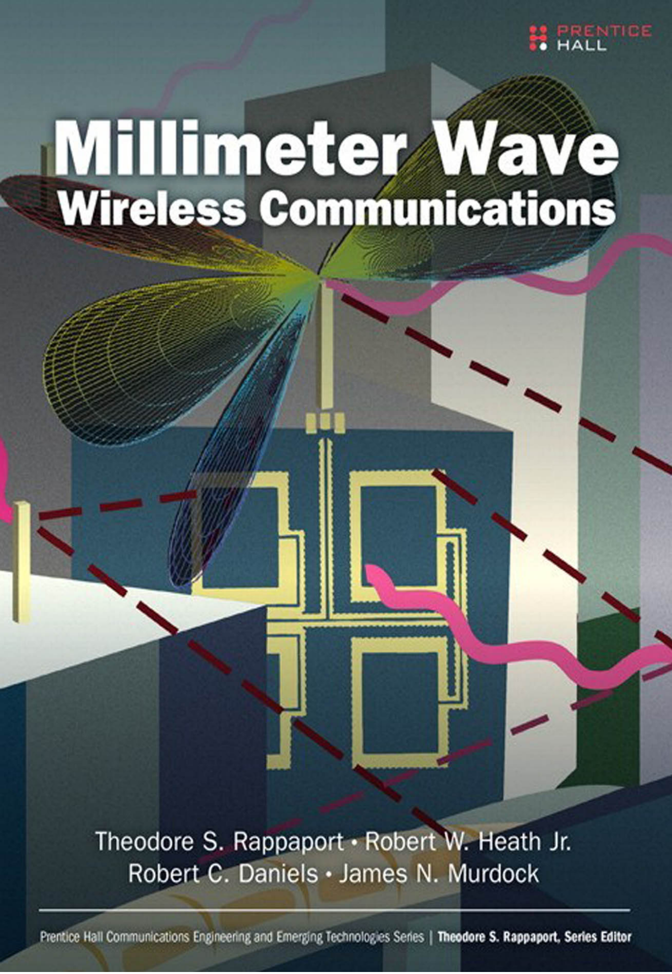

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Millimeter Wave Wireless Communications

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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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

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Contents

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, 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 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

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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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.

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.

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Chapter 1

Introduction

1.1 The Frontier: Millimeter Wave Wireless

Emerging millimeter wave (mmWave) wireless communication systems represent more than a century of evolution in modern communications. Since the early 1900s, when Guglielmo Marconi developed and commercialized the first wireless telegraph communication systems, the wireless industry has expanded from point-to-point technologies, to radio broadcast systems, and finally to wireless networks. As the technology has advanced, wireless communication has become pervasive in our world. Modern society finds itself immersed in wireless networking, as most of us routinely use cellular networks, wireless local area networks, and personal area networks, all which have been developed extensively over the past twenty years. The remarkable popularity of these technologies causes device makers, infrastructure developers, and manufacturers to continually seek greater radio spectrum for more advanced product offerings.

Wireless communication is a transformative medium that allows our work, education, and entertainment to be transported without any physical connection. The capabilities of wireless communications continue to drive human productivity and innovation in many areas. Communication at mmWave operating frequencies represents the most recent game-changing development for wireless systems. Interest in mmWave is in its infancy and will be driven by consumers who continue to desire higher data rates for the consumption of media while demanding lower delays and constant connectivity on wireless devices. At mmWaves, available spectrum is unparalleled compared to cellular and wireless local area network (WLAN) microwave systems that operate at frequencies below 10 GHz. In particular, the unlicensed spectrum at 60 GHz offers 10× to 100× more spectrum than is available for conventional unlicensed wireless local area networks in the Industrial, Scientific, and Medical (ISM) bands (e.g., at 900 MHz, 2.4 GHz, 5 GHz) or for users of WiFi and 4G (or older) cellular systems that operate at carrier frequencies below 6 GHz. To reinforce this perspective, Fig. 1.1 shows the magnitude of spectrum resources at 28 GHz (Local Multipoint Distribution Service [LMDS]) and 60 GHz in comparison to other modern wireless systems. Over 20 GHz of spectrum is waiting to be used for cellular or WLAN traffic in the 28, 38, and 72 GHz bands alone, and hundreds of gigahertz more spectrum could be used at frequencies above 100 GHz. This is a staggering amount of

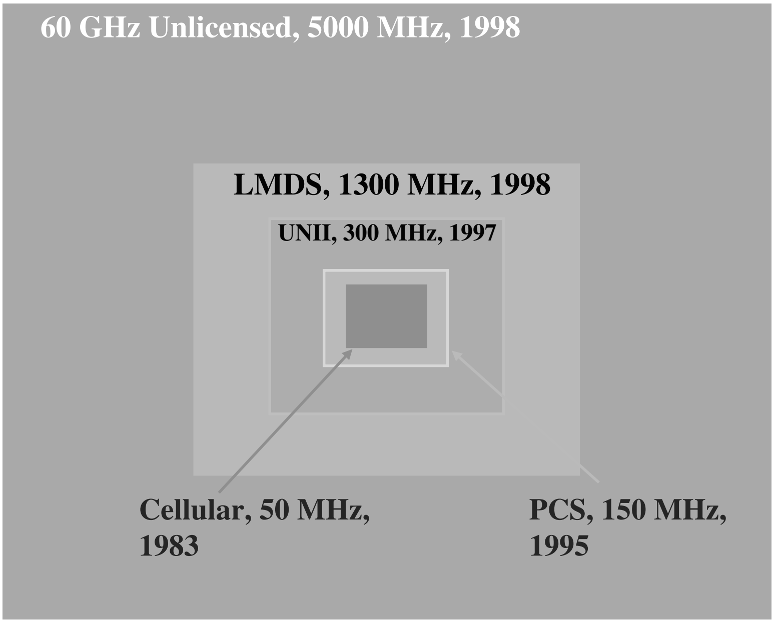

Figure 1.1 Areas of the squares illustrate the available licensed and unlicensed spectrum bandwidths in popular UHF, microwave, 28 GHz LMDS, and 60 GHz mmWave bands in the USA. Other countries around the world have similar spectrum allocations [from [Rap02]].

available new spectrum, especially when one considers that all of the world's cellphones currently operate in less than 1 GHz of allocated spectrum. More spectrum makes it possible to achieve higher data rates for comparable modulation techniques while also providing more resources to be shared among multiple users.

Research in mmWave has a rich and exciting history. According to [Mil],

> In 1895, Jagadish Chandra Bose first demonstrated in Presidency College, Calcutta, India, transmission and reception of electromagnetic waves at 60 GHz, over 23 meters distance, through two intervening walls by remotely ringing a bell and detonating some gunpowder. For his communication system, Bose pioneered the development of entire millimeter-wave components like: spark transmitter, coherer, dielectric lens, polarizer, horn antenna and cylindrical diffraction grating. This is the first millimeter wave communication system in the world, developed more than 100 years ago.

A pioneering Russian physicist, Pyotr N. Lebedew, also studied transmission and propagation of 4 to 6 mm wavelength radio waves in 1895 [Leb95].

Today's radio spectrum has become congested due to the widespread use of smartphones and tablets. Fig. 1.1 shows the relative bandwidth allocations of different spectrum bands in the USA, and Fig. 1.2 shows the spectrum allocations from 30 kHz to 300 GHz according to the Federal Communications Commission (FCC). Note that although Figs. 1.1 and 1.2 represent a particular country (i.e., the USA), other countries around the world have remarkably similar spectrum allocations stemming from the global allocation of spectrum by the World Radiocommunication Conference (WRC) under the auspices of the International Telecommunication Union (ITU). Today's cellular and

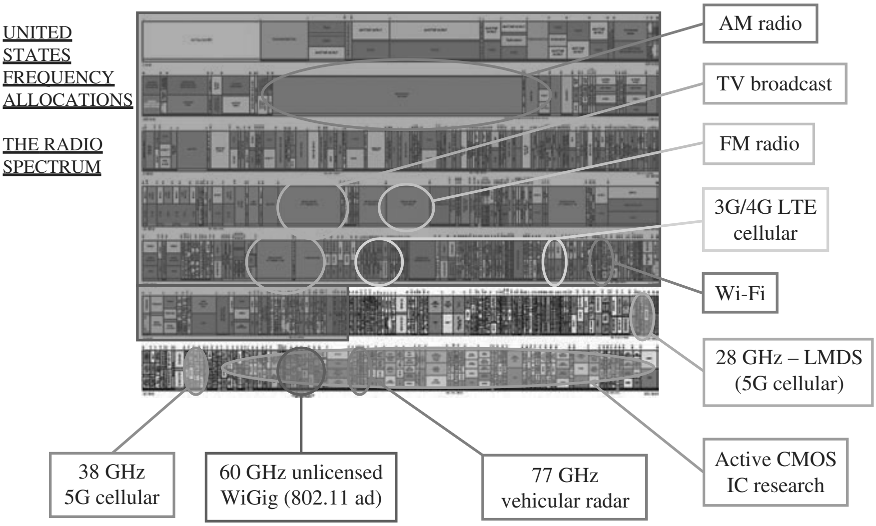

Figure 1.2 Wireless spectrum used by commercial systems in the USA. Each row represents a decade in frequency. For example, today's 3G and 4G cellular and WiFi carrier frequencies are mostly in between 300 MHz and 3000 MHz, located on the fifth row. Other countries around the world have similar spectrum allocations. Note how the bandwidth of all modern wireless systems (through the first 6 rows) easily fits into the unlicensed 60 GHz band on the bottom row [from [Rap12b] U.S. Dept. of Commerce, NTIA Office of Spectrum Management]. See page C1 (immediately following page 8) for a color version of this figure.

personal communication systems (PCS) mostly operate in the UHF ranges from 300 MHz to 3 GHz, and today's global unlicensed WLAN and wireless personal area network (WPAN) products use the Unlicensed National Information Infrastructure (U-NII) bands of 900 MHz, 2.4 MHz and 5.8 MHz in the low microwave bands. The wireless spectrum right now is already allocated for many different uses and very congested at frequencies below 3 GHz (e.g., UHF and below). AM Radio broadcasting, international shortwave broadcasting, military and ship-to-shore communications, and amateur (ham) radio are just some of the services that use the lower end of the spectrum, from the hundreds of kilohertz to the tens of megahertz (e.g., medium-wave and shortwave bands). Television broadcasting is done from the tens of megahertz to the hundreds of megahertz (e.g., VHF and UHF bands). Current cellphones and wireless devices such as tablets and laptops works at carrier frequencies between 700 MHz and 6 GHz, with channel bandwidths of 5 to 100 MHz. The mmWave spectrum, ranging between 30 and 300 GHz, is occupied by military, radar, and backhaul, but has much lower utilization. In fact, most countries have not even begun to regulate or allocate the spectrum above 100 GHz, as wireless technology at these frequencies has not been commercially viable at reasonable cost points. This is all about to change. Given the large amount of spectrum available, mmWave presents a new opportunity for future mobile communications to use channel bandwidths of 1 GHz or more. Spectrum at 28 GHz, 38 GHz, and 70-80 GHz looks especially promising for next-generation cellular systems. It is amazing to note from Fig. 1.2 that the unlicensed band at 60 GHz contains more spectrum than has been used by every satellite, cellular, WiFi, AM Radio, FM Radio, and television station in the world! This illustrates the massive bandwidths available at mmWave frequencies.

MmWave wireless communication is an enabling technology that has myriad applications to existing and emerging wireless networking deployments. As of the writing of this book, mmWave based on the 60 GHz unlicensed band is seeing active commercial deployment in consumer devices through IEEE 802.11ad [IEE12]. The cellular industry is just beginning to realize the potential of much greater bandwidths for mobile users in the mmWave bands [Gro13][RSM$^+$13]. Many of the design examples in this book draw from the experience in 60 GHz systems and the authors' early works on mmWave cellular and peer-to-peer studies for the 28 GHz, 38 GHz, 60 GHz, and 72 GHz bands. But 60 GHz WLAN, WPAN, backhaul, and mmWave cellular are only the beginning — these are early versions of the next generation of mmWave and terahertz systems that will support even higher bandwidths and further advances in connectivity.

New 60 GHz wireless products are exciting, not only because of their ability to satisfy consumer demand for high-speed wireless access, but also because 60 GHz products may be deployed worldwide, thanks to harmonious global spectrum regulations. Harmonized global spectrum allocations allow manufacturers to develop worldwide markets, as demonstrated through the widespread adoption and commercial success of IEEE 802.11b WLANs in 1999, and more recent innovations such as IEEE 802.11a, IEEE 802.11g, IEEE 802.11n, and IEEE 802.11ac WLANs that all operate in the same globally allocated spectrum. WLAN succeeded because there was universal international agreement for the use of the 2.4 GHz ISM and 5 GHz Unlicensed National Information Infrastructure bands, which allowed major manufacturers to devote significant resources to create products that could be sold and used globally. Without international spectral agreements, new wireless technologies will founder for lack of a global market. This was demonstrated by early incarnations of Ultra-wide band (UWB) at the turn of the century, whose initial hype dramatically waned in the face of nonuniform worldwide spectral interference regulations. Fortunately, the governments of the USA, Europe, Korea, Japan, and Australia have largely followed the recommendations of the ITU, which designate frequencies between 57 and 66 GHz for unlicensed communications applications [ITU]. In the USA, the FCC has designated bands from 57 to 64 GHz for unlicensed use [Fed06]. In Europe, the European CEPT has allocated bands from 59 to 66 GHz for some form of mobile application [Tan06]. Korea and Japan have designated bands from 57 to 66 GHz and 59 to 66 GHz, respectively [DMRH10]. Australia has dedicated a smaller band from 59.3 to 62.9 GHz. Consequently, there is roughly 7 GHz of spectrum available worldwide for 60 GHz devices.

At the time of this writing, the cellular industry is just beginning to explore similar spectrum harmonization for the use of mobile cellular networks in frequency bands that are in the mmWave spectrum.[1] Dubbed "Beyond 4G" or "5G" by the industry, new cellular network concepts that use orders of magnitude more channel bandwidth, for simultaneous mobility coverage as well as wireless backhaul, are just now being introduced to governments and the ITU to create new global spectrum bands at carrier frequencies that are at least an order of magnitude greater than today's fourth-generation (4G) Long

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[1] Although the mmWave band is formally defined as the spectrum between 30 and 300 GHz, the industry has loosely considered the term *mmWave* to denote all frequencies between 10 and 100 GHz. The term "sub-terahertz" has been used loosely to define frequencies above 100 GHz but lower than 300 GHz.

Term Evolution (LTE) and WiMax mobile networks. Thus, just as the WLAN unlicensed products have moved from the carrier frequencies of 1 to 5 GHz in their early generations, now to 60 GHz, the 1 trillion USD cellular industry is about to follow this trend: moving to mmWave frequency bands where massive data rates and new capabilities will be supported by an immense increase in spectrum.

Unlicensed spectrum at 60 GHz is readily available throughout the world, although this was not always the case. The FCC initiated the first major regulation of 60 GHz spectrum for commercial consumers through an unlicensed use proposal in 1995 [Mar10a], yet the same idea was considered a decade earlier by England's Office of Communications (OfCom) [RMGJ11]. At that time, the FCC considered the mmWave band to be "desert property" due to its perceived unfavorable propagation characteristics and lack of low-cost commercial circuitry. However, the allocation of new spectrum has ignited and will continue to ignite the inventiveness and creativity of engineers to create new consumer products at higher frequencies and greater data rates. This perception of poor propagation due to low distance coverage is heavily influenced by the O_2 absorption effect where a 60 GHz carrier wave interacts strongly with atmospheric oxygen during propagation, as illustrated in Fig. 1.3 [RMGJ11][Wel09]. This effect is compounded by other perceived unfavorable qualities of mmWave communication links: increased free space path loss, decreased signal penetration through obstacles, directional communication due to high-gain antenna requirements, and substantial intersymbol interference (ISI, i.e., frequency

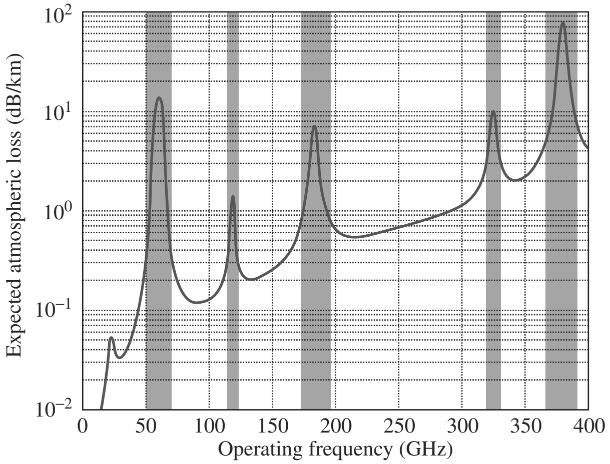


Figure 1.3 Expected atmospheric path loss as a function of frequency under normal atmospheric conditions (101 kPa total air pressure, 22° Celsius air temperature, 10% relative humidity, and 0 g/m^3 suspended water droplet concentration) [Lie89]. Note that atmospheric oxygen interacts strongly with electromagnetic waves at 60 GHz. Other carrier frequencies, in dark shading, exhibit strong attenuation peaks due to atmospheric interactions, making them suitable for future short-range applications or "whisper radio" applications where transmissions die out quickly with distance. These bands may service applications similar to 60 GHz with even higher bandwidth, illustrating the future of short-range wireless technologies. It is worth noting, however, that other frequency bands, such as the 20-50 GHz, 70-90 GHz, and 120-160 GHz bands, have very little attenuation, well below 1 dB/km, making them suitable for longer-distance mobile or backhaul communications.

selectivity) due to many reflective paths over massive operating bandwidths. Furthermore, 60 GHz circuitry and devices have traditionally been very expensive to build, and only in the past few years have circuit solutions become viable in low-cost silicon.

In the early days of 60 GHz wireless communication, many viewed fixed wireless broadband (e.g., fiber backhaul replacement) as the most suitable 60 GHz application, due to requirements for highly directional antennas to achieve acceptable link budgets. Today, however, the propagation characteristics that were once seen as limitations are now either surmountable or seen as advantages. For example, 60 GHz oxygen absorption loss of up to 20 dB/km is almost negligible for networks that operate within 100 meters. The shift away from long-range communications actually benefits close-range communications because it permits aggressive frequency reuse with simultaneously operating networks that do not interfere with each other. Further, the highly directional antennas required for path loss mitigation can actually work to promote security as long as network protocols enable antenna directions to be flexibly steered. Thus, many networks are now finding a home at 60 GHz for communication at distances less than 100 m. Also, the 20 dB/km oxygen attenuation at 60 GHz disappears at other mmWave bands, such as 28, 38, or 72 GHz, making them nearly as good as today's cellular bands for longer-range outdoor mobile communications. Recent work has found that urban environments provide rich multipath, especially reflected and scattered energy at or above 28 GHz — when smart antennas, beamforming, and spatial processing are used, this rich multipath can be exploited to increase received signal power in non-line of sight (NLOS) propagation environments. Recent results by Samsung show that over 1 Gbps can be carried over mmWave cellular at ranges exceeding 2 km, demonstrating that mmWave bands are useful for cellular networks [Gro13].

Although consumer demand and transformative applications fuel the need for more bandwidth in wireless networks, rapid advancements and price reductions in integrated mmWave (>10 GHz) analog circuits, baseband digital memory, and processors have enabled this progress. Recent developments of integrated mmWave transmitters and receivers with advanced analog and radio frequency (RF) circuitry (see Fig. 1.4) and new phased array and beamforming techniques are also paving the way for the mmWave future (such as the product in Fig. 1.5). Operation at 60 GHz and other mmWave frequencies at reasonable costs is largely the result of a continuation of advancements in complementary metal oxide semiconductor (CMOS) and silicon germanium (SiGe technologies). Signal generation into terahertz frequencies (1 to 430 THz) has been possible since at least the 1960s through photodiodes and other discrete components not amenable to small-scale integration and/or mass production [BS66]. Packaging the analog components needed to generate mmWave RF signals along with the digital hardware necessary to process massive bandwidths, however, has only been possible in the last decade. Moore's Law, which has accurately predicted that integrated circuit (IC) transistor populations and computations per unit energy will double at regular intervals every two years [NH08, Chapter 1], explains the dramatic advancements that now allow 60 GHz and other mmWave devices to be made inexpensively. Today, transistors made with CMOS and SiGe are fast enough to operate into the range of hundreds of gigahertz [YCP$^+$09], as shown in Fig. 1.6. Further, due to the immense number of transistors required for modern digital circuits (on the order of billions) each transistor is extremely cheap. Inexpensive circuit production processes will make system-on-chip (SoC) mmWave radios — a complete integration of

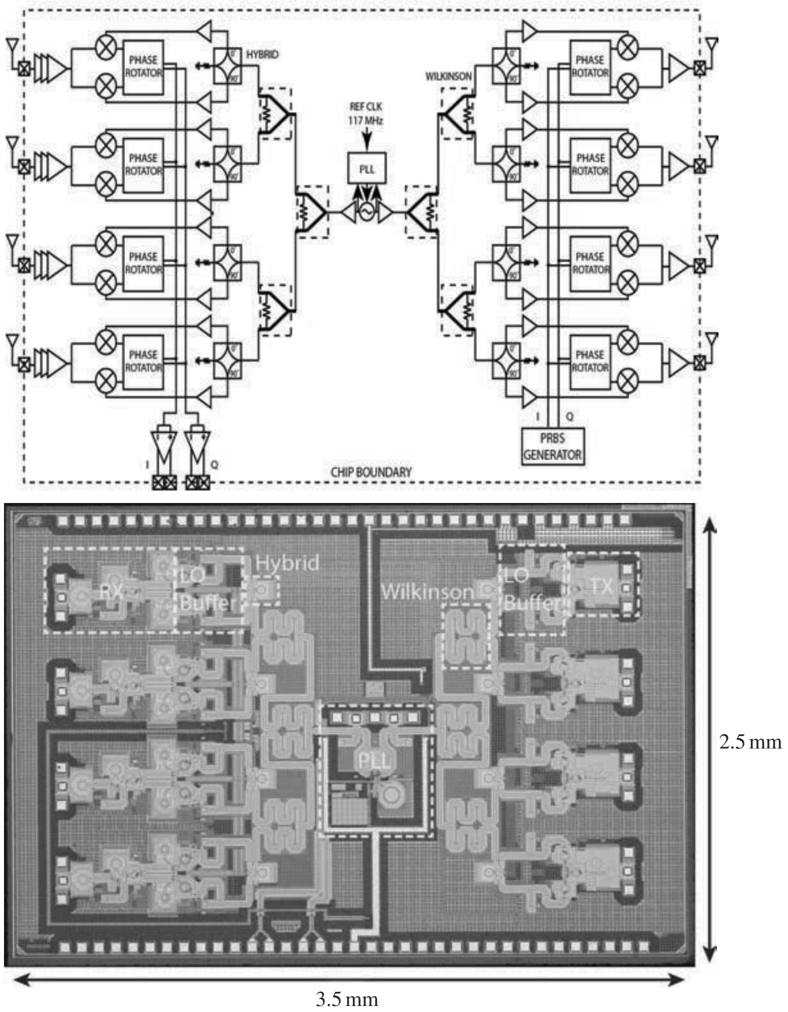


Figure 1.4 Block diagram (top) and die photo (bottom) of an integrated circuit with four transmit and receive channels, including the voltage-controlled oscillator, phase-locked loop, and local oscillator distribution network. Beamforming is performed in analog at baseband. Each receiver channel contains a low noise amplifier, inphase/quadrature mixer, and baseband phase rotator. The transmit channel also contains a baseband phase rotator, up-conversion mixers, and power amplifiers. Figure from [TCM$^+$11], courtesy of Prof. Niknejad and Prof. Alon of the Berkeley Wireless Research Center [© IEEE].

all analog and digital radio components onto a single chip — possible. For mmWave communication, the semiconductor industry is finally ready to produce cost-effective, mass-market products.

Wireless personal area networks (WPANs) provided the first mass-market commercial applications of short-range mmWave using the 60 GHz band. The three dominant 60 GHz WPAN specifications are WirelessHD, IEEE 802.11ad (WiGig), and IEEE 802.15.3c.

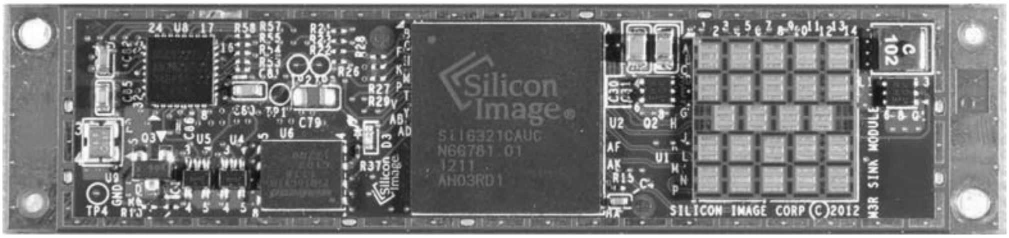


Figure 1.5 Third-generation 60 GHz WirelessHD chipset by Silicon Image, including the SiI6320 HRTX Network Processor, SiI6321 HRRX Network Processor, and SiI6310 HRTR RF Transceiver. These chipsets are used in real-time, low-latency applications such as gaming and video, and provide 3.8 Gbps data rates using a steerable 32 element phased array antenna system (courtesy of Silicon Image) [EWA+11] [© IEEE]. See page C2 (immediately preceding page 9) for a color version of this figure.

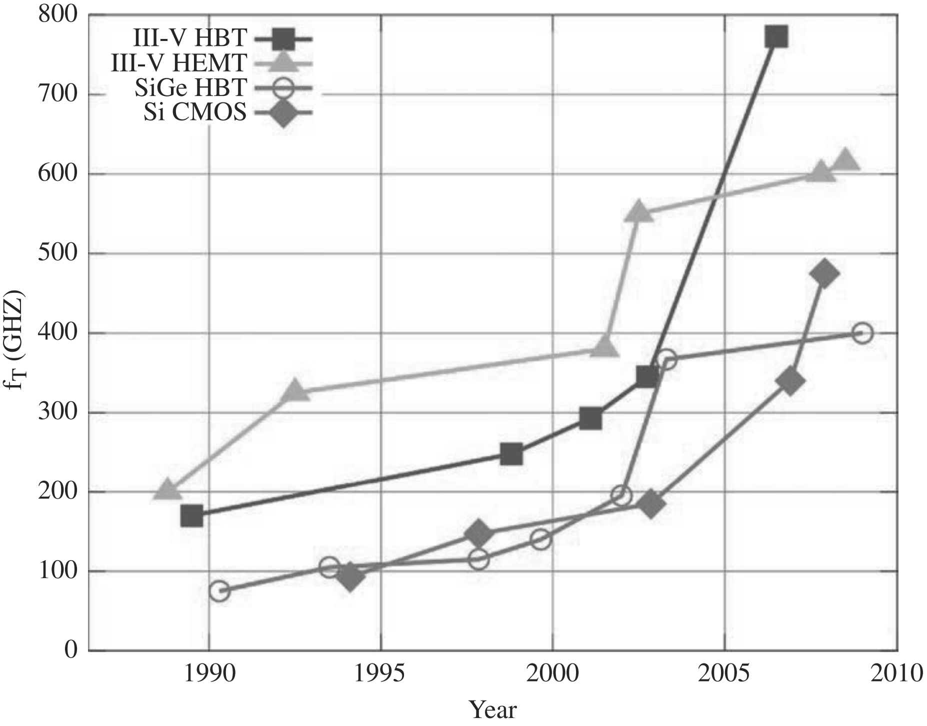


Figure 1.6 Achievable transit frequency (f_T) of transistors over time for several semiconductor technologies, including silicon CMOS transistors, silicon germanium heterojunction bipolar transistor (SiGe HBT), and certain other III-V high electron mobility transistors (HEMT) and III-V HBTs. Over the last decade CMOS (the current technology of choice for cutting edge digital and analog circuits) has become competitive with III-V technologies for RF and mmWave applications [figure reproduced from data in [RK09] © IEEE].

WPANs support connectivity for mobile and peripheral devices; a typical WPAN realization is demonstrated in Fig. 1.7, where products such as those shown in Fig. 1.5 may be used. Currently, the most popular application of WPAN is to provide high-bandwidth connections for cable replacement using the high-definition multimedia interface (HDMI), now proliferating in consumer households. The increasing integration of 60 GHz silicon devices allows implementation on small physical platforms while the massive spectrum allocations at 60 GHz allow media streaming to avoid data compression limitations, which are common at lower frequencies with reduced bandwidth resources. Easing compression requirements is attractive because it reduces signal processing and coding circuity requirements, thereby reducing the digital complexity of a device. This may lead to lower cost and longer battery life in a smaller form factor. Due to major technical and marketing efforts by the Wireless Gigabit Alliance (WiGig), the IEEE 802.11ad standard has been designed to incorporate both WPAN and WLAN capabilities, and WiGig-compliant devices are just starting to ship in laptops, tablets, and smartphones around the world, whereas WirelessHD-compliant devices have been shipping since 2008. The success of today's USB standard in consumer electronics has demonstrated how harmonious interfaces lead to a proliferation of compatible devices. 60 GHz is poised to fill this role for high-definition multimedia systems, as illustrated in Fig. 1.8.

WLANs, which extend the communication range beyond WPAN, also employ mmWave technology in the 60 GHz band. WLANs are used to network computers through a wireless access point, as illustrated in Fig. 1.9, and may connect with other wired networks or to the Internet. WLANs are a popular application of unlicensed spectrum that is being incorporated more broadly into smartphones, tablets, consumer devices, and cars. Currently, most WLAN devices operate under the IEEE 802.11n standard and have

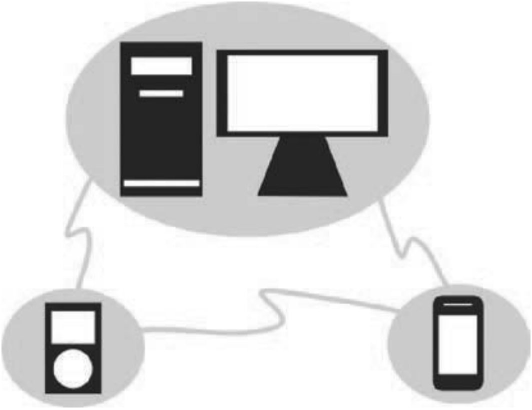


Figure 1.7 Wireless personal area networking. WPANs often connect mobile devices such as mobile phones and multimedia players to each other as well as desktop computers. Increasing the data-rate beyond current WPANs such as Bluetooth and early UWB was the first driving force for 60 GHz solutions. The IEEE 802.15.3c international standard, the WiGig standard (IEEE 802.11ad), and the earlier WirelessHD standard, released in the 2008–2009 time frame, provide a design for short-range data networks (≈ 10 m). All standards, in their first release, guaranteed to provide (under favorable propagation scenarios) multi-Gbps wireless data transfers to support cable replacement of USB, IEEE 1394, and gigabit Ethernet.

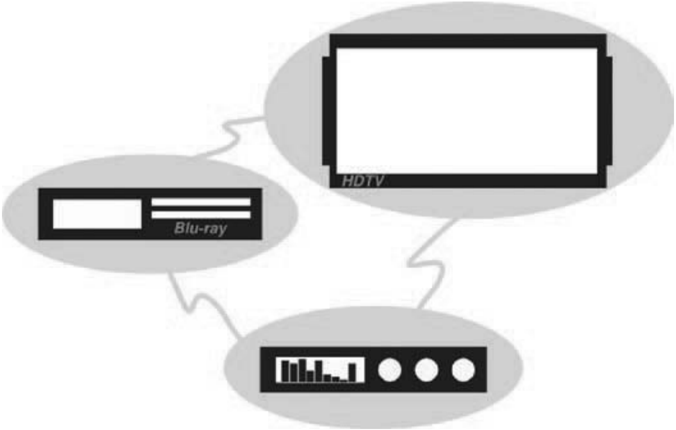


Figure 1.8 Multimedia high-definition (HD) streaming. 60 GHz provides enough spectrum resources to remove HDMI cables without sophisticated joint channel/source coding strategies (e.g., compression), such as in the wireless home digital interface (WHDI) standard that operates at 5 GHz frequencies. Currently, 60 GHz is the only spectrum with sufficient bandwidth to provide a wireless HDMI solution that scales with future HD television technology advancement.

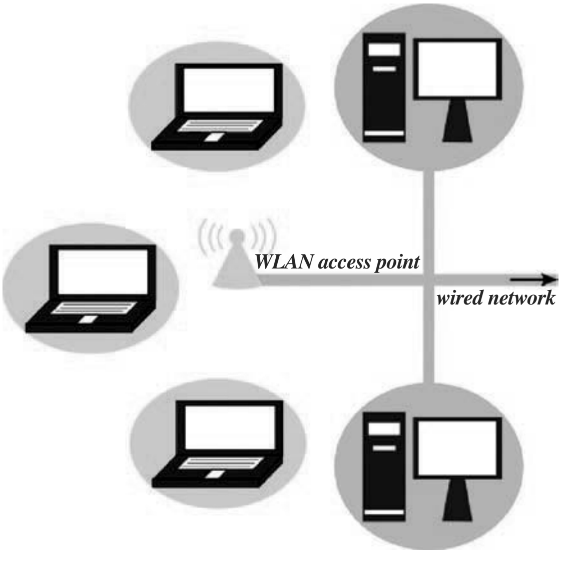


Figure 1.9 Wireless local area networking. WLANs, which typically carry Internet traffic, are a popular application of unlicensed spectrum. WLANs that employ 60 GHz and other mmWave technology provide data rates that are commensurate with gigabit Ethernet. The IEEE 802.11ad and WiGig standards also offer hybrid microwave/mmWave WLAN solutions that use microwave frequencies for normal operation and mmWave frequencies when the 60 GHz path is favorable. Repeaters/relays will be used to provide range and connectivity to additional devices.

the ability to communicate at hundreds of megabits per second. IEEE 802.11n leverages multiple transmit and receive antennas using multiple input multiple output (MIMO) communication methods. These devices carry up to four antennas and operate in the 2.4 GHz or 5.2 GHz unlicensed bands. Until IEEE 802.11n, standard advancements (in terms of data rate capabilities) have been largely linear, that is, a single new standard improves on the previous standard for the next generation of devices. The next generation of WLAN, however, has two standards for gigabit communication: IEEE 802.11ac and IEEE 802.11ad. IEEE 802.11ac is a direct upgrade to IEEE 802.11n through higher-order constellations, more available antennas (up to 8) per device, and up to 4 times more bandwidth at microwave frequencies (5 GHz carrier). IEEE 802.11ad takes a revolutionary approach by exploiting 50 times more bandwidth at mmWave frequencies (60 GHz). It is supported by device manufacturers that recognize the role of mmWave spectrum in the continued bandwidth scaling for next-generation applications. IEEE 802.11ad and mmWave technology will be critical for supporting wireless traffic with speeds competitive not only with gigabit Ethernet, but also 10 gigabit Ethernet and beyond. The largest challenges presented to 60 GHz and mmWave WLAN are the development of power-efficient RF and phased-array antennas and circuitry, and the high attenuation experienced by mmWaves when propagating through certain materials. Many strategies will be employed to overcome these obstacles, including 60 GHz repeaters/relays, adaptive beam steering, and hybrid wired/microwave/mmWave WLAN devices that use copper or fiber cabling or low microwave frequencies for normal operation, and mmWave frequencies when the 60 GHz path loss is favorable. Although the WPAN and WLAN network architectures provide different communication capabilities, several wireless device companies, including Panasonic, Silicon Image, Wilocity, MediaTek, Intel, and Samsung, are aggressively investing in both technologies.

MmWave technology also finds applications in cellular systems. One of the earliest applications of mmWave wireless communication was backhaul of gigabit data along a line-of-sight (LOS) path, as illustrated in Fig. 1.10. Transmission ranges on the order of 1 km are possible if very high-gain antennas are deployed. Until recently, however, 60 GHz and mmWave backhaul has largely been viewed as a niche market and has not

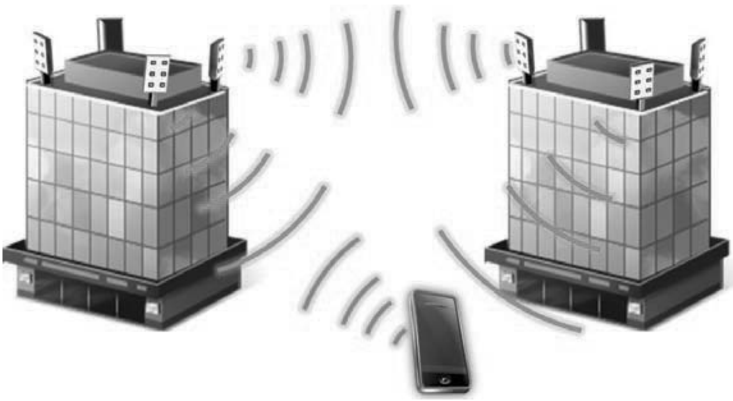


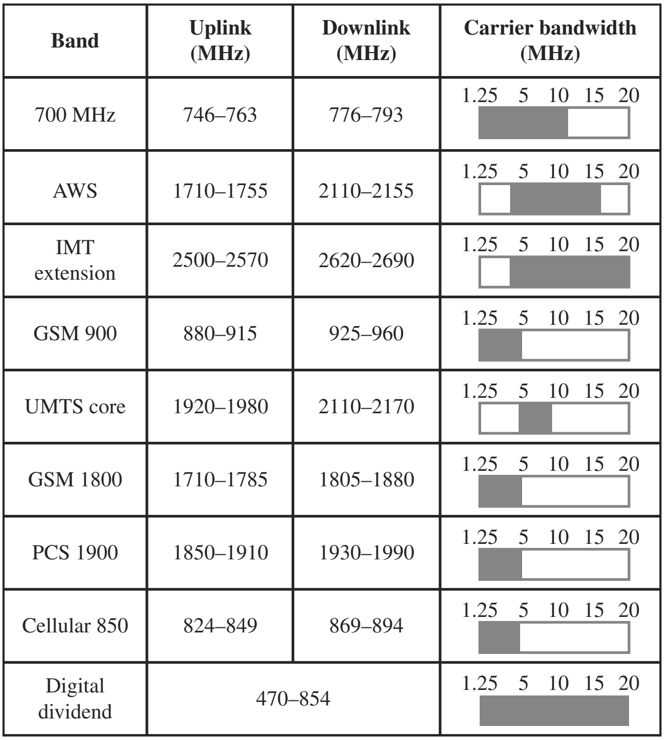
Figure 1.10 Wireless backhaul and relays may be used to connect multiple cell sites and subscribers together, replacing or augmenting copper or fiber backhaul solutions.

drawn significant interest. 60 GHz backhaul physical layer (PHY) design traditionally assumed expensive components to provide high reliability and to maximize range, resulting in bulky equipment and reducing the cost advantage over wired backhaul; however, a new application for wireless backhaul is emerging. Cellular systems are increasing in density (resulting in 1 km or less distances between base stations). Concurrently, cellular base stations require higher-capacity backhaul connections to provide mobile high-speed video and to implement advanced multicell cooperation strategies. If wireless backhaul devices are able to leverage recent mmWave hardware cost reductions, they may be able to service this growing need at a lower cost with more infrastructure flexibility. Further, backhaul systems are investigating LOS MIMO strategies to scale throughput into fiber capabilities [SST$^+$09]. As operators continue to move to smaller cell sizes to exploit spatial reuse, the cost per base station will drop as they become more plentiful and more densely distributed in urban areas. Thus, wireless backhaul will be essential for network flexibility, quick deployment, and reduced ongoing operating costs. Consequently, wireless backhaul is likely to reemerge as an important application of 60 GHz and mmWave wireless communications. In fact, we envisage future cellular and WLAN infrastructure to be able to simultaneously handle backhaul, *fronthaul*, and position location connections using mmWave spectrum.

We foresee that mmWave will play a leading role in fifth-generation (5G) cellular networks. In the past generations of cellular technology, various PHY technologies have been successful in achieving ultra-high levels of spectral efficiency (bits/sec/Hz), including orthogonal frequency division multiplexing, multiple antennas, and efficient channel coding [GRM$^+$10][STB09][LLL$^+$10][SKM$^+$10][CAG08][GMR$^+$12]. Heterogeneous networks, coordinated multipoint transmission, relays, and the massive deployment of small cells or distributed antennas promise to further increase area spectral efficiency (bits/s/Hz/km^2) [DMW$^+$11][YHXM09][PPTH09][HPWZ13][CAG08][GMR$^+$12]. The focus on area spectral efficiency is a result of extremely limited bandwidths available in the UHF and microwave frequency bands where cellular systems are deployed, as illustrated in Fig. 1.11. MmWave cellular will change the current operating paradigm using the untapped mmWave spectrum.

Cellular systems may use mmWave frequencies to augment the currently saturated 700 MHz to 2.6 GHz radio spectrum bands for wireless communications [KP11a]. The combination of cost-effective CMOS technology that can now operate well into the mmWave frequency bands, and high-gain, steerable antennas at the mobile and base station, strengthens the viability of mmWave wireless communications [RSM$^+$13]. MmWave spectrum would allow service providers to offer higher channel bandwidths well beyond the 20 MHz typically available to 4G LTE users. By increasing the RF channel bandwidth for mobile radio channels, the data capacity is greatly increased, while the latency for digital traffic is greatly decreased, thus supporting much better Internet-based access and applications that require minimal latency. Given this significant jump in bandwidth and new capabilities offered by mmWave, the base station-to-device links, as well as backhaul links between base stations, will be able to handle much greater capacity than today's cellular networks in highly populated areas.

Cellular systems that use mmWave frequencies are likely to be deployed in licensed spectrum at frequencies such as 28 GHz or 38 GHz or at 72 GHz, because licensed spectrum better guarantees the quality of service. The 28 GHz and 38-39 GHz bands



Band	Uplink (MHz)	Downlink (MHz)	Carrier bandwidth (MHz)
700 MHz	746–763	776–793	1.25 5 10 15 20
AWS	1710–1755	2110–2155	1.25 5 10 15 20
IMT extension	2500–2570	2620–2690	1.25 5 10 15 20
GSM 900	880–915	925–960	1.25 5 10 15 20
UMTS core	1920–1980	2110–2170	1.25 5 10 15 20
GSM 1800	1710–1785	1805–1880	1.25 5 10 15 20
PCS 1900	1850–1910	1930–1990	1.25 5 10 15 20
Cellular 850	824–849	869–894	1.25 5 10 15 20
Digital dividend	470–854		1.25 5 10 15 20

Figure 1.11 United States spectrum and bandwidth allocations for 2G, 3G, and 4G LTE-A (long-term evolution advanced). The global spectrum bandwidth allocation for all cellular technologies does not exceed 780 MHz. Currently, allotted spectrum for operators is dissected into disjoint frequency bands, each of which possesses different radio networks with different propagation characteristics and building penetration losses. Each major wireless provider in each country has, at most, approximately 200 MHz of spectrum across all of the different cellular bands available to them [from [RSM$^+$13] © IEEE].

are currently available with spectrum allocations of over 1 GHz of bandwidths, and the E-Band above 70 GHz has over 14 GHz available [Gho14]. Originally intended for LMDS use in the late 1990s, the 28 GHz and 38 GHz licenses could be used for mobile cellular as well as backhaul [SA95][RSM$^+$13].

MmWave cellular is a growing topic of research interest [RSM$^+$13]. The use of mmWave for broadband access has been pioneered by Samsung [KP11a][KP11b][PK11][PKZ10][PLK12], where data rates were reported in the range of 400 Mbps to 2.77 Gbps for a 1 GHz bandwidth at 1 km distance. Nokia has recently demonstrated that 73 GHz could be used to provide peak data rates of over 15 Gbps [Gho14]. Propagation characteristics of promising mmWave bands have been evaluated in [RQT$^+$12], [MBDQ$^+$12], [RSM$^+$13], and [MSR14], and show path loss is slightly larger in NLOS conditions compared with today's UHF and microwave bands due to the higher carrier frequency. The scattering effects also become important at mmWave frequencies, causing weak signals to become an important source of diversity, and NLOS paths are weaker, making blockage and coverage holes more pronounced. To allow high-quality links, directional beamforming will be needed at both the base station and at the handset where propagation can be improved [GAPR09][RRE14]. Hybrid architectures for beamforming appear especially attractive as they allow both directional beamforming and more complex forms of precoding while using limited hardware [EAHAS$^+$12a][AELH13]. Applications to picocellular networks are also promising [ALRE13], indicating 15-fold improvements in data rates compared with current 3GPP LTE 4G cellular deployments. Work in [RRE14] shows over 20-fold improvement in end-user data rates over the most advanced 4G LTE networks in New York City. Results in [BAH14] show 12-fold improvements compared with other competing microwave technologies, and results in [ALS$^+$14], [RRE14], and [Gho14] predict 20 times or more capacity improvements using mmWave technologies. As 5G is developed and implemented, we believe the main differences compared to 4G will be the use of much greater spectrum allocations at untapped mmWave frequency bands, highly directional beamforming antennas at both the mobile device and base station, longer battery life, lower outage probability, much higher bit rates in larger portions of the coverage area, cheaper infrastructure costs, and higher aggregate capacity for many simultaneous users in both licensed and unlicensed spectrum, in effect creating a user experience in which massive data-rate cellular and WiFi services are merged.

The architecture of mmWave cellular networks is likely to be much different than in microwave systems, as illustrated in Fig. 1.12. Directional beamforming will result in high gain links between base station and handset, which has the added benefit of reducing out-of-cell interference. This means that aggressive spatial reuse may be possible. Backhaul links, for example, may share the same mmWave spectrum, allowing rapid deployment and mesh-like connectivity with cooperation between base stations. MmWave cellular may also make use of microwave frequencies using, for example, the phantom cell concept [KBNI13] where control information is sent on microwave frequencies and data is sent (when possible) on mmWave frequencies.

A number of universities have research programs in mmWave wireless communication. The University of Surrey, England, has set up a research hub for 5G mobile technology

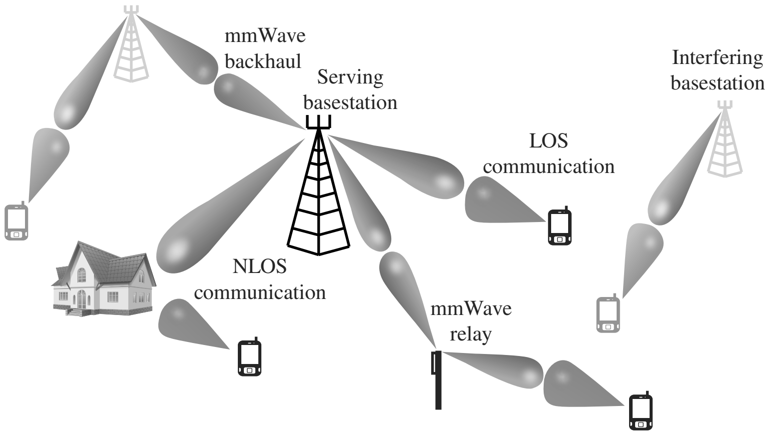


Figure 1.12 Illustration of a mmWave cellular network. Base stations communicate to users (and interfere with other cell users) via LOS, and NLOS communication, either directly or via heterogeneous infrastructure such as mmWave UWB relays.

with a goal to expand UK telecommunication research and innovation [Surrey]. New York University (NYU) recently established the NYU WIRELESS research center to create new technologies and fundamental knowledge for future mmWave wireless devices and networks [NYU12]. Aalborg University has an active mmWave research effort. The Wireless Networking and Communications Group (WNCG) at The University of Texas at Austin has a vibrant research program on 5G cellular technologies including mmWave [Wi14]. Aalto University has an active mmWave research effort. The University of Southern California, the University of California at Santa Barbara, the University of California at Berkeley, the California Institute of Technology, the University of Bristol, and the Korea Advanced Institute of Science and Technology (KAIST) are just some of the many universities that have substantial research efforts on mmWave for future wireless networks.

WPANs, WLANs, and cellular communication mark the beginning of mass consumer applications of mmWave technologies, where we evolve to a world where data is transported to and from the cloud and to each other in quantities we cannot fathom today. We believe that mmWave is the "tip of the iceberg" for dramatic new products and changes in our way of life, and will usher in a new generation of engineers and technologists with new capabilities and expertise. This exciting future will bring about revolutionary changes in the way content is distributed, and will completely change the form factor of many electronic devices, motivating the use of larger bandwidths found in the mmWave spectrum for many other types of networks, far beyond 60 GHz [RMGJ11][Rap12a]. For this to happen, however, many challenges must be overcome. Although we predict that future inexpensive UWB wireless cellular and personal area networks will be enabled through a move to mmWave frequencies and continued advancements in highly integrated digital and analog circuitry, we do not predict that all future advancements will be carried on the shoulders of solid-state process engineers, alone. Future wireless engineers will need to understand not only communications engineering and wireless system design principles, but also circuit design, antenna and propagation models, and mmWave electromagnetic theory to successfully codevelop their designs of future wireless solutions.

1.2 A Preview of MmWave Implementation Challenges

Implementation challenges for mmWave communication involve many layers of the communications stack. At the hardware level of the PHY, antennas are a major challenge. To minimize costs, mmWave chipset vendors may prefer to exploit the short carrier wavelength by incorporating antennas or antenna arrays directly on-chip or in-package. For the simplest and lowest-cost solutions, high-gain single chip solutions are attractive [RGAA09]. Single-antenna solutions, however, must overcome the challenges of low on-chip efficiencies whereas in-package antennas must overcome lossy package interconnects. MmWave systems may also employ many closely spaced antennas in packages or on circuit boards that are much smaller than a centimeter when using high-permittivity materials. Adaptive or switched-beam antenna arrays can provide transmit and receive antenna gain, but require protocol modifications at the signal processing level of the PHY and the data link layer to direct the beams.

A cornerstone of low-cost mmWave circuits is the use of CMOS or SiGe technology. Silicon on Insulator (SOI) CMOS processes are also attractive for high-end applications as they provide impressive quality (Q) factors due to reduced values for parasitic capacitances and inductances. SOI processes, however, suffer from increased costs compared with standard CMOS with a joined device channel and substrate. Because CMOS processes have now reached transit frequencies of hundreds of gigahertz, single-chip mmWave systems are feasible, complete with a digital baseband and mmWave analog front end. On-chip integration will also facilitate techniques like mixed-signal equalization [TKJ$^+$12] [HRA10] that may improve the performance of complete systems versus multichip solutions. Unfortunately, foundries do not yet report relative permittivities or loss-tangents for process materials at mmWave frequencies in process design kits (PDKs), forcing early developers to measure these critical parameters until they are provided.

Communications signal processing at mmWave is also met with new challenges. Although mmWave wireless links can be modeled using conventional linear complex baseband system theory, the characteristics of mmWave wireless propagation combined with mmWave hardware design requirements produce unique design decisions at the PHY. Modulation and equalization algorithm selection must take into account the derived tradeoff between beam steering complexity and equalization complexity. For example, a mmWave system that uses omni directional antennas can suffer from severe ISI due to the multipath channels that cause successive symbols arriving at a receiver to overlap and interfere with each other [Rap02]. Fig. 1.13 illustrates the temporal and spatial variations of a typical omnidirectional 60 GHz impulse response and shows how multipath components may induce tens or even hundreds of nanoseconds of delay. The channel shown in

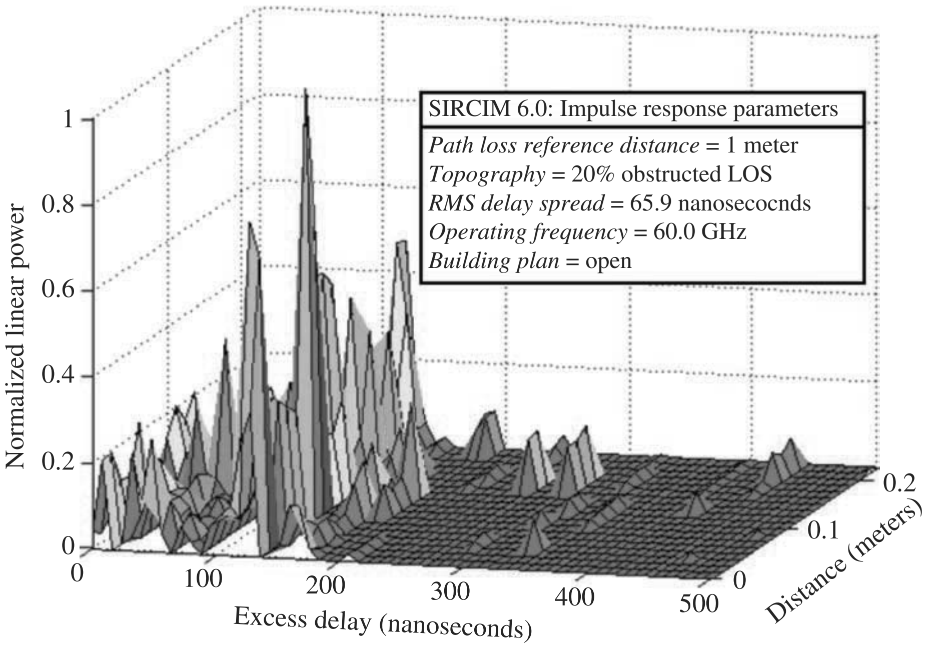


Figure 1.13 Long delay spreads characterize wideband 60 GHz channels and may result in severe inter-symbol interference, unless directional beamforming is employed. Plot generated with Simulation of Indoor Radio Channel Impulse Response Models with Impulse Noise (SIRCIM) 6.0 [from [DMRH10] © IEEE].

Fig. 1.13 has a delay spread of 65.9 ns, which could potentially spread a 60 GHz signal over tens to hundreds of symbol periods (e.g., this much spread would smear a signal over 120 symbols in the Single Carrier-Physical Layer of the IEEE 802.15.3c standard) [DMRH10]. A device operating in this environment would either need nonlinear equalization algorithms in the PHY and/or very long equalization periods, both of which would increase the complexity of the device (possibly erasing digital complexity benefits of 60 GHz relative to lower frequency systems). Directional beam steering antennas such as antenna arrays may be used to reduce the RMS delay spread seen by the device, but beam steering also results in an additional computational burden.

Above the PHY, the medium access control (MAC) of mmWave devices must also consider unique design factors. Most of the computational burden of beam steering would fall in the MAC layer. In addition to reducing complexity by optimal co-design of beam-steering and modulation algorithms, beam steering presents problems related to neighbor discovery and hidden and exposed nodes in a network. Neighbor discovery, which refers to the link protocol that manages link activation and maintenance, is especially difficult with beam steering and mobile devices. The hidden node problem, in which a coordinating device is unable to prevent an interfering device from transmitting, is challenging enough in microwave systems with omnidirectional antennas. The addition of very directional mmWave antennas (to combat mmWave path loss) only compounds this problem. Exposed nodes, which are prevented from communicating due to interference, are more likely to occur with conventional MAC protocols at mmWave because of the directionality of "all clear" messages with mmWave antennas [DMRH10].

1.3 Emerging Applications of MmWave Communications

60 GHz WPAN and WLAN are only the first step in a mmWave communications revolution. In addition to providing the first mass-market mmWave devices and enhancing cross-disciplinary communications design, 60 GHz communications will also have a substantial impact on other network technologies. Data centers may cut costs by employing mmWave communication links to interconnect the computers for high bandwidth, flexibility, and low power. Further, computational platforms may replace lossy, wired interconnects with high-speed wireless interconnects. Together, data center and computational platform improvements extend the reach of cloud computing through new non-traditional wireless applications. Cellular systems may incorporate mmWave to provide higher bandwidths to solve the spectrum crunch by providing mobile networks, peer-to-peer data transfers, and backhaul in the same bands. Not all emerging applications of 60 GHz and mmWave wireless devices, however, are unprecedented. Backhaul wireless links, broadband cellular communication, intra-vehicular communication, inter-vehicular communication, and aerospace communication have all been the subject of research and some market developments. Several technology breakthroughs at mmWave, however, hope to bring these applications to larger markets with vast capabilities.

1.3.1 Data Centers

To accommodate continued growth in the Internet and cloud-based applications, Internet service providers and major Web portals are building thousands of data centers each year. Data centers are used by all major Internet companies, including Google, Microsoft, Yahoo, and Amazon, to distribute processing, memory storage, and caching throughout the global Internet. As multimedia content, for example, high-definition movies, increasingly streams over the Internet, data center buildout continues to accelerate. The buildout of data centers is comparable to the rapid buildout of towers in the early years of the cellular telephone industry.

Individual data centers often provide thousands of co-located computer servers [BAHT11]. Each data center can consume up to 30 megawatts of power, equivalent to the power drain of a small city, and must be built near a large water source (such as a lake or river) to accommodate cooling requirements. Remarkably, over 30% of the power dissipation in a typical data center is for cooling systems, for switching bottlenecks, and for broadband communication connections/circuitry between servers. Broadband circuitry is likely to become problematic as the Internet continues to expand over both wired and wireless connections [Kat09].

There are three types of communication in data centers: chip-to-chip, shelf-to-shelf, and rack-to-rack (less than 100 m). At present, data centers employ wired connections for all three types of data communication. Shelf-to-shelf and rack-to-rack communication is implemented using electrical copper connections and is the biggest bottleneck at present. Table 1.1 compares different copper solutions in terms of their power per port, reach, and link costs.

The broadband wired connections within data centers will not be able to accommodate future bandwidth requirements due to the increase in metal wire signal loss with increasing frequency. Data centers are expected to make a transition to other technologies.

Table 1.1 A representative sample of technology choices for computer interconnections within a data center. This table makes the case for a different interconnect technology [Hor08].

Solution	**Power per Port (W)**	**Port Type**	**Reach**	**Interconnect**	**Link Cost**
CX4	up to 1.6W	Dedicated copper SAS SFF8470	upto 15m	4 lanes of 3.125G copper in heavy-gauge casing	$ 250
10GBASE-T	~4W	Dedicated copper RJ45	30 m (or 100 m)	CAT5/CAT6 copper cable	$ 500
Active Twin-ax	1W	Hot pluggable SFP + or XFP	up to 30 m	Thin-gauge twin-ax copper Cable	$ 150
10GBASE-SR	1W	up to 300 m	Hot pluggable SFP + or XFP	Optical glass fiber	$ 500

Solution	**Power per Port (W)**	**California Elec $/kWh**	**Cost per Year**	**CO_2 per Year per 1600 Ports (ton)**	**OPEX Cost per Year per DataCenter Cluster ($K)**
CX4	up to 1.6W	20.72	$ 291	17	465
10GBASE-T	~4W	20.72	$ 727	42	1162
Active Twin-ax	1W	20.72	$ 182	11	291
10GBASE-SR	1W	20.72	$ 182	11	291

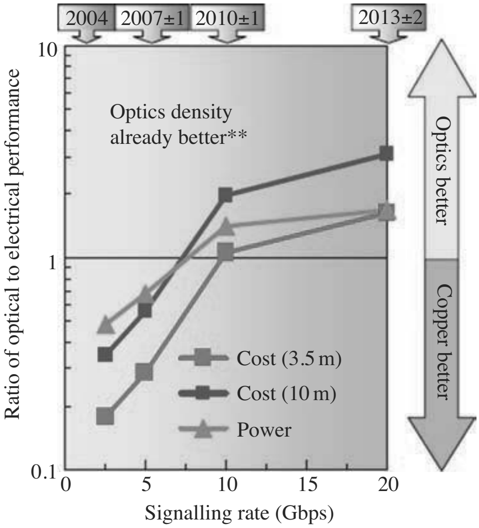


Figure 1.14 Comparison between optical and electrical performance in terms of cost and power for short cabled interconnects. The results show that optical connections are preferred to electrical copper connections for higher data rates, assuming wires are used [adapted from [PDK$^+$07] © IEEE].

For example, Fig. 1.14 shows how optical interconnects have cost and power advantages over copper interconnects for longer ranges and/or higher power. Both cable technologies, though, have disadvantages. For example, electrical connections typically have lower bandwidth and higher dielectric losses in FR4 (a common material used for the construction of printed circuit boards), whereas optical connections typically are not standardized and installation may be costly.

MmWave wireless communication using 60 GHz is an alternative to wired connections in data centers that could offer lower cost, lower power consumption, and greater flexibility. For example, a 10 m wireless 60 GHz link has a power budget in which 200 mW is dissipated before the power amplifier (e.g., by mixers or a voltage-controlled oscillator), 200 mW dissipated by the transmitter/antenna power amplifiers, and 600 mW of power dissipated in the channel/antennas giving a total of 1 W [Rap12b] [Rap09], which is comparable to the solutions in Table 1.1. A wireless solution allows flexible design of the data center, for example, placement of the servers, and permits easy reconfiguration. More flexible designs and a reduction in the numbers of cables and conduits allow for better placement of heat sources, and in turn, results in less stringent cooling and power requirements.

1.3.2 Replacing Wired Interconnects on Chips

The integrated antennas used to link individual 60 GHz devices may serve as the precursor of antennas used to link different components on a single chip or within a package, or within a close proximity as illustrated in Fig. 1.15. These links may be used for power combining, or more critically, signal delivery. On-chip antenna connections for power combining were evaluated as early as the mid 1980s [Reb92], but the market for high-frequency systems was limited and the technology was ahead of its time. Many

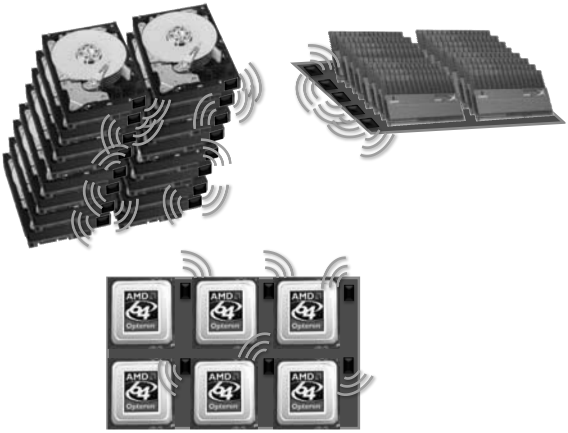


Figure 1.15 MmWave wireless will enable drastic changes to the form factors of today's computing and entertainment products. Multi-Gbps data links will allow memory devices and displays to be completely tetherless. Future computer hard drives may morph into personal memory cards and may become embedded in clothing [Rap12a][Rap09][RMGJ11].

researchers have experimented with on-chip or in-package wireless signal delivery (i.e., wireless interconnects) using highly integrated antennas [OKF+05]. This research demonstrates several challenges facing digital circuit design, including clock skew [FHO02] and interconnect delay [ITR09].[2,3] Of these challenges, interconnect delay may be the most important to consider. The International Roadmap for Semiconductors (ITRS) identified interconnect delay as the most critical phenomenon affecting high-performance products [ITR09].

The bandwidth of copper interconnects used on-chip is also an important issue. When clock frequencies increase, the passband bandwidth is decreased due to the increased resistance exhibited by a metal wire as frequency increases. This is exhibited by the square-root dependence of metal surface resistance on frequency in addition to the skin and proximity effects that also increase resistance. An on-chip or in-package antenna may mitigate these challenges because it would reduce the total length of wire seen by a signal. Therefore, the antennas developed for 60 GHz systems may provide value across many future applications requiring very high data rates within a chip or package.

1.3.3 Information Showers

With massive mmWave spectrum and low-cost electronics now available for the first time ever, the transfer of information will become truly ubiquitous and virtually unlimited. By replacing copper wiring with massive bandwidth radio links that are located at building entrances, hallways, roadway on-ramps, and lampposts, it will soon be possible to beam

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[2] Clock skew limits the size of a digital chip due to reduced component synchronization as the chip becomes larger.

[3] Interconnect delay is the time required for a signal to propagate across a connection between different components on a chip.

entire libraries of information to people as they walk or drive. Consider today's student, who carries a heavy backpack full of books between classes. By using a concept known as the *information shower*, enormous amounts of content may be transferred in seconds, with or without the student's knowledge, as illustrated in Fig. 1.16.

Memory storage and content delivery will be revolutionized using the information shower, making real-time updates and access to the latest versions of books, media, and Web content appear seamless and automatic. The student of the future will merely need a handheld communicator to obtain all of the content for her entire educational lifetime, downloaded in a matter of seconds, and updated through continual access to information showers. Furthermore, peer-to-peer networking will enable very close range wireless communications between different users, so that massive downloads by an individual user may be shared to augment content of another nearby user. Information showers will exploit both cellular and personal area networks so that future consumers of content may use low-power and lightweight devices that will replace today's bulky and power-hungry televisions, personal computers, and printed matter.

1.3.4 The Home and Office of the Future

As mmWave devices and products evolve over the next couple of decades, the way in which our homes and offices are wired will radically change. As content from Web servers moves closer to the edge of the network, the bandwidth carried around our homes and enterprises will skyrocket by orders of magnitude. Also, the number of wireless devices that we rely upon will increase dramatically [Rap11][RMGJ11]. Today's Internet cables will likely be replaced with massive-bandwidth mmWave radio networks, obviating the need for wired ports for Internet and telephone service, as shown in Fig. 1.17. Many low-power wireless memory devices will replace books and hard drives that are bulky and inefficient. Untethered access to information within a room and between rooms will become the norm, as humans adapt to the renaissance of wireless communications, in which our personal devices are linked by massive-bandwidth data links that carry tens of gigabits of data per second. Even today's building wiring (e.g., Cat6 Ethernet cables) will be replaced by low-cost, high-bandwidth, rapidly deployable wireless systems that

Figure 1.16 Future users of wireless devices will greatly benefit from the pervasive availability of massive bandwidths at mmWave frequencies. Multi-Gbps data transfers will enable a lifetime of content to be downloaded on-the-fly as users walk or drive in their daily lives [Rap12a][Rap09][RMGJ11].

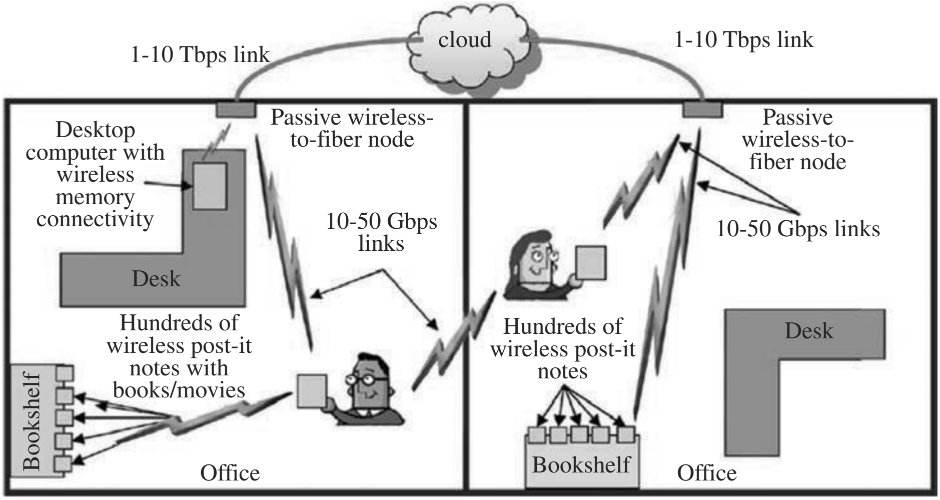

Figure 1.17 The office of the future will replace wiring and wired ports with optical-to-RF interconnections, both within a room and between rooms of a building. UWB relays and new distributed wireless memory devices will begin to replace books and computers. Hundreds of devices will be interconnected with wide-bandwidth connections through mmWave radio connections using adaptive antennas that can quickly switch their beams [Rap11] [from [RMGJ11] © IEEE].

have switchable beams to adapt coverage and capacity for any building floor plan. Later chapters of this text provide the technical details needed to engineer such systems.

1.3.5 Vehicular Applications

There are many applications of mmWave in the context of vehicles. Broadband communication within an automobile is being pursued to remove wired connections of vehicular devices (e.g., wires between dashboard DVD player and backseat displays) as well as to provide multimedia connectivity of portable devices inside the vehicle (e.g., MP3 players, cellphones, tablets, laptops). MmWave is especially attractive for intravehicle communications due to its inability to easily penetrate and interfere with other vehicular networks (due to high vehicle penetration losses). There are other applications outside the vehicle, as illustrated in Fig. 1.18. Vehicle-to-vehicle (V2V) communication may be used for collision avoidance or to exchange traffic information. Vehicle-to-infrastructure (V2I) links may also be used to communicate traffic information or to provide range and coverage extension of mobile broadband networks. Realization of intervehicle communication at mmWave is challenging due to the high Doppler and variable PHY and MAC conditions, which increase overhead for maintaining links, and lower transmitter height above ground, which limits the distance between automobiles of a connected network. While the current vehicle-to-vehicle standard IEEE 802.11p uses a 5.9 GHz band allocated for intelligent transportation systems, mmWave transmission is already employed at 24 and 77 GHz for automotive radar and cruise control. This makes it foreseeable that mmWave will find its way into other vehicular applications in the coming years.

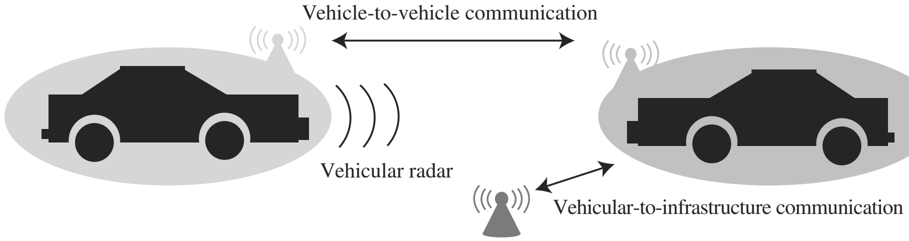

Figure 1.18 Different applications of mmWave in vehicular applications, including radar, vehicle-to-vehicle communication, and vehicle-to-infrastructure communication.

1.3.6 Cellular and Personal Mobile Communications

Today's cellular networks throughout the world use frequencies in the UHF and low microwave spectrum bands, between 400 MHz and 4.0 GHz. The use of these relatively low frequency spectrum bands has not changed in the 40 years of the cellular radio industry [RSM$^+$13]. Even today, tiny slivers of spectrum (e.g., tens of MHz) within these bands continue to be allocated by governments around the world for the deployment of the fourth generation (i.e., 4G) of cellular technologies based on the LTE standard.

Demand for cellular data, however, has been growing at a staggering pace, and capacity projections are clear — cellular networks will require much greater spectrum allocations than have ever been available before. Conservative estimates of per-user data consumption growth range from 50% to 70% per year. Some wireless carriers, such as China Mobile, are already reporting even greater data consumption increases (e.g., 77% per year increase in data consumption per user from 2011 to 2012), and operators continue to experience incredible increases in video and live streaming traffic on their networks. This trend will only accelerate with time, especially as new social networking and machine-to-machine applications evolve, and as the Internet of things becomes a reality [CIS13].

The wireless community is steadily beginning to realize that the radio propagation at mmWave frequencies (dubbed "Beyond 4G," and called "5G" by some early researchers) may not only be viable, but may actually have greater benefits than today's cellular networks, when one considers the ability to use miniature, high-gain directionally steerable antennas, spatial multiplexing, new low-power electronics, advanced signal processing, and dormant or lightly used spectrum bands that have many tens of gigahertz of bandwidth available to them. The key technological components are about to become mature to enable multi-Gpbs mobile data rates for future mmWave wireless networks using cellular radio architectures.

Recent capacity results show that future mmWave cellular networks may use 1 or 2 GHz channels, instead of LTE's 40 MHz RF channel bandwidths, and by using Time Division Duplexing (TDD) in a relatively small cell (200 m radius) scenario, end-user data rates will easily be increased by a factor of 20 over most LTE networks, enabling multi-Gbps mobile links for cellphone users [RRE14].

As shown in the remaining chapters of this textbook, particularly in Chapters 3-8, the frequencies above 10 GHz are a new frontier for the cellular communications field, as many orders of magnitude greater bandwidth are available for immediate use. The smaller wavelength of mmWave cellular will enable great capacity gains by exploiting spatial and temporal multipath in the channel, in a far greater manner than today's 4G wireless networks. When additional capacity gains from beamforming and spatial multiplexing are combined with the vastly larger channel bandwidths available at mmWave carrier frequencies, it is clear that low-cost, UWB mobile communication systems with data rates and system capacities that are orders of magnitudes greater than today's wireless networks will evolve.

Such advances in capacity are not only required as today's cellular users demand more video and cloud-based applications, they are also logical when one considers that fact that advances in Moore's law have brought similar order-of-magnitude increases to computer clock speeds and memory sizes over the past four decades. Wireless communications, and cellular and WiFi networks in particular, are about to realize massive increases in data rates through the use of much more bandwidth than ever available before, and with this massive bandwidth will come new architectures, capabilities, and use cases for cellphone subscribers [PK11]. Such advances will usher in the renaissance of wireless communications [Rap12a].

1.3.7 Aerospace Applications

Because of the significant absorption of signals in oxygen, the 60 GHz spectrum is ideal for aerospace communication where terrestrial eavesdropping must be avoided [Sno02].[4] Consequently, many spectrum regulations, including FCC regulations in the USA [ML87], have allocated 60 GHz for intersatellite communication. Intersatellite communication links are LOS, and special design considerations for satellite systems result in few technology translations to consumer applications. One emerging 60 GHz aerospace application is multimedia distribution in aircraft, as illustrated in Fig. 1.19, to reduce the cabin wiring [GKT$^+$09]. The localization of 60 GHz signals and the massive bandwidth resources make 60 GHz attractive versus microwave frequencies [BHVF08]. Unfortunately, to protect intersatellite communication from wireless in-aircraft applications, regulations currently disallow 60 GHz wireless communication in aircraft.

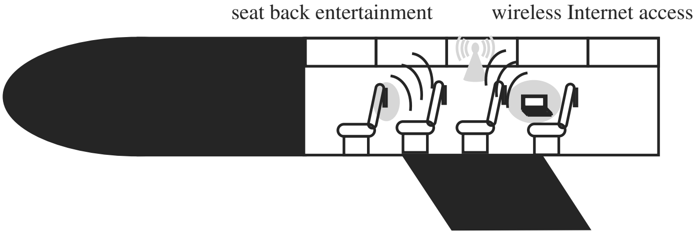

Figure 1.19 Different applications of mmWave in aircraft including providing wireless connections for seat-back entertainment systems and for wireless cellular and local area networking. Smart repeaters and access points will enable backhaul, coverage, and selective traffic control.

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[4] Figure 1.3 shows that the 180, 325, and 380 GHz bands are also well suited for "whisper radios" that are hard to eavesdrop on.

Regulations, however, are likely to change in the future with enough industry pressure and demonstration of the feasibility of network coexistence. Also, as mmWave wireless becomes more mature, additional high-attenuation bands, such as 183 and 380 GHz, will find use in aerospace applications.

1.4 Contributions of This Textbook

Today, active mmWave wireless device and product research programs exist at several major companies, such as Samsung [EAHAS$^+$12] [KP11a] [PK11], Intel [CRR08], L3, Qualcomm, Huawei, Ericsson, Broadcom, and Nokia, and universities such as Georgia Tech [DSS$^+$09], New York University [RSM$^+$13][RRE14][PR07][RBDMQ12] [RQT$^+$12] [AWW$^+$13] [SWA$^+$13] [RGAA09] [AAS$^+$14] [ALS$^+$14] [SR14] [Gho14] [SR14a] [MSR14], UC Berkeley [SB08][SB09a], UCLA [Raz08], UC San Diego [AJA$^+$14] [BBKH06][DHG$^+$13], UC Santa Barbara [RVM12][TSMR09], University of Florida [OKF$^+$05], USC [BGK$^+$06a], The University of Texas at Austin [GAPR09][GJRM10] [RGAA09][DH07][PR07][PHR09][DMRH10][BH13b][BH13c][BH14][EAHAS$^+$12][AEAH12], and The University of Texas at Dallas [CO06][SMS$^+$09]. Further, multiple textbooks and research books on the subject of mmWave devices and communications are available [Yng91][NH08][HW11]. Despite this research and progress, we have endeavored to create the first comprehensive text that brings communications and network-centric viewpoints to the intersection of antennas, propagation, semiconductors, and circuit design and fabrication for future wireless systems. Some existing texts on mmWave evolved from the circuits or packaging area but lack fundamental communications and network expertise. This book is distinct, since the ability to create future wireless communication systems requires a deep and fundamental understanding of multiple-user communications, antennas and propagation, and network theory, in addition to fundamental circuit design and microelectronics knowledge. It is rare that communications and network researchers work with circuit designers or semiconductor scientists in a university setting; this gap portends a huge void in the world's wireless research capabilities. Innovation and leadership are enhanced through interdisciplinary approaches to the creation and fabrication of broadband mmWave wireless devices and networks. This book endeavors to guide engineering practitioners, researchers, and students to find new, interdisciplinary ways to create mmWave broadband wireless devices and the networks they will form.

In this text, we demonstrate the state of the art in the areas of antennas, propagation, semiconductors, analog and digital circuits, communications, networks, and standards, while identifying critical interdependencies that will impact the future of communications at the edge of the network. By combining previously separated research fields of semiconductor devices and circuit design with the fundamentals of antennas and propagation, communications, and networking research, this book illustrates the problems and provides the knowledge to create the next generation of devices that will operate at the spectral frontier of mmWave frequencies.

For communications engineers, this book provides key insights into circuits challenges and fundamental semiconductor physics, along with antenna and propagation fundamentals. This is important because the formation of design tradeoffs requires insights into multiple fields. For example, instead of using higher-order signaling constellations, the analog-to-digital converter can be simplified or even eliminated by using simple binary modulation, even something as simple as on-off keying or differential phase shift keying. Essentially, this becomes a tradeoff between low-cost communication efficiency and mixed-signal power efficiency. As semiconductor devices continue to scale toward higher frequencies, even into the terahertz (300 GHz and above) range by 2020 [SMS$^+$09], communications researchers will be unable to produce working sensors, channel measurement systems, and other critical research tools that help to provide fundamental knowledge [RGAA09] unless they have core circuit design knowledge at the mmWave regime and above.

For analog, mixed-signal, and RF circuit designers, this book provides foundations in the operations of the higher layers, including radio channel aspects, digital signal processing, and network protocols. This will facilitate better technical interactions with communication engineers. While the wide majority of today's wireless devices still use the standard superheterodyne and homodyne (direct conversion) architectures developed by Major Edwin Armstrong over a century ago, completely new receiver architectures, which fuse the detection and memory capabilities for pipelining received data, must be developed to handle such massive transmission bandwidths with low power consumption. New concepts in organizing memory cells at the chip level need to be integrated with communications coding techniques in order to implement the power efficient devices of the future, especially when considering that high-gain advanced antenna techniques, such as MIMO and phased arrays, will be implemented in such tiny physical sizes.

Coverage in the book is intentionally broad, but is also fundamental in nature, transferring key knowledge in mmWave communication, propagation, antennas, circuits, algorithms, design approaches, and standards. Such knowledge is crucial for understanding and balancing the demands for power, capacity, and delay in the era of wireless networks with unprecedented bandwidths.

1.5 Outline of This Textbook

This book is organized to allow the engineering practitioner, researcher, or student to rapidly find useful information on specific topics that are central to the infant world of mmWave wireless communications, including the nascent but commercially viable world of 60 GHz communication. Each chapter begins with an introduction that previews the material in each section and is completed with a summary that reviews salient points of each topic discussed. Chapter 1 serves as an introduction to the entire book, and motivates the study of mmWave communication.

Chapter 2 provides background material for wireless communication system design. This chapter begins with an introduction to the complex baseband signal representation and its relationship to the wireless medium that provides the physical channel for communication. Then, using the complex baseband model, the design of discrete-time wireless communication systems to send and receive information through the transmission of data symbols is discussed. This includes a summary of equalization concepts to deal with channel distortion effects and error-correcting codes to deal with degradations due to impairments in the channel and communication hardware. A special section is included on Orthogonal Frequency Division Multiplexing (OFDM) modulation, which is popular in many commercial standards such as 4G LTE and IEEE 802.11n. Finally, Chapter 2 concludes with implementation topics including the estimation and detection of signals at the receiver, the architecture used for RF/analog/digital circuits in a communication system, and the layering of a communication system.

Chapter 3 transitions into the fundamentals of mmWave propagation and summarizes the physical characteristics of the wireless channel at operating frequencies around 60 GHz and other mmWave frequencies. This chapter consists of several different aspects of the wireless channel, each of which builds a complete picture of a mmWave wireless channel model. New results for the 28, 38, and 73 GHz outdoor urban cellular environments are given in this chapter, and they demonstrate the improvements that adaptive antennas can make in both link budget and reduction of multipath delay spread. First, measurement results that characterize the large-scale path loss are summarized. Then the penetration/reflection ability of mmWave signals is reviewed, which will be important to determine the feasibility of NLOS communication. A special section is devoted to the loss experienced by mmWave signals due to atmospheric effects such as energy absorption of oxygen and water molecules. Ray tracing is also described, as this approach will be critical for accurate site selection and deployment of future mmWave systems, where both indoor and outdoor channel conditions are considered. Finally, the indoor and outdoor mmWave channels are summarized in terms of their temporal, spectral, and spatial characteristics with respect to realistic mobility scenarios.

Chapter 4 provides background on antenna theory with an emphasis on techniques that are relevant for mmWave communication: in-package and on-chip antennas. The high cable losses at mmWave frequencies motivate pushing the antennas as close to the signal processing as possible. An in-package integrated antenna is one that is manufactured as part of the packaging process whereas an on-chip antenna is one that is built as part of the semiconductor process. Cost savings can potentially be realized with on-chip antennas if research can provide designs of high efficiency. Potential antenna topologies for mmWave are reviewed including planar, lens, aperture, and array antennas. Although many classic textbooks have dealt with the important area of antennas, we focus on the key concepts that are vital for on-chip and in-package antennas that will be used in mmWave consumer electronic products in the future. Also, array theory and fundamental semiconductor properties are treated, so readers can understand the challenges and approaches for implementing on-chip antennas. Although these approaches are nascent, and far from perfected at the time of this writing, future integrated wireless devices operating in the 30-300 GHz range will likely rely on tight integration not used at conventional UHF microwave bands. The chapter concludes with a survey of classical results on array processing, which are relevant for mmWave using adaptive antenna arrays.

Chapter 5 describes semiconductor device basics and enumerates the hardware design challenges at mmWave carrier frequencies. This includes a discussion of the RF hardware design issues including antenna design and amplifier design in the front end. Amplifier design is summarized by first presenting the challenges associated with characterizing and measuring mmWave signals. To address these challenges, S-parameters and Y-parameters are defined, and the design/cost issues that surface with different technologies including GaAs, InP, SiGe, and CMOS are interpreted. Circuit design at traditional frequencies (<10 GHz) takes advantage of lumped element assumptions because circuit dimensions are much smaller than the wavelength of the carrier frequency. Unfortunately, with mmWave frequencies, these assumptions cannot be made. This problem is discussed in detail via transmission line modeling followed by a summary of the design of passive and active elements in mmWave circuits. The key analog circuit components of mmWave transceivers are covered in detail in Chapter 5, and the chapter concludes with a novel and powerful figure of merit, the consumption factor, for determining and comparing power efficiencies for any mmWave circuit or system.

Chapter 6 discusses digital baseband issues. Much of the discussion is devoted to analog-to-digital conversion (ADC) and digital-to-analog conversion (DAC), as this consumes a substantial amount of power in mmWave circuit implementations. The impact of device fabrication mismatch, design architectures, fundamentals of DAC and ADC circuit design, and promising techniques for achieving multi-Gbps sampling and signal reproduction are given in this chapter.

Chapter 7 presents the design and applications of mmWave systems through a summary of 60 GHz PHY algorithms. The design of 60 GHz baseband algorithms is intrinsically linked to the wireless channel and hardware constraints discussed in Chapters 3 through 6. This relationship between the constraints and the PHY design is presented in the beginning of this chapter. Following this discussion, PHY design rules within these constraints are offered through sections on modulation, coding, and channel equalization. This chapter ends with a section that analyzes the impact of future/emerging hardware technology and its ability to relax certain design constraints for mmWave PHYs.

Chapter 8 reviews higher layer (above the PHY) design issues for mmWave systems with a particular emphasis on techniques relevant to 60 GHz and emerging cellular and backhaul systems. The use of directional beam steering, the limited coverage of mmWave signal propagation, and sensitivity to effects like human blockage of dominant signal paths present challenges that must be addressed at higher layers. This chapter reviews the key problems from a higher layer-perspective then expands on select topics in more detail. First, the incorporation of beam steering into a MAC protocol is described in more detail. Then, multihop operation using relays is reviewed as a way to achieve better coverage and to provide resilience to human blockages. Next, because multimedia is an important application for indoor systems, the cross-layer incorporation of video using unequal error protection is described in more detail. Finally, multiband strategies are discussed in which low frequency control signals are used to make network establishment and management easier.

Chapter 9 concludes the technical content of this text with a review of design elements from the standardization efforts for 60 GHz wireless communication systems. Three different WPAN standards are presented including IEEE 802.15.3c for WPAN, Wireless HD for uncompressed high-definition video streaming, and ECMA-387. Each of these WPAN standards has a distinct approach to the physical and MAC layer of the wireless communication system design, and these differences will be highlighted in this chapter. Two different WLAN standards are also presented including IEEE 802.11ad and WiGig (from which IEEE 802.11ad was based), which stretch WLAN into gigabit capabilities through 60 GHz spectrum.

1.5.1 Illustrations for this Textbook

You can find the color versions of the illustrations in this book at informit.com/title/9780132172288.

1.6 Symbols and Common Definitions

We use the notation in Table 1.2 and assign specific definitions to the variables in Table 1.3 throughout this text.

Table 1.2 Generic notation used in this text.

$\triangleq$	by definition
$\star$	convolution operator
$\mathbf{a}$	bold lowercase is used to denote column vectors
$\mathbf{A}$	bold uppercase is used to denote matrices
a, A	non-bold letters are used to denote scalar values
$\lvert a\rvert$	magnitude of scalar a
$\lVert\mathbf{a}\rVert$	vector 2-norm of $\mathbf{a}$
$\lVert\mathbf{A}\rVert_F$	Frobenius norm of $\mathbf{A}$
$\mathcal{A}$	calligraphic letters denote sets
$\lvert\mathcal{A}\rvert$	cardinality of set $\mathcal{A}$
$\mathbf{A}^T$	matrix transpose
$\mathbf{A}^*$	conjugate transpose
$\mathbf{A}^c$	conjugate
$\mathbf{A}^{1/2}$	matrix square root
$\mathbf{A}^{-1}$	matrix inverse
$\mathbf{A}^{\dagger}$	Moore-Penrose pseudo inverse
$\mathbf{a}_k$	k^{th} entry of vector $\mathbf{a}$
$[\mathbf{A}]_{k,l}$	scalar entry of $\mathbf{A}$ in k^{th} row l^{th} column
$[\mathbf{A}]_{:,k}$	k^{th} column of matrix $\mathbf{A}$
$[\mathbf{A}]_{:,k:m}$	column consisting of rows $k, k+1, \ldots, m$ of matrix $\mathbf{A}$
$(\cdot)$	used to index a continuous signal
$a(t)$	continuous scalar signal and value at t
$\mathbf{a}(t)$	continuous vector signal and value at t
$\mathbf{A}(t)$	continuous matrix signal and value at t
$[\cdot]$	used to index a discrete-time signal
$a[n]$	denotes discrete-time scalar signal and value at n
$\mathbf{a}[n]$	discrete-time vector signal and value at n
$\mathbf{A}[n]$	discrete-time matrix signal and value at n
$\mathsf{\mathbf{a}}[n]$	denotes discrete-time vector signal in frequency domain at subcarrier n
$\mathsf{\mathbf{A}}[n]$	discrete-time matrix signal in frequency domain at subcarrier n
log	denotes $\log_2$ unless otherwise mentioned

Table 1.3 Common definitions used in this text.

E_s	signal energy
N_o	noise energy
L	channel order
$\{h[\ell]\}_{\ell=0}^{L}$	discrete-time ISI channel impulse response with $(L+1)$ taps
$\mathsf{H}[k] = \sum_{\ell=0}^{L} h[\ell]e^{-j2\pi k\ell/N}$	frequency domain channel transfer function
$y[n]$	symbol sampled received signal
$x[n]$	symbol sampled transmitted signal
$s[n]$	symbol sampled transmitted signal before precoding
$\mathbf{I}_N$	$N \times N$ identity matrix
$\mathbf{0}_{N,M}$	$N \times M$ all zeros matrix
j	imaginary number $j = \sqrt{-1}$
$\mathbb{E}$	expectation operator
$x \sim \mathcal{N}\left(m, \sigma^2\right)$	means that x is a Gaussian random variable with mean m and variance σ^2
$x \sim \mathcal{N}_c\left(m, \sigma^2\right)$	means that x is a circularly symmetric complex Gaussian random variable with complex mean m, total variance σ^2, the real and imaginary parts of x are independent, and the variance of the real and imaginary parts are each $\sigma^2/2$
A_{eff}	effective aperture of an antenna (square meters)
$A_{\max}$	maximum effective aperture of an antenna (square meters)
d	transmitter-receiver separation distance (meters)
EIRP	effective isotropic radiated power
λ	wavelength (meters)
c	speed of light in free space = 3×10^8 m/s

1.7 Chapter Summary

Communications and network researchers, circuit designers, and antenna engineers seldom interact at universities or within the industry, leading to the potential for a huge void in mmWave wireless research capabilities. The innovative skills needed to ensure global leadership in the next revolution of wireless communications at the edge of the network, and in future mobile cellular systems, are not presently supported in an interdisciplinary manner by the government or the industrial research complex. We must teach researchers new, interdisciplinary strategies to create the ever-evolving broadband wireless devices and systems at mmWave, and beyond. To this end, it is our hope that you find this text to be a useful guide, enabling the creation of myriad new devices and applications that will soon be using the mmWave spectrum.

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