GLOBAL EDITION

Wireless Communication Networks and Systems

Cory Beard • William Stallings

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Wireless Communication Networks and Systems

Global Edition

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For my loving wife, Tricia

—WS

For Michelle, Ryan, and Jonathan,
gifts from God to me

—CB

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CONTENTS

PREFACE

OBJECTIVES

Wireless technology has become the most exciting area in telecommunications and networking. The rapid growth of mobile telephone use, various satellite services, the wireless Internet, and now wireless smartphones, tablets, 4G cellular, apps, and the Internet of Things are generating tremendous changes in telecommunications and networking. It is not an understatement to say that wireless technology has revolutionized the ways that people work, how they interact with each other, and even how social structures are formed and transformed. This book provides a unified overview of the broad field of wireless communications. It comprehensively covers all types of wireless communications from satellite and cellular to local and personal area networks. Along with the content, the book provides over 150 animations, online updates to technologies after the book was published, and social networking tools to connect students with each other and instructors with each other.

The organization of the book reflects an attempt to break this massive subject into comprehensible parts and to build, piece by piece, a survey of the state of the art. The title conveys a focus on all aspects of wireless systems—wireless communication techniques, protocols and medium access control to form wireless networks, then the deployment and system management to coordinate the entire set of devices (base stations, routers, smartphones, sensors) that compose successful wireless systems. The best example of an entire wireless system is 4G Long Term Evolution (LTE).

For those new to the study of wireless communications, the book provides comprehension of the basic principles and topics of fundamental importance concerning the technology and architecture of this field. Then it provides a detailed discussion of leading-edge topics, including Gigabit Wi-Fi, the Internet of Things, ZigBee, and 4G LTE-Advanced.

The following basic themes serve to unify the discussion:

- **Technology and architecture:** There is a small collection of ingredients that serves to characterize and differentiate wireless communication and networking, including frequency band, signal encoding technique, error correction technique, and network architecture.
- **Network type:** This book covers the important types of wireless networks, including wireless LANs, wireless personal area networks, cellular, satellite, and fixed wireless access.
- **Design approaches:** The book examines alternative principles and approaches to meeting specific communication requirements. These considerations provide the reader with comprehension of the key principles that will guide wireless design for years to come.
- **Standards:** The book provides a comprehensive guide to understanding specific wireless standards, such as those promulgated by ITU, IEEE 802, and 3GPP, as well as standards developed by other organizations. This emphasis reflects the importance of such standards in defining the available products and future research directions in this field.
- **Applications:** A number of key operating systems and applications (commonly called "apps") have captivated the attention of consumers of wireless devices. This book examines the platforms and application development processes to provide apps that make wireless devices easily accessible to users.

The book includes an extensive online glossary, a list of frequently used acronyms, and a bibliography. Each chapter includes problems and suggestions for further reading. Each chapter also includes, for review, a list of key words and a number of review questions.

INTENDED AUDIENCES

This book is designed to be useful to a wide audience of readers and students interested in wireless communication networks and systems. Its development concentrated on providing flexibility for the following.

- **Variety of disciplines:** The book provides background material and depth so those from several disciplines can benefit.
  - Those with **computer science** and **information technology** backgrounds are provided with accessible and sufficient background on signals and systems. In addition to learning about all of the wireless systems, they can especially study complete systems like the Evolved Packet System that supports LTE and mobile device operating systems and programming.
  - Those from **electrical engineering**, **computer engineering**, and **electrical engineering technology** (and even other areas of engineering) are given what they need to know about networking and protocols. Then this book provides material sufficient for a senior undergraduate communications course with no prerequisite of another communication course. It provides substantial depth in Chapters 6 through 10 on wireless propagation, modulation techniques, OFDM, CDMA, and error control coding. The technologies in the later chapters of the book can then be used as examples of these techniques. This book not only provides fundamentals but also understanding of how they are used in current and future wireless technologies.
- **Ranges of experience:** Those who are novices with wireless communications, or even communication technologies themselves, are led through the knowledge they need to become proficient. And those with existing knowledge learn about the latest advances in wireless networking.
- **Levels of depth:** This book offers options for the level of depth used to cover different topics. Most notably Chapter 5, entitled Overview of Wireless Communications, provides tutorial-level coverage of the important wireless concepts needed to understand the rest of the book. For those needing more detailed understanding, however, Chapters 6 through 10 cover the same topics in more depth for fuller understanding. This again makes the book accessible to those with a variety of interests, level of prior knowledge, and expertise.

PLAN OF THE TEXT

The objective of this book is to provide a comprehensive technical survey of wireless communications fundamentals, wireless networks, and wireless applications. The book is organized into four parts as illustrated in Figure P.1.

Part One, Technical Background: Provides background material on the process of data and packet communications, as well as protocol layers, TCP/IP, and data networks.

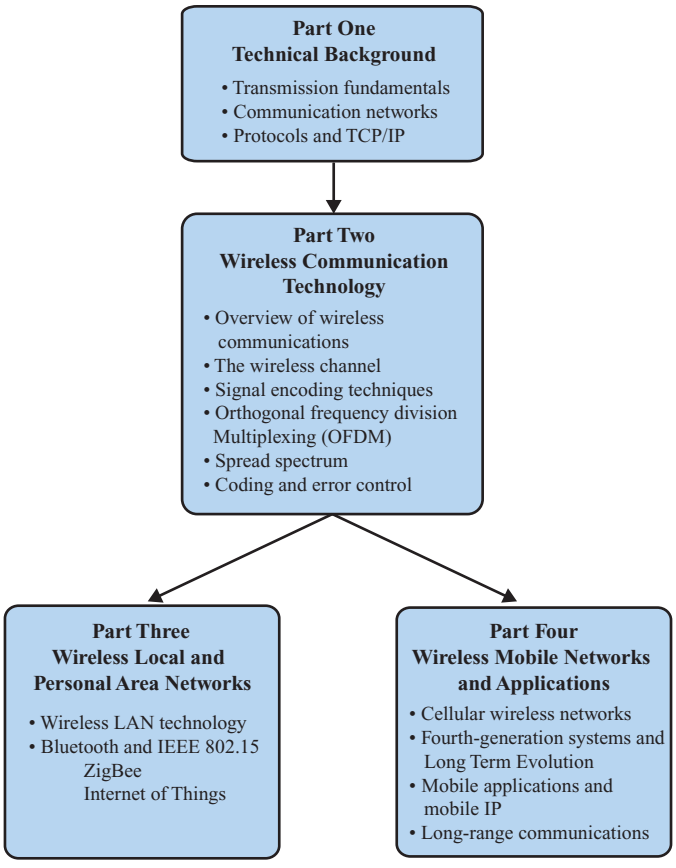


Figure P.1 Wireless Topics

Part Two, Wireless Communication Technology: Covers all of the relevant information about the process of sending a wireless signal and combating the effects of the wireless channel. The material can be covered briefly with Chapter 5, Overview of Wireless Communications, or through five chapters on the wireless channel (antennas and propagation), signal encoding, OFDM, spread spectrum, and error control coding.

Part Three, Wireless Local and Personal Area Networks: Provides details on IEEE 802.11, IEEE 802.15, Bluetooth, the Internet of Things, and ZigBee.

Part Four, Wireless Mobile Networks and Applications: Provides material on mobile cellular systems principles, LTE, smartphones, and mobile applications. It also covers long-range communications using satellite, fixed wireless, and WiMAX.

The book includes a number of pedagogic features, including the use of over 150 animations and numerous figures and tables to clarify the discussions. More details are given below. Each chapter also includes a list of key words, review questions, homework problems, and suggestions for further reading. The book also includes an extensive online glossary, a list of frequently used acronyms, and a reference list.

ORDER OF COVERAGE

With a comprehensive work such as this, careful planning is required to cover those parts of the text most relevant to the students and the course at hand. The book provides some flexibility. For example, the material in the book need not be studied sequentially. As a matter of fact, it has been the experience of the authors that students and instructors are more engaged if they are able to dive into the technologies themselves as soon as possible. One of the authors in his courses has routinely studied IEEE 802.11 (Chapter 11) before concentrating on the full details of wireless communications. Some physical layer details may need to be skipped at first (e.g., temporarily skipping Sections 11.5 and 11.6), but students are more engaged and able to perform projects if they've studied the actual technologies earlier.

The following are suggestions concerning paths through the book:

- Chapter 5, Overview of Wireless Communications, can be substituted for Chapters 6 through 10. Conversely, Chapter 5 should be omitted if using Chapters 6 through 10.
- Part Three can be covered before Part Two, omitting some physical layer details to be revisited later. Part Two should precede Part Four, however.
- Chapters 2 through 4 can be left as outside reading assignments. Especially by using animations provided with the book, some students can be successful studying these topics on their own.
- Within Part Three, the chapters are more or less independent and can be studied in either order depending on level of interest.
- The chapters in Part Four can also be studied in any order, except Chapters 13 and 14 on cellular systems and LTE should be studied as a unit.
- Computer science and information technology courses could focus more on Wi-Fi, IEEE 802.15, and mobile applications in Chapters 11, 12, and 15, then proceed with projects on MAC protocols and mobile device programming.
- Electrical engineering and engineering technology students can focus on Chapters 6 through 10 and proceed with projects related to the modulation and error control coding schemes used for IEEE 802.11 and LTE.

ANIMATIONS

Animations provide a powerful tool for understanding the complex mechanisms discussed in this book, including forward error correction, signal encoding, and protocols. Over 150 Web-based animations are used to illustrate many of the data communications and protocol concepts in this book.

The animations progressively introduce parts of diagrams and help to illustrate data flow, connection setup and maintenance procedures, error handling, encapsulation, and the ways technologies perform in different scenarios. For example, see Figure P.2 and its animation. This is actually Figure 13.7. From the print version, the animations can be accessed through the QR code next to the figure or through the book's Premium Web site discussed below. Walking step-by-step through the animation can be accomplished with a click or tap on the animation. This figure shows possible choices of handoff decisions at different locations between two base stations. The original figure might be difficult for the reader to first understand, but the animations give good enhanced understanding by showing the

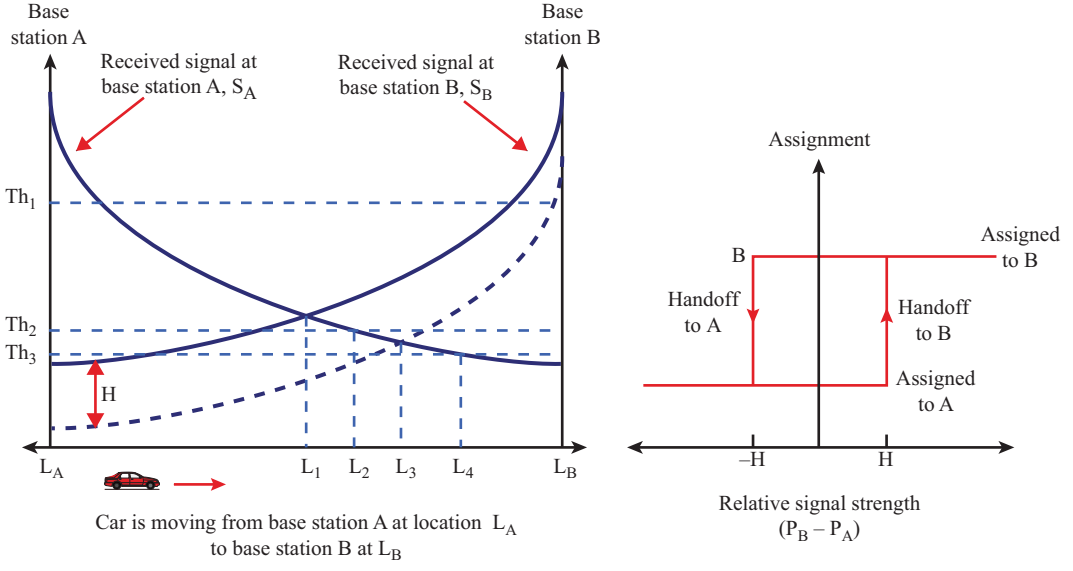
figure piece-by-piece with extra explanation. These animations provide significant help to the reader to understand the purpose behind each part of the figure.

INSTRUCTOR SUPPORT MATERIALS

The major goal of this text is to make it as effective a teaching tool for this exciting and fast-moving subject as possible. This goal is reflected both in the structure of the book and in the supporting material. The text is accompanied by the following supplementary material to aid the instructor:

- **Solutions manual:** Solutions to all end-of-chapter Review Questions and Problems.
- **Supplemental problems:** More problems beyond those offered in the text.
- **Projects manual:** Suggested project assignments for all of the project categories listed in the next section.
- **PowerPoint slides:** A set of slides covering all chapters, suitable for use in lecturing.
- **PDF files:** Reproductions of all figures and tables from the book.
- **Wireless courses:** Links to home pages for courses based on this book. These pages may be useful to other instructors in providing ideas about how to structure their course.
- **Social networking:** Links to social networking sites that have been established for instructors using the book, such as on Facebook and LinkedIn, where instructors can interact.

All of these support materials are available at the **Instructor Resource Center (IRC)** for this textbook, which can be reached through the publisher's Web site



(a) Handoff decision as a function of handoff scheme **(b) Hysteresis mechanism**

Figure P.2 Handoff Between Two Cells

www.pearsonglobaleditions.com/Stallings. To gain access to the IRC, please contact your local Pearson sales representative.

The **Companion Web site**, at www.corybeardwireless.com, includes technology updates, Web resources, etc. This is discussed in more detail below in the section about student resources.

PROJECTS AND OTHER STUDENT EXERCISES

For many instructors, an important component of a wireless networking course is a project or set of projects by which students get hands-on experience to reinforce concepts from the text. This book provides an unparalleled degree of support for including a projects component in the course. The IRC not only provides guidance on how to assign and structure the projects but also includes a set of User's Manuals for various project types plus specific assignments, all written especially for this book. Instructors can assign work in the following areas:

- **Practical exercises:** Using network commands, students gain experience in network connectivity.
- **Wireshark projects:** Wireshark is a protocol analyzer that enables students to study the behavior of protocols. A video tutorial is provided to get students started, in addition to a set of Wireshark assignments.
- **Simulation projects:** Students can use different suggested simulation packages to analyze network behavior. The IRC includes a number of student assignments.
- **Performance modeling projects:** Multiple performance modeling techniques are introduced. The IRC includes a number of student assignments.
- **Research projects:** The IRC includes a list of suggested research projects that would involve Web and literature searches.
- **Interactive assignments:** Twelve interactive assignments have been designed to allow students to give a specific set of steps to invoke, or devise a sequence of steps to achieve a desired result. The IRC includes a set of assignments, plus suggested solutions, so that instructors can assess students' work.

This diverse set of projects and other student exercises enables the instructor to use the book as one component in a rich and varied learning experience and to tailor a course plan to meet the specific needs of the instructor and students.

RESOURCES FOR STUDENTS

A substantial amount of original supporting material for students has been made available online, at two Web locations. The **Companion Web site**, at www.corybeardwireless.com, includes the following.

- **Social networking tools**: Students using the book can interact with each other to share questions and insights and develop relationships. Throughout the lifetime of

the book, various social networking tools may become prevalent; new social networking sites will be developed and then links and information about them will be made available here.

- **Useful Web sites:** There are links to other relevant Web sites which provide extensive help in studying these topics. Links to these are provided.
- **Errata sheet:** An errata list for this book will be maintained and updated as needed. Please e-mail any errors that you spot from the link at corybeardwireless.com.
- **Documents:** These include a number of documents that expand on the treatment in the book. Topics include standards organizations and the TCP/IP checksum.
- **Wireless courses:** There are links to home pages for courses based on this book. These pages may be useful to other instructors in providing ideas about how to structure their course.

Purchasing this textbook new also grants the reader twelve months of access to the **Premium Content site**, which includes the following:

- **Animations:** Those using the print version of the book can access the animations by going to this Web site. The QR codes next to the book figures give more direct access to these animations. The ebook version provides direct access to these animations by clicking or tapping on a linked figure.
- **Glossary:** List of key terms and definitions.
- **Appendices:** Three appendices to the book are available on traffic analysis, Fourier analysis, and data link control protocols.
- **Technology updates:** As new standards are approved and released, new chapter sections will be developed. They will be released here before a new edition of the text is published. The book will therefore not become outdated in the same way that is common with technology texts.

To access the Premium Website, click on the *Premium Website* link at www.pearsonglobaleditions.com/Stallings and enter the student access code found on the card in the front of the book.

William Stallings also maintains the Computer Science Student Resource Site, at computersciencestudent.com. The purpose of this site is to provide documents, information, and useful links for computer science students and professionals. Links are organized into four categories:

- **Math:** Includes a basic math refresher, a queuing analysis primer, a number system primer, and links to numerous math sites
- **How-to:** Advice and guidance for solving homework problems, writing technical reports, and preparing technical presentations
- **Research resources:** Links to important collections of papers, technical reports, and bibliographies
- **Miscellaneous:** A variety of useful documents and links

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This book has benefited from review by a number of people, who gave generously of their time and expertise. The following professors and instructors provided reviews: Alex WijesIinha (Towson University), Dr. Ezzat Kirmani (St. Cloud State University), Dr. Feng Li (Indiana University-Purdue University Indianapolis), Dr. Guillermo A. Francia III (Jacksonville State University), Dr. Kamesh Namuduri (University of North Texas), Dr. Melody Moh (San Jose State University), Dr. Wuxu Peng (Texas State University), Frank E. Green (University of Maryland, Baltimore County), Gustavo Vejarano (Loyola Marymount University), Ilker Demirkol (Rochester Institute of Tech), Prashant Krishnamurthy (University of Pittsburgh), and Russell C. Pepe (New Jersey Institute of Technology).

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About the Authors

Dr. William Stallings has authored 17 textbooks, and counting revised editions, over 40 books on computer security, computer networking, and computer architecture. In over 30 years in the field, he has been a technical contributor, a technical manager, and an executive with several high-technology firms. Currently he is an independent consultant whose clients have included computer and networking manufacturers and customers, software development firms, and leading-edge government research institutions. He has 13 times received the award for the best Computer Science textbook of the year from the Text and Academic Authors Association.

He created and maintains the Computer Science Student Resource Site at ComputerScienceStudent.com. This site provides documents and links on a variety of subjects of general interest to computer science students (and professionals). He is a member of the editorial board of Cryptologia, a scholarly journal devoted to all aspects of cryptology.

Dr. Stallings holds a PhD from MIT in computer science and a BS from Notre Dame in electrical engineering.

Dr. Cory Beard is an Associate Professor of Computer Science and Electrical Engineering at the University of Missouri-Kansas City (UMKC). His research areas involve the prioritization of communications for emergency purposes. This work has involved 3G/4G cellular networks for public safety groups, MAC layer performance evaluation, call preemption and queuing, and Internet traffic prioritization. His work has included a National Science Foundation CAREER Award.

He has received multiple departmental teaching awards and has chaired degree program committees for many years. He maintains a site for book-related social networking and supplemental materials at corybeardwireless.com.

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CHAPTER 1

INTRODUCTION

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Describe how wireless communications have developed.
- Explain the purposes of various generations of cellular technology.
- Describe the ways mobile devices have revolutionized and will continue to revolutionize society.
- Identify and describe future trends.

This book is a survey of the technology of wireless communication networks and systems. Many factors, including increased competition, the introduction of digital technology, mobile device user interface design, video content, and social networking have led to unprecedented growth in the wireless market. In this chapter, we discuss some of the key factors driving this wireless networking revolution.

1.1 WIRELESS COMES OF AGE

Guglielmo Marconi invented the wireless telegraph in 1896.[1] In 1901, he sent telegraphic signals across the Atlantic Ocean from Cornwall to St. John's Newfoundland, a distance of about 3200 km. His invention allowed two parties to communicate by sending each other alphanumeric characters encoded in an analog signal. Over the last century, advances in wireless technologies have led to the radio, the television, communications satellites, mobile telephone, and mobile data. All types of information can now be sent to almost every corner of the world. Recently, a great deal of attention has been focused on wireless networking, cellular technology, mobile applications, and the Internet of Things.

Communications satellites were first launched in the 1960s; today satellites carry about one-third of the voice traffic and all of the television signals between countries. Wireless networking allows businesses to develop WANs, MANs, and LANs without a cable plant. The IEEE 802.11 standard for wireless LANs (also known as Wi-Fi) has become pervasive. Industry consortiums have also provided seamless short-range wireless networking technologies such as ZigBee, Bluetooth, and Radio Frequency Identification tags (RFIDs).

The cellular or mobile telephone started with the objective of being the modern equivalent of Marconi's wireless telegraph, offering two-party, two-way communication. Early generation wireless phones offered voice and limited data services through bulky devices that gradually became more portable. Current third and

[1]The actual invention of radio communications more properly should be attributed to Nikola Tesla, who gave a public demonstration in 1893. Marconi's patents were overturned in favor of Tesla in 1943 [ENGE00].

fourth generation devices are for voice, texting, social networking, mobile applications, mobile Web interaction, and video streaming. These devices also include cameras and a myriad of sensors to support the device applications. The areas of coverage for newer technologies are continually being expanded and focused on key user populations.

The impact of wireless communications has been and will continue to be profound. Very few inventions have been able to "shrink" the world in such a manner, nor have they been able to change the way people communicate as significantly as the way wireless technology has enabled new forms of social networking. The standards that define how wireless communications devices interact are quickly converging, providing a global wireless network that delivers a wide variety of services.

Figure 1.1 highlights some of the key milestones in the development of wireless communications.[2] Wireless technologies have gradually migrated to higher frequencies. As will be seen in later chapters, higher frequencies enable the support of greater data rates and throughput but require higher power, are more affected by obstructions, and have shorter effective range.

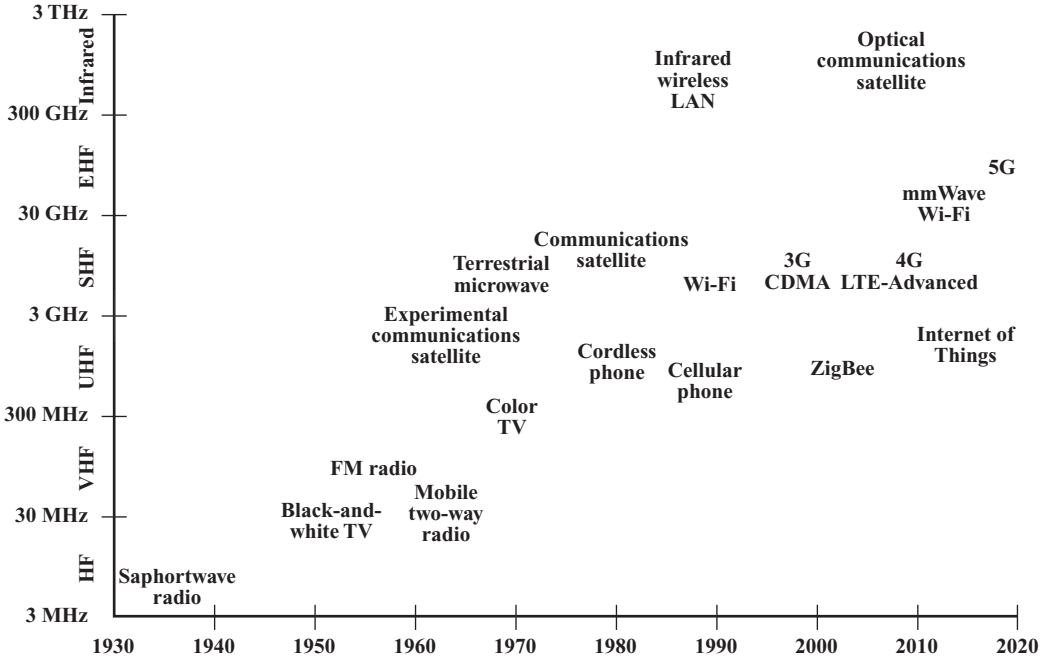

Figure 1.1 Some Milestones in Wireless Communications

[2]Note the use of a log scale for the *y*-axis. A basic review of log scales is in the math refresher document at the Computer Science Student Resource Site at computersciencestudent.com.

1.2 THE GLOBAL CELLULAR NETWORK

The cellular revolution is apparent in the growth of the mobile phone market alone. In 1990, the number of users was approximately 11 million [ECON99]. Today, according to 4G Americas, that number is over seven billion. There are a number of reasons for the dominance of mobile devices. Mobile devices are convenient; they move with people. In addition, by their nature, they are location aware. Mobile cellular devices communicate with regional base stations that are at fixed locations. In many geographic areas, mobile telephones are the only economical way to provide phone service to the population. Operators can erect base stations quickly and inexpensively when compared with digging up ground to lay cables in harsh terrain.

Today there is no single cellular network. Devices support several technologies and generally work only within the confines of a single operator's network. To move beyond this model, work is being done to define and implement standards.

The dominant first-generation wireless network in North America was the Advanced Mobile Phone System (AMPS). The key second generation wireless systems are the Global System for Mobile Communications (GSM), Personal Communications Service (PCS) IS-136, and PCS IS-95. The PCS standard IS-136 uses time division multiple access (TDMA); GSM uses a combination of TDMA and frequency division multiple access (FDMA), and IS-95 uses code division multiple access (CDMA). 2G systems primarily provide voice services, but also provide some moderate rate data services.

The two major third-generation systems are CDMA2000 and Universal Mobile Telephone Service (UMTS). Both use CDMA and are meant to provide packet data services. CDMA2000 released 1xRTT (1 times Radio Transmission Technology) and then 1xEV-DO (1 times Evolution-Data Only) through Release 0, Revision A, and Revision B. The competing UMTS uses Wideband CDMA. It is developed by the Third Generation Partnership Project (3GPP); its first release was labeled Release 99 in 1999, but subsequent releases were labeled Releases 4 onward.

The move to fourth generation mainly involved competition between IEEE 802.16 WiMAX, described in Chapter 15, and Long Term Evolution (LTE), described in Chapter 14. Both use a different approach than CDMA for high spectral efficiency in a wireless channel called orthogonal frequency division multiplexing (OFDM). The requirements for 4G came from directives by the International Telecommunication Union (ITU), which said that 4G networks should provide all-IP services at peak data rates of up to approximately 100 Mbps for high-mobility mobile access and up to approximately 1 Gbps for low-mobility access. LTE, also developed by 3GPP, ended up the predominant technology for 4G, and 3GPP Release 8 was its first release. Although LTE Release 8 does not meet the ITU requirements (even though marketers have called it "4G LTE"), the later Release 10 achieves the goals and is called LTE-Advanced. There are a wide number of Release 8 deployments so far but much fewer Release 10 upgrades.

1.3 THE MOBILE DEVICE REVOLUTION

Technical innovations have contributed to the success of what were originally just mobile phones. The prevalence of the latest devices, with multi-megabit Internet access, mobile apps, high megapixel digital cameras, access to multiple types of wireless networks (e.g., Wi-Fi, Bluetooth, 3G, and 4G), and several on-board sensors, all add to this momentous achievement. Devices have become increasingly powerful while staying easy to carry. Battery life has increased (even though device energy usage has also expanded), and digital technology has improved reception and allowed better use of a finite spectrum. As with many types of digital equipment, the costs associated with mobile devices have been decreasing.

The first rush to wireless was for voice. Now, the attention is on data; some wireless devices are only rarely used for voice. A big part of this market is the wireless Internet. Wireless users use the Internet differently than fixed users, but in many ways no less effectively. Wireless smartphones have limited displays and input capabilities compared with larger devices such as laptops or PCs, but mobile apps give quick access to intended information without using Web sites. Because wireless devices are location aware, information can be tailored to the geographic location of the user. Information finds users, instead of users searching for information. Tablet devices provide a happy medium between the larger screens and better input capabilities of PCs and the portability of smartphones.

Examples of wireless technologies that are used for long distance are cellular 3G and 4G, Wi-Fi IEEE 802.11 for local areas, and Bluetooth for short distance connections between devices. These wireless technologies should provide sufficient data rates for the intended uses, ease of connectivity, stable connections, and other necessary quality of service performance for services such as voice and video. There are still improvements needed to meet these requirements in ways that are truly invisible to end users.

For many people, wireless devices have become a key part of how they interact with the world around them. Currently, this involves interaction with other people through voice, text, and other forms of social media. They also interact with various forms of multimedia content for business, social involvement, and entertainment. In the near future, many envision advanced ways for people to interact with objects and machines around them (e.g., the appliances in a home) and even for the devices themselves to perform a more active role in the world.

1.4 FUTURE TRENDS

As 4G LTE-Advanced and higher speed Wi-Fi systems are now being deployed, many see great future untapped potential to be realized. Great potential exists for Machine to Machine (MTM) communications, also called the Internet of Things (IoT). The basic idea is that devices can interact with each other in areas such as healthcare, disaster recovery, energy savings, security and surveillance, environmental awareness, education, inventory and product management, manufacturing, and many others. Today's current smart devices could interact with myriads of objects

equipped with wireless networking capabilities. This could start with information dissemination to enable data mining and decision support, but could also involve capabilities for automated remote adaptation and control. For example, a residential home could have sensors to monitor temperature, humidity, and airflow to assess human comfort levels. These sensors could also collaborate with home appliances, heating and air conditioning systems, lighting systems, electric vehicle charging stations, and utility companies to provide homeowners with advice or even automated control to optimize energy consumption. This would adjust when homeowners are at home conducting certain activities or away from home. Eventually these wirelessly equipped objects could interact in their own forms of social networking to discover, trust, and collaborate.

Future wireless networks will have to significantly improve to enable these capabilities. Some envision a 100-fold increase in the number of communication devices. And the type of communication would involve many short messages, not the type of communication supported easily by the current generations of the technologies studied in this book. If these communications were to involve control applications between devices, the real-time delay requirements would be much more stringent than that required in human interaction.

Also, the demands for capacity will greatly increase. The growth in the number of subscribers and per-user throughput gives a prediction of a 1000-fold increase in data traffic by 2020. This has caused the development of the following technologies for what may be considered 5G (although the definition of 5G has not been formalized). Some of these will be better understood after studying the topics in this book, but we provide them here to set the stage for learning expectations.

- **Network densification** will use many small transmitters inside buildings (called femtocells) and outdoors (called picocells or relays) to reuse the same carrier frequencies repeatedly.
- **Device-centric architectures** will provide connections that focus on what a device needs for interference reduction, throughput, and overall service quality.
- **Massive multiple-input multiple-output (MIMO)** will use 10 or more than 100 antennas (both on single devices and spread across different locations) to focus antenna beams toward intended devices even as the devices move.
- **Millimeter wave (mmWave)** frequencies in the 30 GHz to 300 GHz bands have much available bandwidth. Even though they require more transmit power and have higher attenuation due to obstructions and atmosphere, massive MIMO can be used to overcome those limitations.
- **Native support for mobile to mobile (MTM) communication** will accommodate low data rates, a massive number of devices, sustained minimum rates, and very low delays.

Throughout this book, the reader will see the methods by which technologies such as Wi-Fi have expanded and improved. We will review the foundational technologies and see the ways in which new directions such as OFDM and LTE-Advanced have created dramatic improvements. This provides excellent preparation so that researchers and practitioners will be ready to participate in these future areas.

1.5 THE TROUBLE WITH WIRELESS

Wireless is convenient and often less expensive to deploy than fixed services, but wireless is not perfect. There are limitations, political and technical difficulties, that may ultimately hamper wireless technologies from reaching their full potential. Two issues are the wireless channel and spectrum limitations.

The delivery of a wireless signal does not always require a free line-of-sight path, depending on the frequency. Signals can also be received through transmission through objects, reflections off objects, scattering of signals, and diffraction around the edges of objects. Unfortunately, reflections can cause multiple copies of the signal to arrive at the receiver at different times with different attenuations. This creates the problem of **multipath fading** when the signals add together and can cause the signal to be significantly degraded. Wireless signals also suffer from noise, interference from other users, and Doppler shifting caused by movement of devices.

A series of approaches are used to combat these problems of wireless transmission. All are discussed in this book.

- **Modulation** sends digital data in a signal format that sends as many bits as possible for the current wireless channel.
- **Error control coding**, also known as channel coding, adds extra bits to a signal so that errors can be detected and corrected.
- **Adaptive modulation and coding** dynamically adjusts the modulation and coding to measurements of the current channel conditions.
- **Equalization** counteracts the multipath effects of the channel.
- **Multiple-input multiple-output** systems use multiple antennas to point signals strongly in certain directions, send simultaneous signals in multiple directions, or send parallel streams of data.
- **Direct sequence spread spectrum** expands the signal over a wide bandwidth so that problems in parts of the bandwidth are overcome because of the wide bandwidth.
- **Orthogonal frequency division multiplexing** breaks a signal into many lower rate bit streams where each is less susceptible to multipath problems.

Spectrum regulations also affect the capabilities of wireless communications. Governmental regulatory agencies allocate spectrum to various types of uses, and wireless communications companies frequently spend large amounts of money to acquire spectrum. These agencies also give rules related to power and spectrum sharing approaches. All of this limits the bandwidth available to wireless communications. Higher frequencies have more available bandwidth but are harder to use effectively due to obstructions. They also inherently require more transmission power. Transition from today's 1 GHz to 5 GHz bands to millimeter wave (mmWave) bands in the 30 GHz to 300 GHz range is of increasing interest since they have more bandwidth available.

Part One

Technical Background

CHAPTER 2

TRANSMISSION FUNDAMENTALS

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Distinguish between digital and analog information sources.
- Explain the various ways in which audio, data, image, and video can be represented by electromagnetic signals.
- Discuss the characteristics of analog and digital waveforms.
- Explain the roles of frequencies and frequency components in a signal.
- Identify the factors that affect channel capacity.
- Compare and contrast various forms of wireless transmission.

The purpose of this chapter is to make this book self-contained for the reader with little or no background in data communications. For the reader with greater interest, references for further study are supplied at the end of the chapter.

2.1 SIGNALS FOR CONVEYING INFORMATION

In this book, we are concerned with electromagnetic signals used as a means to transmit information. An electromagnetic signal is a function of time, but it can also be expressed as a function of frequency; that is, the signal consists of components of different frequencies. It turns out that the **frequency domain** view of a signal is far more important to an understanding of data transmission than a **time domain** view. Both views are introduced here.

Time Domain Concepts

Viewed as a function of time, an electromagnetic signal can be either analog or digital. An **analog signal** is one in which the signal intensity varies in a smooth fashion over time. In other words, there are no breaks or discontinuities in the signal. A **digital signal** is one in which the signal intensity maintains a constant level for some period of time and then changes to another constant level.[1] Figure 2.1 shows examples of both kinds of signals. The analog signal might represent speech, and the digital signal might represent binary 1s and 0s.

The simplest sort of signal is a **periodic signal**, in which the same signal pattern repeats over time. Figure 2.2 shows an example of a periodic analog signal (sine wave) and a periodic digital signal (square wave). Mathematically, a signal $s(t)$ is defined to be periodic if and only if

$$s(t + T) = s(t) \qquad -\infty < t < +\infty$$

where the constant T is the period of the signal (T is the smallest value that satisfies the equation). Otherwise, a signal is **aperiodic**.

[1]This is an idealized definition. In fact, the transition from one voltage level to another will not be instantaneous, but there will be a small transition period. Nevertheless, an actual digital signal approximates closely the ideal model of constant voltage levels with instantaneous transitions.

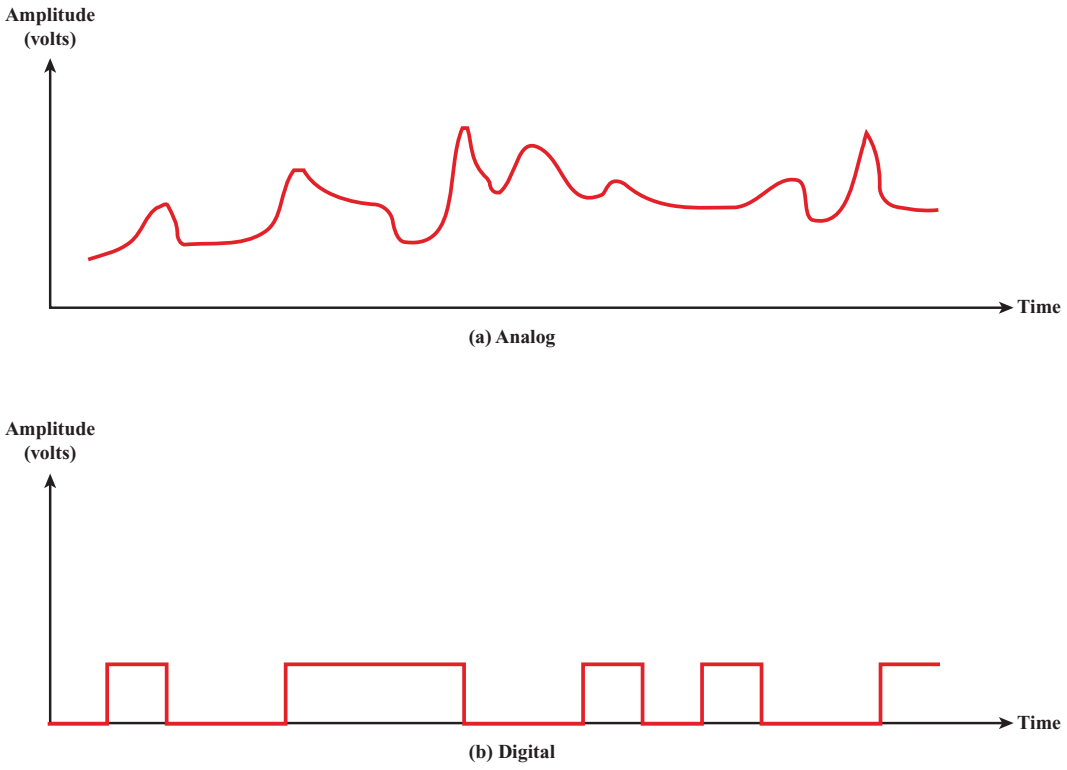

Figure 2.1 Analog and Digital Waveforms

The sine wave is the fundamental analog signal. A general sine wave can be represented by three parameters: peak amplitude (A), frequency (f), and phase (ϕ). The **peak amplitude** is the maximum value or strength of the signal over time; typically, this value is measured in volts. The **frequency** is the rate [in cycles per second, or Hertz (Hz)] at which the signal repeats. An equivalent parameter is the **period** (T) of a signal, which is the amount of time it takes for one repetition; therefore, $T = 1/f$. **Phase** is a measure of the relative position in time within a single period of a signal, as illustrated later.

The general sine wave can be written as

$$s(t) = A \sin(2\pi ft + \phi) \tag{2.1}$$

A function with the form of Equation (2.1) is known as a **sinusoid**. Figure 2.3 shows the effect of varying each of the three parameters. In part (a) of the figure, the frequency is 1 Hz; thus the period is $T = 1$ second. Part (b) has the same frequency and phase but a peak amplitude of 0.5. In part (c) we have $f = 2$, which is equivalent to $T = 0.5$. Finally, part (d) shows the effect of a phase shift of $\pi/4$ radians, which is 45 degrees (2π radians $= 360° = 1$ period).

In Figure 2.3 the horizontal axis is time; the graphs display the value of a signal at a given point in space as a function of time. These same graphs, with a change of

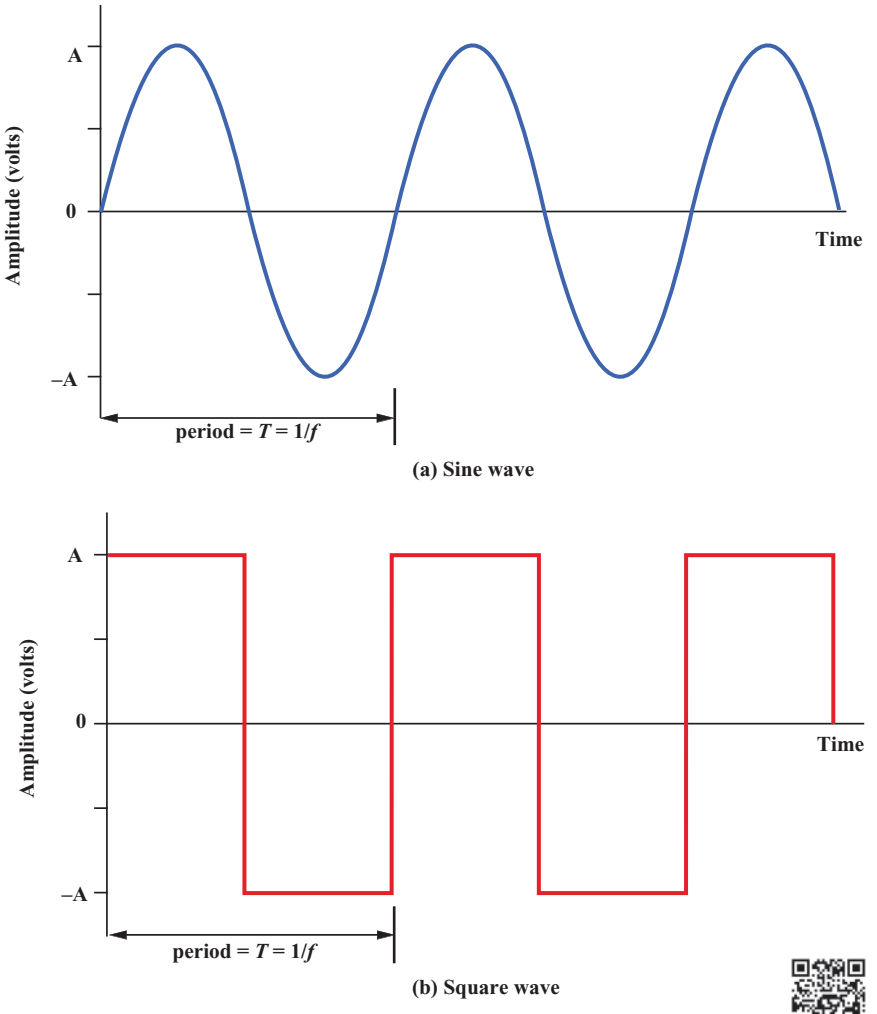

Figure 2.2 Examples of Periodic Signals

scale, can apply with horizontal axes in space. In that case, the graphs display the value of a signal at a given point in time as a function of distance. For example, for a sinusoidal transmission (e.g., an electromagnetic radio wave some distance from a radio antenna or sound some distance from loudspeaker) at a particular instant of time, the intensity of the signal varies in a sinusoidal way as a function of distance from the source.

There is a simple relationship between the two sine waves, one in time and one in space. The **wavelength** (λ) of a signal is the distance occupied by a single cycle, or, put another way, the distance between two points of corresponding phase of two consecutive cycles. Assume that the signal is traveling with a velocity v. Then the wavelength is related to the period as follows: $\lambda = vT$. Equivalently, $\lambda f = v$. Of particular relevance to this discussion is the case where $v = c$, the speed of light in free space, which is approximately 3×10^8 m/s.