless communication systems have barely budged.

Why would wireless be so delinquent in moving up in the frequency bands? Why would the wireless industry wait until now to exploit the vast frontier of spectrum that, to date,



MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 16 of 24

has seen little use, yet offers such vast potential for greater capacity? After all, as we show in Chapter 1 of this book, England's Ofcom and the US FCC considered millimeter wave (mmWave) for mobile communications in the 1980s. And more than 100 years ago, Jagadis Chandra Bose and Pyotr Lebedev (also spelled "Lebedew") reportedly conducted the first 60 GHz wireless transmissions. To address these questions, and to offer the fundamental technical details needed by the next generation of engineers who will be fortunate to conquer this new frontier of mmWave wireless, we have written this textbook.

The answers to why consumer wireless networks have not exploited mmWave frequencies have to do with many factors, such as the slow standards process and even slower global spectrum regulatory process; myths and lack of fundamental understanding of radio propagation, antennas, circuits, and networks; the amount of entrenched investments and the competition between traditional (and emerging) business models to provide broadband wireless coverage and capacity; the competing standards that dilute capital needed to bring about a new cellular or WiFi technology; the existing and expanding infrastructure needed to carry such large bandwidths; and, most of all, the cost of designing, fabricating, and deploying widespread consumer technologies that deliver an unmet need, such that they justify the massive investments needed to bring them to the marketplace.

Today, semiconductor technologies are able to make reliable radio frequency circuits with gate lengths at or below 30 nm. The ability to fabricate low-cost radio frequency circuits and on-chip antennas systems at frequencies much higher than 5 GHz is now firmly in place. Optical fiber backbones are now being deployed throughout the world, and mmWave wireless systems will enable a much greater proliferation of backhaul to support data rates that meet or exceed those of 4G cellular systems. The processing power of smartphones and tablets, and the insatiable public demand for content offered through these devices, is also now proven. New wireless local area network (WLAN) products based on IEEE 802.11ad are offering multi-gigabit per second data rates. Recent work has shown that outdoor radio propagation is viable at mmWave frequencies when directional, steerable phased-array antennas are used. Thus, all of the key components are set for wireless to expand from its current low microwave carrier frequency to a new frequency regime that promises several orders of magnitude more capacity for future cellphone and local area network users.

This textbook has evolved from our research programs in many technical areas that must come together to make mmWave mobile communications a reality. We have sought to explore the literature and we have used our own personal experiences as researchers, entrepreneurs, inventors, and consultants to build a textbook that empowers engineers at all levels to work on the exciting future of mmWave wireless. Fundamental principles in many important areas of mmWave communications, circuits, antennas, and propagation are treated in this book. We also provide a wealth of references to assist the reader in exploring specific areas of interest where specific challenges or advances must still be made.

The material in this book is designed to provide a solid foundation in mmWave fundamentals, including communication theory, channel propagation, circuits, and antennas. Chapter 1 provides an introduction and illustrates the vast capabilities and new architectures that will evolve as wireless moves from the UHF and microwave bands to the

mmWave spectrum. Conventional applications of mmWave, including WLANs, wireless personal area networks (WPANs), and cellular networks are described, along with new applications of mmWave for applications in the office of the future, data centers, personal interconnects, and the automotive and aerospace industries. Chapter 2 provides an introduction to the fundamentals of digital communication. Important topics including baseband signal and channel models, modulation, equalization, and error control coding are discussed with an emphasis on the techniques that are already found in early mmWave systems. Multiple input multiple output (MIMO) wireless communication principles, which leverage large-antenna arrays, are also reviewed. Background is provided on hardware architectures for upconversion and downconversion and the fundamentals of the network stack.

The treatment of the fundamentals of mmWave starts in Chapter 3, where elemental principles on radio wave propagation for both indoor and outdoor applications of mmWave communication are taught. Radio propagation characteristics for mmWave are reviewed in detail, with special attention paid to the fundamental issues that are pertinent to building mmWave wireless networks. Chapter 4 delves into antennas and antenna arrays for mmWave communication systems. Because mmWave antennas will be very small and integrated, important background is provided on the fundamentals of on-chip and in-package antennas, describing the challenges associated with fabricating efficient mmWave antennas as part of the chip fabrication or packaging. Chapter 5 provides in-depth treatment of analog circuit design and provides fundamental treatment of key design challenges and operating considerations when building RF circuitry. Background is provided on several topics, including analog millimeter wave transistors, their fabrication, and important circuit design approaches for the basic building blocks within a transceiver. The treatment of analog circuits has intentionally included details of complementary metal oxide semiconductor (CMOS) and metal oxide semiconductor field-effect transistors (MOSFET) semiconductor theory in sufficient detail to allow communications engineers to appreciate and understand the fundamentals and challenges of mmWave analog circuits, and to understand the capabilities and approaches used to create circuits that will enable the mmWave revolution. Key parameters used to characterize active and passive analog components as well as key qualities of merit are also reviewed with great detail. Design approaches for transmission lines, amplifiers (both power amplifiers and low-noise amplifiers) frequency synthesizers, voltage-controlled oscillators (VCOs), and frequency dividers are also reviewed. Chapter 6 delves into baseband circuit design. It presents a wide range of technical design issues and references to help the reader understand the fundamentals of designing multi-gigabit per second high-fidelity digital-to-analog (DAC) and analog-to-digital (ADC) converters, and the challenges with reaching such high bandwidths.

The book concludes with a detailed treatment of mmWave design and applications. Chapter 7 presents physical layer aspects of the design of a mmWave communication system. The emphasis is on the physical layer algorithmic choices and design considerations for 60 GHz communication systems. Important concepts include practical impairments such as clipping, quantization, nonlinearity, phase noise, and emerging physical layer design concepts such as spatial multiplexing. The choice of modulation and equalization is discussed in terms of tradeoffs that can be made between complexity and

MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 18 of 24

throughput. Chapter 8 reviews higher-layer (above the physical layer) design issues for mmWave systems, with a particular emphasis on techniques relevant to 60 GHz systems, but also speculates on the impact in mmWave cellular and backhaul systems. Chapter 8 provides background on the challenge associated with networking mmWave devices. Select topics are treated, including beam adaptation protocols, relaying, multimedia transmission, and multiband considerations. Finally, Chapter 9 concludes the technical content with a review of design elements from the standardization efforts for 60 GHz wireless communication systems. Several standards are reviewed, including IEEE 802.15.3c for WPAN, Wireless HD, ECMA-387, IEEE 802.11ad, and the Wireless Gigabit Alliance (WiGig) standard. The key features of each standard are presented along with important details about their physical layer and medium access control design choices.

Just as the cellphone has morphed from a voice-only analog communications device into today's impressive smartphone, the frontier of mmWave wireless communications is sure to usher in even more astounding capabilities and is certain to spawn new businesses, new consumer use cases, and complete transformations of how we live and work. The vast mmWave spectrum, and the new technologies that will conquer it, will bring wireless into its renaissance where it pervades all aspects of our lives. Our hope is that this textbook offers some assistance for the engineering explorers who are called to create this exciting future.

# Acknowledgments

A book of this nature is not a small undertaking, and we have been fortunate to benefit from many colleagues who have helped provide insights, materials, and suggestions in the preparation of this book over the past several years. Leaders from industry who have provided us with valuable and detailed suggestions and who have helped inspire us to write this book include Wonil Roh and Jerry Z. Pi of Samsung, Amitava Ghosh of Nokia, Ali Sadri of Intel Corp., and Bob Cutler of Agilent Technologies. This text has benefited greatly from their thorough reviews, sponsorship, and inspiration, and we are grateful for their involvement. Graduate and undergraduate students at New York University (NYU) and The University of Texas at Austin (UT), as well as many industry practitioners, leading academics from many areas, and our corporate sponsors, have contributed immeasurably to this textbook, and we wish to express our sincere gratitude to them here. Colleagues Bob Brodersen and Ali Niknejad (University of California, Berkeley), Lajos Hanzo (University of Southampton), Andrea Goldsmith (Stanford University), Gerhard Fettweis (TU Dresden), and Andreas Molisch (University of Southern California) all have offered important suggestions that have made this book better. NYU graduate students Krupa Vijay Panchal, Nikhil Suresh Patne, George Robert MacCartney, Shuai Nie, Shu Sun, Abhi Shah (who helped collect inputs from the NYU students), Mathew Samimi, Sijia Ding, and Junhong Zhang offered critical suggestions to make the material accessible and better organized. NYU undergraduate students George Wong, Yaniv Azar, Jocelyn Shulz, Kevin Wang, and Hang (Celine) Zhao also provided proofreading and editing and were involved in the pioneering measurements covered in Chapter 3. UT graduate students Andrew Thornburg, Tianyang Bai, and Ahmed Alkhateeb provided proofreading, editing, and help with the figures. Vutha Vu provided special help with proofreading as well as tracking and implementing many critical edits. Professors Hao Ling, Andrea Alu, Ranjit Gharpurey, and Eric Swanson should also be mentioned for providing critical insights into antenna and circuit design.

Once the manuscript was complete, the Prentice Hall team worked tirelessly to turn this manuscript into a book. Our editor, Bernard Goodwin, commissioned the work and ensured that a seamless and professional typesetting and editing team would be available through production. Julie Nahil, Pearson's Full-Service Production Manager, brought in the stellar production team—copy editor Stephanie Geels and project manager Vicki Rowland. Stephanie's expert editing and insightful questions pushed us to clarify and



MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 20 of 24

refine the manuscript, while Vicki deftly kept track of myriad loose ends and seemed to be available at whatever odd hour if a question or issue popped up. Additionally, proofreaders Linda Begley and Archie Brodsky's eagle eyes caught numerous little glitches that somehow slipped by everyone else. We are most grateful to this superb and dedicated Pearson/Prentice Hall team for their commitment and dedication to this project.

MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 21 of 24

# About the Authors

**Theodore (Ted) S. Rappaport** is the David Lee/Ernst Weber Professor of Electrical and Computer Engineering at New York University's Polytechnic School of Engineering. He also holds professorships in NYU's Courant Institute and Medical School. During his career, he founded three major academic wireless research centers at Virginia Tech, The University of Texas at Austin, and New York University, and he founded and sold two wireless technology companies to publicly traded firms. His technical expertise encompasses antennas, propagation, systems, and circuits for wireless communications, and he has over 100 US or international patents issued or pending. His other textbooks include *Wireless Communications: Principles and Practice* (2002), which has been translated into seven other languages, *Smart Antennas for Wireless Communications* (1999), and *Principles of Communication Systems Simulation with Wireless Applications* (2004). When he is not working Ted enjoys jogging and amateur (ham) radio (his call sign is N9NB).

**Robert W. Heath Jr.,** is a Cullen Trust Endowed Professor in the Department of Electrical and Computer Engineering at The University of Texas at Austin. He is founder of MIMO Wireless Inc. and cofounder of Kuma Signals, LLC. His research includes many aspects of multiple antenna communication: limited feedback techniques, multiuser, multihop, multicell networking, and millimeter wave, as well as other areas of signal processing, including adaptive video transmission, manifold signal processing, and applications of machine learning to wireless communication. He has published more than 300 refereed conference or journal publications and has nearly 50 US patents issued. His other textbooks include *Digital Wireless Communication: Physical Layer Exploration Lab Using the NI USRP* (2012) and several others forthcoming. Robert also enjoys cycling, windsurfing, scuba diving, and sailing. His amateur radio call sign is KE5NCG.



MASSIVELY BROADBAND, IPR2025-01564, Ex.2023, Page 22 of 24

**Robert (Bob) C. Daniels** is the cofounder and CTO at Kuma Signals, LLC, in Austin, Texas. At Kuma, he serves as the principal investigator on wireless communications research and development contracts, and he guides the technical direction of internal development. Bob is an expert in the theory and practical application of digital wireless communications, especially for the design of multiuser, large bandwidth, multiple-antenna wireless communication networks. He has published dozens of peer-reviewed IEEE publications and has also been the sole architect of several RF-proven physical layer implementations through general purpose and special purpose (i.e., field-programmable graphic array) hardware for various standards, including IEEE 802.11n and the Wideband Networking Waveform (WNW). He holds B.S. degrees in Electrical Engineering and Mathematics from The Pennsylvania State University, and M.S.E. and Ph.D. degrees in Electrical and Computer Engineering from The University of Texas at Austin.

**James N. Murdock** is an RF and analog engineer at Texas Instruments (TI), where he focuses on low-power and mmWave frequency circuits. Prior to joining TI, James studied for his B.S. and M.S. degrees in Electrical Engineering at The University of Texas at Austin under the mentorship of Dr. Rappaport. James's master's thesis covered low-power techniques for RF systems and applications of these techniques to large-scale communication systems, in addition to mmWave channel modeling. James has cowritten more than ten conference papers in topics ranging from low-power timing circuits (ISSCC 2014) to on-chip mmWave antennas (MTT-S 2011) to mmWave channel modeling (WCNC 2012). James has cowritten three journal papers.

Wireless Communications

***"This is a great book on mmWave systems that covers many aspects of the technology and is targeted for beginners all the way to the advanced users. The authors are some of the most credible scholars I know of, who are well respected by the industry. I highly recommend studying this book in detail."***

**—Ali Sadri, PhD, Sr. Director, Intel Corporation, MCG mmWave Standards and Advanced Technologies**

## The Definitive, Comprehensive Guide to Cutting-Edge Millimeter Wave Wireless Design

Millimeter wave (mmWave) is today's breakthrough frontier for emerging wireless mobile cellular networks, wireless local area networks, personal area networks, and vehicular communications. In the near future, mmWave applications, devices, and networks will change our world.

In ***Millimeter Wave Wireless Communications***, four of the field's pioneers draw on their vast experience to empower engineers at all levels to succeed with mmWave. They deliver fundamental, end-to-end coverage of all aspects of future mmWave wireless communications systems.

The authors explain new multi-Gigabit per second products and applications, mmWave signal propagation, analog and digital circuit design, mmWave antenna designs, and current and emerging wireless standards. They cover comprehensive mmWave wireless design issues for 60 GHz and other mmWave bands, from channel to antenna to receiver, introducing emerging design techniques that will be invaluable for research engineers in both industry and academia.

**Theodore (Ted) S. Rappaport** is David Lee/Ernst Weber Professor of Electrical and Computer Engineering at New York University's Polytechnic School of Engineering. He has authored or co-authored many books, including the best-seller *Wireless Communications: Principles and Practice, Second Edition* (Prentice Hall, 2002).

**Robert W. Heath Jr.** is Cullen Trust Endowed Professor, Department of Electrical and Computer Engineering, The University of Texas at Austin; founder of MIMO Wireless, Inc.; and cofounder of Kuma Signals, LLC.

**Robert C. Daniels,** cofounder/CTO at Kuma Signals, LLC, is principal investigator on its wireless R&D contracts and guides its technical direction.

**James N. Murdock,** RF and analog engineer at Texas Instruments, specializes in low-power and mmWave frequency circuits.

**Topics include**

- Digital communication: baseband signal/channel models, modulation, equalization, error control coding, multiple input multiple output (MIMO) principles, and hardware architectures
- Radio wave propagation characteristics: indoor and outdoor channel models and beam combining
- Antennas/antenna arrays, including on-chip and in-package antennas, fabrication, and packaging
- Analog circuit design: mmWave transistors, fabrication, and transceiver design approaches
- Baseband circuit design: multi-gigabit-per-second, high-fidelity DAC and ADC converters
- Physical layer: algorithmic choices, design considerations, and impairment solutions; and how to overcome clipping, quantization, and nonlinearity
- Higher-layer design: beam adaptation protocols, relaying, multimedia transmission, and multiband considerations
- 60 GHz standardization: IEEE 802.15.3c for WPAN, Wireless HD, ECMA-387, IEEE 802.11ad, Wireless Gigabit Alliance (WiGig)

informit.com/series/communications
tedrappaport.com
profheath.org

Cover illustration by Jennifer Rappaport, www.jennyrap.com

Text printed on recycled paper

ISBN-13: 978-0-13-217228-8
ISBN-10: 0-13-217228-3

9 780132 172288 90000

PRENTICE HALL

ALWAYS LEARNING

PEARSON