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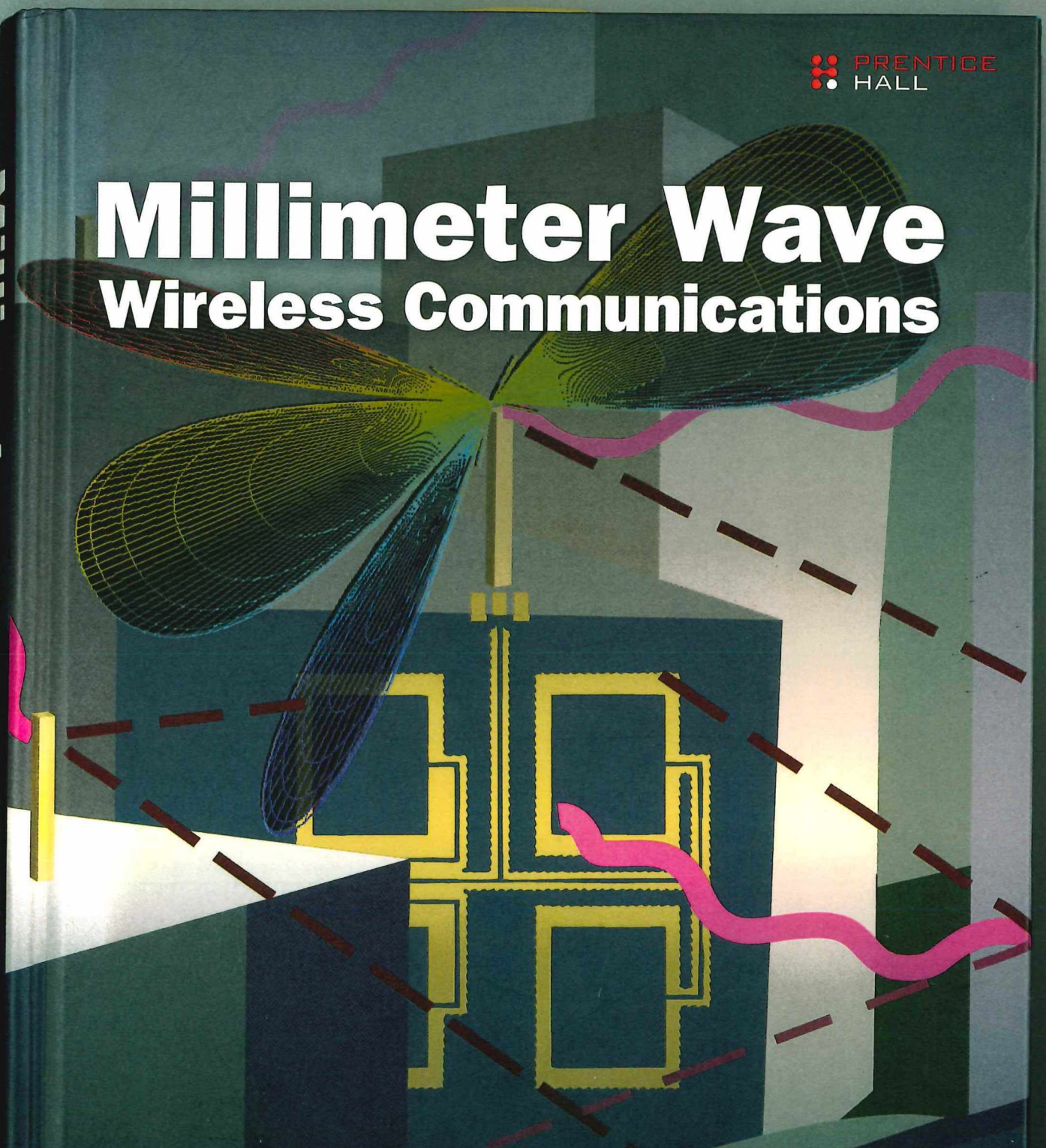
Millimeter Wave Wireless Communications



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

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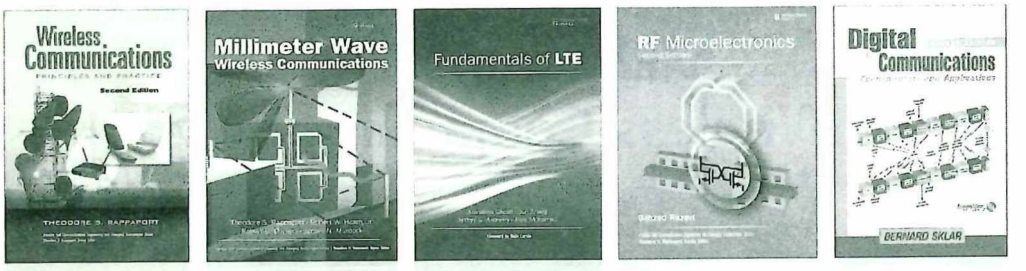

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To my wife, Brenda, and our children, Matthew, Natalie, and Jennifer. Their love is a gift from God that I am thankful for every day.

—TSR

To my family, Garima, Pia, and Rohan, for their love and support;
to my parents, Bob and Judy Heath, for their encouragement;
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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,

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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

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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

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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

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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.

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Wireless Communications

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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)

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