

4th edition

Introduction to
**Wireless &
Mobile Systems**

Dharma Prakash Agrawal
Qing-An Zeng



Fourth Edition

Introduction to
**Wireless and
Mobile Systems**

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Dharma Prakash Agrawal

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Dedication

In memory of my parents, Shri Saryoo Prasad Agrawal and Shrimati Chandrakanta Bai Agrawal, who raised me affectionately in a small, unknown village and encouraged me to learn and excel. The fourth edition is inspired by love and affection from my grandchildren Aneesh, Neeraj, Rajeev, Akhil, Jaya, and Dhevan.

Dharma Prakash Agrawal

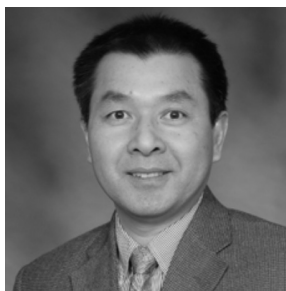
To my wife, Min, and to our children, Selena and Andrew.

Qing-An Zeng

About the Authors



Dr. Dharma P. Agrawal is the Ohio Board of Regents Distinguished Professor of Computer Science and Engineering and the founding director of the Center for Distributed and Mobile Computing in the Department of EECS, University of Cincinnati, Ohio. During his sabbatical leave, he served as a visiting professor of ECE at Carnegie Mellon University. He has been a faculty member at North Carolina State University, Raleigh, North Carolina (1982–1998) and Wayne State University, Detroit (1977–1982). His recent research interests include applications of sensor networks in monitoring Parkinson’s disease patients and neurosis, applications of sensor networks in monitoring athletes’ personnel wellness and fitness, applications of sensor networks in monitoring firefighters physical condition in action, applications of efficient secured communication in sensor networks, applications of secured group communication in vehicular networks, use of femtocells in LTE technology and interference issues, use of heterogeneous wireless networks, and resource allocation and security in mesh networks for fourth-generation (4G) technology. He has seven approved patents and twenty-three patent filings in the area of wireless cellular networks. He has given tutorials and extensive training courses in various conferences in the United States and numerous institutions in Taiwan, Korea, Jordan, the United Arab Emirates, Malaysia, and India in the areas of ad hoc and sensor networks and mesh networks. He was an editor of the *Journal of Parallel and Distributed Systems* and the *International Journal of Ad Hoc & Sensor Wireless Networks*. He has served as an editor of the *IEEE Computer Magazine* and *IEEE Transactions on Computers*. He has been the Program Chair and General Chair for many international conferences and meetings. He has received numerous certificates and awards from the IEEE Computer Society and has been elected as a core member. He was awarded a Third Millennium Medal by the IEEE for his past outstanding contributions. He has also delivered keynote speeches for thirty-four international meetings and has been named as an ISI Highly Cited Researcher in Computer Science. He is a Fellow of the IEEE, the ACM, the AAAS, and the WIF; he is Charter Fellow of National Academy of Inventors; and he is a recipient of 2008 IEEE CS Harry Goode Award.



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Preface to the Fourth Edition

We are pleased and honored to present this fourth edition of *Introduction to Wireless and Mobile Systems*. Wireless and mobile communication technologies are advancing at an unexpected speed, and the timely release of the fourth edition is our attempt to keep the readers up to date with these rapid changes.

New to This Edition

The content of this edition has been revised based on extensive reviews conducted on the third edition of this book. With rapid adoption of Access Points, we have created a separate chapter on this topic. Other major changes include enhancing the chapter on Sensor Networks and creating a new chapter dealing with security aspects of different wireless technologies. We have integrated some of the topics from the third edition into various chapters and have added discussions of 3GPP, WiMax, and LTE. We have also updated the last chapter thoroughly by adding discussions of new concepts such as two-tier visual sensor networks, application of coding in wireless multi-hop networks, delay tolerant and mobile opportunistic networks, as well as discussions of 5G and beyond, Android, iOS, and the Internet of Things.

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap version have access to the book's MindTap Reader and are able to complete homework and assessment material online, through their desktop, laptop, or iPad. If you are using a Learning Management System (such as Blackboard or Moodle) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

In MindTap, instructors can:

- Personalize the Learning Path to match your course syllabus by rearranging content or appending original material to the online content.
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension
- Promote student engagement through interactivity and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes, create their own flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and homework.

Acknowledgments

Creating a new edition is a lot of work, and we are indebted to numerous individuals who have helped to make this revision possible. We are deeply indebted to Yang Chi, Vaibhav Pandit, Hailong Li, Peter Jun, Rupen Mitra, and

Dr. David Chung for their direct or indirect help in updating the edition. We are indebted to all of the reviewers of the third edition for their assistance in making this edition even better than earlier. Reviewers willing to be acknowledged are Junghwan Kim, Hermann J. Helgert, and Sarvesh Kulkarni. Our sincere thanks also go to our publisher and staff at Cengage Learning, including Hilda Gowans and Eavan Cully.

Finally, we are eternally grateful to our wives for their patience during the course of this revision.

DHARMA PRAKASH AGRAWAL
QING-AN ZENG



Preface to the Third Edition

We are pleased and honored to present this third edition of *Introduction to Wireless and Mobile Systems*. Wireless and mobile communication technologies are advancing at an unprecedented rate, and the timely release of the third edition is our endeavor to keep pace with this rapid technological evolution.

New to This Edition

The content of this edition has been revised based on extensive reviews conducted on the second edition of this book. In keeping with the reviewers' recommendations, we have moved the chapter on Network Protocols to before the chapter on Mobile Communications Systems. Other major changes include splitting the previous single chapter on Ad Hoc and Sensor Networks into two separate chapters. In this way, we were able to include more of the most recent material on Sensor Networks. We have also enhanced the discussion of the security aspects of both Ad Hoc and Sensor Networks. We have also added a major section on Wireless Mesh Networks. In addition, we have included discussions on such new concepts as Femto Cells, Cognitive Radio, and Heterogeneous Networks.

Another important improvement to this edition includes the addition of new laboratory experiments and the inclusion of an open-ended lab problem at the end of each chapter. We have also added many new homework questions.

Supplements and Instructors' Resources

A Solutions Manual will be made available to instructors and PowerPoint slides will be available for each chapter. Both can be obtained from the Cengage Learning product website at www.cengage.com/engineering/agrawal.

Acknowledgments

Creating a new edition is a lot of work, and we are indebted to numerous individuals who have helped to make this revision possible. We are deeply indebted to Weihuang Fu and Talmai Oliveira for their help in updating the text for this edition. Many individuals, including Weihuang Fu, Jung Hyun Jun, Junfang Wang, Asitha Bandranayake, Amit Gaur, Anoosha Prathaponi, Chittabrata Ghosh, Hai-long Li, Kuheli Louha, Cheng Zhu, Hao Luan, and Vineet Joshi, helped collect useful information. We thank them for their efforts.

We are indebted to all of the reviewers of the second edition for their assistance in making this third edition even better than the second. Reviewers willing to be acknowledged are Bharat Bhargava from Purdue University and Murat Uysal from University of Waterloo.

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Finally, we are eternally grateful to our wives for their patience during the course of this revision.

DHARMA PRAKASH AGRAWAL
QING-AN ZENG



Preface to the Second Edition

We are very pleased to see an overwhelming acceptance of our book by the worldwide wireless community. In response to recent changes in this technological field, it is our honor to present a new edition of our book within two years of the first printing. The draft version of the second edition was sent to six reviewers by the publisher. Many thanks for their constructive criticism. We have made special efforts to incorporate their useful suggestions, and we hope the readers will find this edition comprehensive, easy to understand, and up to date. The task has been very challenging, and we hope our efforts are reflected in this edition by making it easy to appreciate the advances in this exciting technology.

In this edition, we have retained all the chapters and their sequence as used in the original edition. The major changes are summarized as follows: addition of explanations and motivation for many of the concepts, numerical examples wherever possible, additional problems at the end of each chapter, and an introduction of some new concepts to reflect the state of the art. Specifically, we have emphasized the importance of the probability theory in the wireless and mobile systems area. We have also added the generalized Nakagami distribution to show the usefulness of the CRC scheme. We have explicitly illustrated how to form a cluster of given size for FDMA/TMDA systems. We have included derivations of pure and slotted ALOHA and ARQ; we have added CSMA/CD protocol and augmented security schemes. We have added two new multiple access concepts of OFDM and SDMA. A description of SMS has been added, and the explanation of the Bellman-Ford algorithm has been given to calculate the shortest path between any two nodes. We have reorganized sections on routing in ad hoc networks and added multipath routing and explicitly identified WiFi as 802.11b. We have changed Chapter 14 to Wireless MAN, LAN, and PAN by adding a MAN portion and organizing the contents for enhanced clarity. We have incorporated many new topics in Chapter 16, such as Multimedia Transmission in Multimedia, PTT Technology, WiMax, Scheduling in Piconets, and Use of Directional Antennas.

Putting together this second edition has not been an easy job. Help from numerous individuals has made this formidable task both manageable and enjoyable. Professor Anup Kumar of University of Louisville and Professor Hassan Peyravi of Kent State University were the first ones to provide feedback on our first edition. Professor Ramesh C. Joshi, Indian Institute of Technology—Roorkee gave very useful comments on the draft of this second edition. Ashok Roy and Wei Li helped in reorganizing Chapter 14, while Anurag Gupta and Kumar Anand helped in redoing part of Chapter 12. Many students in our research group provided comments on the contents of Chapter 15, including Torsha Banerjee, Carlos Cordeiro, Chittabrata Ghosh, Hrishikesh Gossain, Neha Jain, and Dhananjay Lal. Many thanks are also due to Weiqun Chen, Yunli Chen, Hang Chen, Hongmei Deng, Aditya Gupta, Vivek Jain, Xiaodong Li, Anindo Mukherjee, Wei Shen, Demin Wang, Haitang Wang, and Qi Zhang for reading different versions of our book and providing many helpful hints.

Our sincere thanks go to our publisher, Bill Stenquest, for asking us to prepare a second edition within such a short time following the first edition. We would also like to thank Kamilah Reid Burrell, development editor, Thomson Engineering, and Rose Kernan, production editor, for converting our electronic version of the text, figures, tables, and index into the final form.

We are very grateful to our families for their encouragement and countless hours of patience and endurance during the course of this revision.

DHARMA PRAKASH AGRAWAL
QING-AN ZENG



Preface to the First Edition

Wireless systems have been around for quite some time, and their obvious use in garage-door openers and cordless phones has gone unnoticed until recently. The unique ability of mobile phone providers to maintain the same contact number even if the user moves from one location to another has made mobile phones increasingly popular. Wireless telephones are not only convenient but are also providing flexibility and versatility. The introduction of affordably priced wireless and mobile telephones has made them attractive for the general population worldwide. Thus, the number of wireless phone subscribers as well as service providers has proliferated.

Wireless and mobile communications have been useful in areas such as commerce, education, and defense. According to the nature of a particular application, they can be used in home-based and industrial systems or in commercial and military environments. In a home-based system, a central access point communicates with various appliances and controls them using a localized wireless node. This kind of system enables close coordination among appliances in the home (or industry) and achieves control over the home (or industry) Access Point using voice or a short message. To facilitate this, a consortium of companies is working on the Bluetooth project. There are many novel applications of such a wireless system—for example, a bracelet worn by a subscriber can constantly monitor body parameters and take action if needed (like informing the family physician about a health problem). However, the design and implementation of such a system brings with it a lot of important issues, such as standardization and infrastructure for Internet access, audio/video editing, and distributed decision-making software.

In a commercial system, the common issues are the range of the system, number of distribution infrastructure access points, number of users for each access point, and so on. For instance, we need to have several access points uniformly distributed on each floor of a factory so that users have continuous access to them. But this gives rise to problems such as appropriate coordination of channels between access points and the channel bandwidth requirements. Any loss of information (voice or data packet) in wireless switching is unacceptable; hence care should be taken to ensure the reliable transmission and reception of information. Wireless systems, such as the traditional infrastructure system, satellite system, or the more recent ad hoc networks formed by mobile users, find tremendous use in defense applications. Ad hoc networks involve information transfer in the peer-to-peer mode, but we have to deal with the problem of power consumption for a wide coverage area. Other problems involve channel allocation based on address, traffic types (voice, video, data, or audio), mobility pattern, routing techniques, and so on.

Wireless technology has also influenced the instructional infrastructure at many institutions. Carnegie Mellon University has taken the lead in creating a campus-wide wireless network. Steps have also been taken at the University of Cincinnati by installing wireless access points at several selected buildings and

by requiring all incoming engineering undergraduate students to have laptops with wireless capability. Similar phenomena can be observed across the country at different organizations. Within Engineering and Computer and Information Science disciplines, communication technology recently has advanced at an unparalleled speed. In particular, combinations of wireless communication and computer technologies have revolutionized the world of telecommunications. To fully explore and utilize this new technology, universities need to offer new courses and train students in the field so that they can continue their graduate work in this area. However, students in Computer Science and Engineering (CSE) and Electrical Engineering (EE) are at best exposed to data communication aspects, while wireless communication systems remain untouched, as it is relatively difficult to learn about wireless technology without having substantial background in communications technology. On the other hand, EE students learn about the Radio Frequency (RF) communication aspect only, and the topic of data communication and computing system issues and their correlation in nomadic seamless computing remains untouched.

Although there are many texts related to wireless and mobile communications, these books can be roughly classified into two groups. The first group focuses on readers in the RF communication field, and the other covers only the general knowledge of data communication and is designed for sales agents and managers. The books in the first group require a detailed background in RF communication and signal processing and, therefore, are not suitable for students in CSE. Many recent texts emphasize microwave radar and sensor systems. However, books in the second group do not provide any depth in the data communication aspects of wireless technology. Many institutions do offer courses in the wireless and mobile networking area, primarily for graduate students, and then only as special topics. Most of these courses are EE types with many prerequisites as EE courses. Thus, most undergraduate seniors in CSE are deprived of exposure to wireless and mobile communications. In addition, most existing books are tailored toward RF communication and antenna design aspects of the technology, making them difficult to use for CSE students.

Dharma Agrawal envisioned the need for this book when he spent his sabbatical five years ago with AT&T Laboratory. After joining the University of Cincinnati in the autumn of 1998, he started offering an introductory-level course in the wireless and mobile systems area for upper-level undergraduate and entering graduate students. Agrawal primarily used an old textbook, self-prepared notes, and some recent papers. Qing-An Zeng joined the University of Cincinnati in 1999 and started helping organize the course. He noticed the need to develop class notes so that the CSE students, with limited communications background, could understand the subject matter. This led to the foundation of this textbook. The designed course complements the RF communication background of EE students.

Creating such a unique instructional curriculum requires a great deal of effort. Planning such a text is a relatively difficult task because of the diverse background requirements. The limitations of most existing books and courses affect the wireless industries in the United States. Companies must train newly hired college graduates for a long time before they can get into the wireless industry. To the best of our knowledge, such an organized course has not been taught anywhere in the United States or the world. Teaching the introductory course strictly from research papers is difficult for the professor, which in turn causes students to learn the material inefficiently. Preparing systematic notes

in this emerging area will enhance training, increase the availability of well-educated personnel, shorten the new employee-training period within industries, encourage students to do graduate work in this area, and allow nations to continue to advance the research in this technological field.

This book explains how wireless systems work, how mobility is supported, how infrastructure underlies such systems, and what interactions are needed among different functional components. It is not our intention to cover various existing wireless technologies, the chronological history behind their development, or the work being carried out, but to make EE and CSE students understand how a cell phone starts working as soon as you get out of an airplane. We have selected chapter topics that focus on qualitative descriptions and realistic explanations of relationships between wireless systems and performance parameters. The chapters are organized as follows:

- Chapter 1: Introduction
- Chapter 2: Probability, Statistics, and Traffic Theories
- Chapter 3: Mobile Radio Propagation
- Chapter 4: Channel Coding and Error Control
- Chapter 5: Cellular Concept
- Chapter 6: Multiple Radio Access
- Chapter 7: Multiple Division Techniques for Traffic Channels
- Chapter 8: Traffic Channel Allocation
- Chapter 9: Mobile Communication Systems
- Chapter 10: Network Protocols
- Chapter 11: Existing Wireless Systems
- Chapter 12: Access Points and Variants
- Chapter 13: Ad Hoc Networks
- Chapter 14: Sensor Networks
- Chapter 15: Wireless LANs, PANs, BANs, and MANs
- Chapter 16: Security and Privacy in Wireless Networks
- Chapter 17: Satellite Systems
- Chapter 18: Recent Advances in Wireless Technologies

Mathematical formulations are needed in engineering and computer science work, and we include some of the important concepts so that students can appreciate their usefulness in numerous wireless and mobile systems. In all these applications, both security and privacy issues are important. Both ad hoc and sensor networks are finding increasing use in military and commercial applications, so detailed discussions are included. The introduction of the Bluetooth standard allows easy replacement of connector cables with wireless devices and is discussed in detail. Recent advances are covered in the last chapter, with emphasis on the research work being carried out in the wireless and mobile computing area, even though a comprehensive discussion is beyond the scope of this book. In the questions at the end of each chapter, special efforts have been made to explore potential uses of the various technologies. Depending on availability of time (especially for undergraduates), students should be encouraged to use one of the simulators (ns, OPNET, or other stable simulators) to get a feel for the overall system complexity. A list of possible group simulation projects is included in each chapter. The authors have tried such projects for several years and have found them highly effective in training students. Many undergraduates have also used them as their follow-up, year-long capstone design project.

This book is written both for academic institutions and for working professionals. It can be used as a textbook for a one-semester or a one-quarter course. The book also can be used for training current or new employees of wireless companies and could be adopted for short-term training courses. The chapters are organized to provide a great deal of flexibility; emphasis can be given to different chapters, depending on the scope of the course and the instructor's own interests or emphasis. The following are some suggestions for undergraduate students:

- For a one-quarter system, Chapter 17 can be skipped and the project could be optional for extra credit. Chapters 2, 11, 12, and 18 can be covered in brief. Chapter 6 on modulation techniques could be skipped as well.
- For a one-semester system, Chapter 17 can be skipped. Chapters 2 and 11 can be covered briefly, or Chapter 2 could be used for self-study and a simplified version of the project could be assigned.

In this textbook, we have tried to provide an overview of the basic principles behind wireless technology and its associated support infrastructure. We hope that we have been able to achieve our goal of helping students and others working in this area to have a basic knowledge of this exciting technology. Our efforts will not go to waste if we are able to accomplish this.

DHARMA PRAKASH AGRAWAL
QING-AN ZENG



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We are very grateful to Christine Sheckels, sales consultant, for persuading and convincing us to communicate with Thomson for the possible publication of our book, to our publisher, Bill Stenquist, and to Rose Kernan, production editor, for their help in publishing this book so quickly.

The authors welcome any comments and suggestions for improvements or changes that could be incorporated in forthcoming editions of this book. Please contact them at <dpa@ececs.uc.edu> and <qzeng@ncat.edu>.

DHARMA PRAKASH AGRAWAL
QING-AN ZENG

Introduction

1.1 History of Cellular Systems

Long-distance communication began with the introduction of telegraphs and simple coded pulses, which were used to transmit short messages. Since then, numerous advances have rendered reliable transfer of information both easier and quicker. There is a long history of how the field has evolved and how telephony has introduced a convenient way of conversing by transmitting audio signals. Hardware connections and electronic switches have made transfer of digital data feasible. The use of the Internet has added another dimension to the wireline communication field, and both voice and data are being processed extensively. In parallel to wireline communication, radio transmission has progressed substantially. Feasibility of wireless transmission has brought drastic changes in the way people live and communicate. New innovations in radio communication have brought about the use of this technology in new application areas [1.1]. A chronological evolution of radio communication is given in Table 1.1, with specific events that occurred in different years clearly marked [1.2]. Table 1.2 lists how, for different applications, radio frequency (RF) bands have been allocated [1.3].

Wireless systems have been around for quite some time, and their obvious use in garage-door openers and cordless telephones had gone unnoticed until recently. The introduction of affordably priced wireless telephones has made them attractive for the general population. Their main usefulness is their capability to maintain the same contact number even if the user moves from one location to another, and this is illustrated in Figure 1.1. Wireless systems have evolved over time, and the chronological development of first-generation (1G) and second-generation (2G) cellular systems (known as mobile systems outside North America) is given in Tables 1.3 and 1.4, respectively.

The first-generation wireless systems were primarily developed for voice communication using frequency division multiplexing. To have efficient use of communication channels, time division multiplexing was used in the second-generation systems so that data could be also processed. The third-generation systems evolved due to the need for transmitting integrated voice, data, and multimedia traffic. The channel capacity is still limited, and attempts are being made to compress the amount of information without compromising the quality of received signals.

TABLE 1.1

History and Start (continued on next page)

Based on Mobile Communications Engineering: Theory and Applications by Lee, McGraw-Hill, 1997.

Year	Event and Characteristics
1860	Maxwell's equation relating electric and magnetic fields
1880	Hertz—Initial demonstration of practical radio communication
1897	Marconi—Radio transmission to a tugboat over an 18-mile path
1921	Detroit Police Department—Police car radio dispatch (2 MHz frequency band)
1933	FCC (Federal Communications Commission)—Authorized four channels in the 30 to 40 MHz range
1938	FCC—Ruled for regular service
1946	Bell Telephone Laboratories—152 MHz (simplex)
1956	FCC—450 MHz (simplex)
1959	Bell Telephone Laboratories—Suggested 32 MHz band for high-capacity mobile radio communication
1964	FCC—152 MHz (full duplex)
1964	Bell Telephone Laboratories—Active research at 800 MHz
1969	FCC—450 MHz (full duplex)
1974	FCC—40 MHz bandwidth allocation in the 800 to 900 MHz range
1981	FCC—Release of cellular land mobile phone service in the 40 MHz bandwidth in the 800 to 900 MHz range for commercial operation
1981	AT&T and RCC (Radio Common Carrier) reach an agreement to split 40 MHz spectrum into two 20 MHz bands. Band A belongs to nonwireline operators (RCC), and band B belongs to wireline operators (telephone companies). Each market has two operators
1982	AT&T is divested, and seven RBOCs (Regional Bell Operating Companies) are formed to manage the cellular operations
1982	MFJ (Modified Final Judgment) is issued by the U.S. Department of Justice. All the operators were prohibited to (1) operate long-distance business, (2) provide information services, and (3) do manufacturing business
1983	Ameritech system in operation in Chicago
1984	Most RBOC markets in operation
1986	FCC allocates 5 MHz in extended band
1987	FCC makes lottery on the small metropolitan service area and all rural service area licenses
1988	TDMA (Time Division Multiple Access) voted as a digital cellular standard in North America
1992	GSM (Global System for Mobile Communications) operable in Germany D2 system
1993	CDMA (Code Division Multiple Access) voted as another digital cellular standard in North America
1994	American TDMA operable in Seattle, Washington

TABLE 1.1

History and Start (Continued)

1994	PDC (Personal Digital Cellular) operable in Tokyo, Japan
1994	Two of six broadband PCS (Personal Communication Services) license bands in auction
1995	CDMA operable in Hong Kong
1996	U.S. Congress passes Telecommunication Reform Act Bill
1996	The auction money for six broadband PCS licensed bands (120 MHz) almost reaches 20 billion U.S. dollars
1997	Broadband CDMA considered as one of the third-generation mobile communication technologies for UMTS (Universal Mobile Telecommunication Systems) during the UMTS workshop conference held in Korea
1999	ITU (International Telecommunication Union) decides the next generation mobile communication systems (e.g., W-CDMA (wideband-CDMA), cdma2000, TD-SCDMA (Time Division Synchronous CDMA))
2001	W-CDMA commercial service beginning in Japan and Europe
2002	W-CDMA commercial service beginning in South Korea
2002	FCC approves additional frequency band for UWB (Ultra-Wideband)
2003	cdma2000 commercial service beginning in the United States
2009	cdma200 and W-CDMA commercial services beginning in China FDD-LTE (Frequency Division Duplex Long Term Evolution) commercial service beginning in Sweden
2010	FDD-LTE commercial service beginning in the United States
2011	FDD-LTE commercial service beginning in South Korea
2013	TD-LTE (Time Division Long Term Evolution) commercial service beginning in China

TABLE 1.2

Selected U.S. Frequency Allocations (3 kHz ~ 300 GHz) (continued on next page)

Based on “FCC Online Table of Frequency Allocations,” 47 C.F.R. § 2.106, Revised on January 25, 2010, <http://www.fcc.gov/oet/spectrum/>, <http://www.ntia.doc.gov/osmhome/allochrt.pdf>, http://en.wikipedia.org/wiki/Ultra_high_frequency and Thomas W. Hazlett, “Optimal Abolition of FCC Spectrum Allocation,” *Journal of Economic Perspectives*—Volume 22, Number 1—Winter 2008—Pages 103–128.

Application	Frequency Band	Unit
Aeronautical Mobile	200~285, 325~415	kHz
	2.85~3.155, 3.4~3.5, 4.65~4.75, 5.45~5.73, 6.525~6.765, 8.815~9.040, 10.005~10.1, 11.175~11.4, 13.2~13.36, 15.10~15.10, 17.9~18.03, 21.924~22.0, 23.2~23.35, 117.975~137.0, 849~851, 894~896	MHz
Aeronautical Mobile Satellite	1545~1559 (Space to Earth)	MHz

TABLE 1.2

Selected U.S. Frequency Allocations (3 kHz ~ 300 GHz) (continued on next page)

Application	Frequency Band	Unit
Aeronautical Radio Navigation	190~285, 285~405 (Radio beacon), 415~495, 510~535 (Radio beacon)	kHz
	74.8~75.2, 108.0~117.975, 328.6~335.4, 980~1215, 1300~1350, 2700~2900	MHz
	3.5~3.65 (Ground), 4.2~4.4, 5.0~5.15, 5.35~5.46, 9.0~9.2, 13.25~13.4, 15.4~15.7	GHz
Amateur	1800~1900	kHz
	3.5~4.0, 7.0~7.3, 10.01~10.05, 14.0~14.35, 18.068~18.168, 21.0~21.45, 24.89~24.99, 28.0~29.7, 50.0~54.0, 144.0~148.0, 216.0~220.0, 222.0~225.0, 420.0~450.0, 902.0~928.0, 1240~1300, 2300~2310, 2390~2450	MHz
	3.3~3.5, 5.56~5.925, 10.0~10.5, 24.0~24.05, 47.0~47.2, 75.5~81.0, 119.98~120.02, 142.0~149.0, 241.0~250.0	GHz
Amateur Satellite	7.0~7.1, 14.0~14.25, 18.068~18.168, 21.0~21.45, 24.89~24.99, 28.0~29.7, 144.0~146.0	MHz
	5.83~5.85, 10.45~10.5, 24.0~24.05, 47.0~47.2, 75.5~76.0, 77.0~81.0, 142.0~149.0, 241.0~250.0	GHz
Broadcasting	535~1705 (AM Radio)	kHz
	5.90~6.2, 7.3~7.35, 9.4~9.9, 11.6~12.10, 13.57~13.87, 15.10~15.8, 17.48~17.9, 18.9~19.02, 21.45~21.85, 25.67~26.1, 54.0~72.0 (TV Channel 2~4), 76.0~88.0 (TV Channel 5~6), 88.0~108.0 (FM Radio), 174.0~216.0 (TV Channel 7~13), 470.0~512.0 (TV Channel 14~20), 512.0~608.0 (TV Channel 21~36), 614.0~698 (TV Broadcasting), 698~764, 776~794, 40.5~42.5, 84.0~86.0	MHz
Broadcasting Satellite	2310~2360, 2655~2690	MHz
	12.2~12.7, 17.3~17.7, 40.05~42.5, 84.0~86.0	GHz
Earth Exploration Satellite	2025~2110, 2200~2290, 2655~2700	MHz
	8.025~8.4, 10.6~10.7, 31.3~31.8, 36.0~37.0, 40.0~40.5, 50.2~50.4, 52.6~59.3, 65.0~66.0, 86.0~92.0, 100.0~102.0, 105.0~126.0, 150.0~151.0, 164.0~168.0, 174.0~176.0, 182.0~185.0, 200.0~202.0, 217.0~231.0, 235.0~238.0, 250.0~252.0	GHz
Fixed	14.0~19.95, 20.05~59.0, 61.0~90.0, 110.0~190.0, 1705.0~1800.0, 2000.0~2065.0, 2107.0~2170.0, 2194.0~2495.0, 2505.0~2850.0	kHz
	3.155~3.4, 4.0~4.063, 4.438~4.65, 4.75~4.995, 5.005~5.45, 5.73~5.95, 6.765~7.0, 7.3~8.195, 9.040~9.5, 9.9~9.995, 10.15~11.175, 11.4~11.65, 12.05~12.23, 13.41~13.6, 13.8~14.0, 14.35~14.990, 15.6~16.36, 17.41~17.55, 18.03~18.068, 18.168~18.78, 18.9~19.68, 19.80~19.990, 20.010~21.0, 21.85~21.924, 22.855~23.2, 23.35~24.89, 25.33~25.55, 26.48~26.96, 27.32~28.0, 29.8~37.0, 38.0~39.0, 40.0~43.69, 46.6~47.0, 49.6~50.0, 72.0~73.0, 74.6~74.8, 75.2~76.0, 138.0~144.0, 148.0~149.9, 150.05~152.855, 154.0~156.2475, 157.45~161.575, 162.0125~174.0, 216.0~222.0, 225.0~328.6, 335.4~399.9, 406.1~420.0, 454.0~455.0, 456.0~462.5375, 462.7375~467.5375, 467.7375~512.0, 698.0~821.0, 824.0~849.0, 851.0~866.0, 869.0~894.0, 896.0~902.0, 928.0~960.0, 1350.0~1395.0, 1427.0~1435.0, 1670.0~1675.0, 1700.0~2000.0, 2020.0~2025.0, 2110.0~2180.0, 2200.0~2300.0, 2305.0~2390.0, 2450.0~2483.5, 2500.0~2690.0	MHz

TABLE 1.2

Selected U.S. Frequency Allocations (3 kHz ~ 300 GHz) (continued on next page)

Application	Frequency Band	Unit
	3.65~4.2, 4.4~4.99, 5.925~6.425, 6.525~8.5, 10.55~10.68, 10.7~11.7, 12.2~13.25, 14.4~15.35, 17.7~18.3, 19.3~19.7, 21.2~23.6, 24.25~24.45, 25.05~29.5, 31.0~31.3, 36.0~40.0, 40.543.5, 46.9~47.0, 47.2~50.2, 50.4~52.6, 55.78~66.0, 71.0~75.5, 81.086.0, 92.095.0, 102.0~105.0, 116.0~134.0, 149.0164.0, 168.0~182.0, 185.0~190.0, 200~217.0, 231.0~241.0, 265.0~300.0	GHz
Fixed Satellite	1390~1392, 1430~1432, 2500~2690	MHz
	3.6~4.2, 4.5~4.8, 5.15~5.25, 5.85~7.075, 7.25~7.75, 7.90~8.4, 10.7~12.2, 12.7~13.25, 13.75~14.5, 15.43~15.63, 17.3~21.2, 24.75~25.25, 27.5~31.0, 37.6~41.0, 42.5~45.5, 47.2~50.2, 50.4~51.4, 71.0~75.5, 81.0~84.0, 92.0~95.0, 102.0~105.0, 149.0~150.0, 151.0~164.0, 202.0~217.0, 231.0~241.0, 265.0~275.0	GHz
Inter-Satellite	22.55~23.55, 24.45~24.75, 25.25~27.5, 32.0~33.0, 54.25~58.2, 59.071.0, 116.0~134.0, 170.0~182.0, 185.0~190.0	GHz
Land Mobile	2107~2170, 2194~2495, 2505~2850	kHz
	25.01~25.07, 25.21~25.33, 26.175~26.48, 27.41~27.54, 29.7~29.8, 30.56~32.0, 33.0~34.0, 35.0~36.0, 37.0~38.0, 39.0~40.0, 42.0~46.6, 47.0~49.6, 150.8~156.2475, 157.1875~161.575, 161.625~162.0125, 173.2~173.4, 220.0~222.2, 450.0~512.0, 806.0~849.0, 851.0~894.0, 896.0~901.0, 931.0~932.0, 935.0~941.0, 1395.0~1400.0, 1427.0~1432.0	MHz
Land Mobile Satellite	14.0~14.5	GHz
Maritime Mobile	14~19.95, 20.05~59.0, 61.0~90.0, 110.0~190.0, 415.0~495.0, 505.0~525.0, 2000.0~2065.0, 2065.0~2107.0 (telephone), 2107.0~2170.0, 2170.0~2173.0 (telephone), 2190.0~2194.0 (telephone), 2194.0~2495.0, 2505.0~2850.0	kHz
	4.0~4.438, 6.2~6.525, 8.1~8.815, 12.23~13.2, 16.36~17.41, 18.78~18.9, 19.68~19.80, 22.0~22.855, 25.07~25.21, 26.1~26.175, 156.2475~157.1875, 161.575~161.625, 161.775~162.0125	MHz
Maritime Mobile Satellite	1530.0~1544.0	MHz
Maritime Radio Navigation	275~335	kHz
	3.0~3.1, 9.2~9.3	GHz
Meteorological Aids	400.15~406.0, 1668.4~1670.0, 1675.0~1700.0, 2700.0~2900.0	MHz
	5.6~5.65, 9.3~9.5	GHz
Meteorological Satellite	400.15~403.0, 460.0~470.0, 1675~1710	MHz
	7.45~7.55, 8.175~8.215	GHz
Mobile	495~505, 525~535, 1605~1615, 1705~1800, 2000~2065, 2107~2170, 2173.5~2190.5, 2194~2495, 2505~2850	kHz

TABLE 1.2

Selected U.S. Frequency Allocations (3 kHz ~ 300 GHz) (continued on next page)

Application	Frequency Band	Unit
	3.155~3.4, 4.438~4.65, 4.75~4.995, 5.065~5.45, 5.73~5.95, 6.765~7.0, 7.3~8.1, 10.15~11.175, 13.41~13.6, 13.8~14.0, 14.35~14.990, 18.168~18.78, 20.010~21.0, 23.0~23.2, 23.35~24.89, 25.33~25.55, 26.48~26.95, 26.96~27.41, 27.54~28.0, 29.89~29.91, 30.0~30.56, 32.0~33.0, 34.0~35.0, 36.0~37.0, 38.0~39.0, 40.0~42.0, 46.6~47.0, 49.6~50.0, 72.0~73.0, 74.6~74.8, 75.2~76.0, 138.0~144.0, 148.0~149.9, 150.05~150.8, 162.0125~173.2, 173.4~174.0, 216.0~220.0, 225.0~328.6, 335.4~399.9, 406.1~410.0, 698~806, 901~902, 930~931, 1350~1395, 1432~1535, 1670~1675, 1710~2000, 2020~2155, 2160~2180, 2290~2390	MHz
	3.65~3.7, 4.4~4.99, 6.425~6525, 6.875~7.125, 11.7~12.2, 127~15.35, 21.2~23.6, 25.25~29.5, 31.0~31.3, 36.0~40.0, 40.5~43.5, 45.5~47.0, 47.2~50.2, 50.4~52.6, 55.78~75.5, 81.0~86.0, 92.0~100.0, 116.0~142.0, 149.0~151.0, 168.0~182.0, 185.0~217.0, 231.0~241.0, 252.0~300.0	GHz
Mobile Satellite	137.0~138.0, 148.0~150.05, 235.0~322.0, 335.4~400.05, 400.15~401.0, 406.0 ~ 406.1, 1525~1558.5, 1610.0~1660.5, 2000.0~2020.0, 2180.0~2200.0, 2483.5~2500.0	MHz
	7.25~7.75, 7.90~8.4, 19.7~21.2, 29.5~31.0, 39.5~40.5, 43.5~47.0, 50.4~51.4, 66.0~74.0, 81.0~84.0, 95.0~100.0, 134.0~142.0, 190.0~200.0, 252.0~265.0	GHz
Radio Astronomy	13.38~13.41, 25.55~25.67, 37.5~38.25, 73.0~74.6, 149.9~150.05, 406.1~410.0, 608.0~614.0, 1400.0~1427.0, 1610.6~1613.8, 1660.0~1670.0, 2655.0~2700.0	MHz
	4.99~5.0, 10.6~10.7, 15.35~15.4, 22.21~22.5, 23.6~24.0, 31.3~31.8, 42.5~43.5, 86.0~92.0, 105.0~116.0, 164.0~168.0, 182.0~185.0, 217.0~231.0, 265.0~275.0	GHz
Radio Determination Satellite	1610.0~1626.5, 2483.5~2500.0	MHz
Radio Location	70.0~90.0, 110.0~130.0, 1705.0~1800.0, 1900.0~2000.0	kHz
	3.230~3.4, 216.0~225.0, 420.0~450.0, 902.0~928.0, 1215.0~1390.0, 2305.0~2385.0, 2417.0~2483.5, 2700.0~3000.0	MHz
	3.0~3.65, 5.25~5.85, 8.5~10.55, 13.4~14.0, 15.7~17.7, 24.05~24.25, 33.4~36.0, 59.0~64.0, 76.0~81.0, 92.0~100.0, 126.0~142.0, 144.0~149.0, 231.0~235.0, 238.0~248.0	GHz
Radio Location Satellite	24.65~24.75	GHz
Radio Navigation	9~14, 90~110, 405~415	kHz
	5.46~5.47, 9.3~9.5, 14.0~14.2, 24.45~24.65, 24.75~25.05, 31.8~32.0, 32.0~32.3, 32.3~33.0, 33.0~33.4, 66.0~71.0, 95.0~100.0, 134.0~142.0, 190.0~200.0, 252.0~265.0	GHz
Radio Navigation Satellite	149.0~150.05, 399.9~400.05, 1215.0~1240.0, 1559.0~1610.0	MHz
	45.5~47.0, 66.0~71.0, 95.0~100.0, 134.0~142.0, 190.0~200.0, 252.0~265.0	GHz
Space Operation	137.0~138.0, 400.15~402.0, 2025.0~2110.0, 2200.0~2290.0	MHz

TABLE 1.2

Selected U.S. Frequency Allocations (3 kHz ~ 300 GHz) (Continued)

Application	Frequency Band	Unit
Space Research	2.501~2.505, 5.003~5.005, 10.003~10.005, 15.005~15.010, 19.990~19.995, 20.005~20.010, 25.005~25.01, 137.0~138.0, 400.15~401.0, 410.0~420.0, 1400.0~1427.0, 1660.5~1668.4, 2025.0~2110.0, 2200.0~2300.0, 2655.0~2700.0	MHz
	4.99~5.0, 7.19~7.235, 8.4~8.5, 10.6~10.7, 12.75~14.2, 14.5~15.4, 16.6~17.1, 17.2~17.3, 18.6~18.8, 21.2~21.4, 22.21~22.5, 23.6~24.0, 31.332.3, 36.0~38.0, 40.0~40.5, 50.2~50.4, 52.6~59.3, 65.0~66.0, 86.0~92.0, 100.0~102.0, 105.0~126.0, 150.0~151.0, 164.0~168.0, 174.0~176.5, 182.0~185.0, 200.0~202.0, 217.0~231.0, 235.0~238.0, 250.0~252.0	GHz
Standard Frequency and Time Signal Satellite	19.95~20.05, 95.0~61.0, 2495.0~2505.0	kHz
	4.995~5.005, 9.995~10.005, 14.990~15.010, 19.990~20.010, 24.99~25.01, 400.05~400.15	MHz
	13.4~14.0, 20.2~21.2, 25.25~27.0, 30.0~31.3	GHz

FIGURE 1.1

Maintaining the telephone number in a wireless and mobile system.
cell phone: Anna Chelnokova/Shutterstock.com

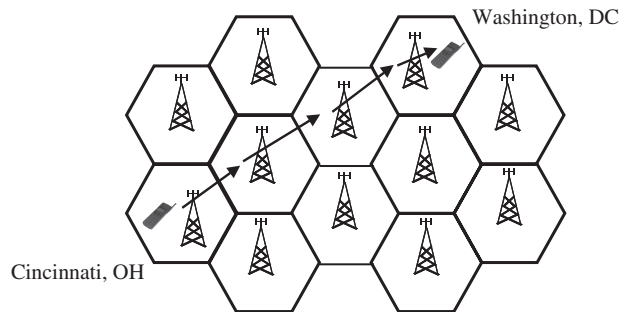


TABLE 1.3:

First-Generation Wireless Systems and Services

Year	Events
1970s	Developments of radio and computer technologies for 800/900 MHz mobile communication
1976	WARC (World Administrative Radio Conference) allocates spectrum for cellular radio
1979	NTT (Nippon Telephone & Telegraph) introduces the first cellular system in Japan
1981	NMT (Nordic Mobile Telephone) 900 system introduced by Ericsson Radio System AB and deployed in Scandinavia
1984	AMPS (Advanced Mobile Phone Service) introduced by AT&T in North America

TABLE 1.4

Second-Generation Wireless Systems and Services

Year	Events
1982	CEPT (European Conference of Postal and Telecommunications Administrations) establishes GSM (Global Special Mobile) to define future Pan-European cellular radio standards
1990	Interim Standard IS-54 (USDC: United States Digital Cellular) adopted by TIA (Telecommunications Industry Association)
1990	Interim Standard IS-19B (NAMPS: Narrowband AMPS) adopted by TIA
1991	Japanese PDC system standardized by the MPT (Ministry of Posts and Telecommunications)
1992	Phase I GSM system is operational
1993	Interim Standard IS-95 (CDMA) adopted by TIA
1994	Interim Standard IS-136 adopted by TIA
1995	PCS Licenses issued in North America
1996	Phase II GSM is operational
1997	North American PCS deploys GSM, IS-54, IS-95
1999	IS-54: used in North America; IS-95: used in North America, Hong Kong, Israel, Japan, South Korea, and China; GSM: used in 110 countries

The second-generation wireless systems have been designed for both indoor and vehicular environments with an emphasis on voice communication. An increased acceptance of mobile communication networks for conventional services has led to demands for high-bandwidth wireless multimedia services. These ever-growing demands require a new generation of high-speed mobile infrastructure networks that can provide the capacity needed for high traffic volumes as well as flexibility in communication bandwidth or services. There is a need for frequent Internet access and multimedia data transfer, both of which may also involve the use of satellite communication. Thus, the third-generation (3G) systems (IMT-2000: International Mobile Telecommunications 2000) need to support real-time data communication while maintaining compatibility with second-generation systems. There are two schools of thought on the third-generation systems. In the United States, people are inclined to use cdma2000 as the basic technology, while in Europe and Japan, W-CDMA is being considered as the future scheme. In principle, both these schemes are similar, but there are differences in their implementations. These are basically design issues, and anticipated characteristics are identified in Tables 1.5–1.7. There are subtle differences between wireless and mobile systems—for example, a system could be immobile but wireless, or a system could be mobile but not wireless. For the purpose of this text, we do not differentiate between the two and use these terms interchangeably.

TABLE 1.5

Third-Generation Wireless Systems and Services

IMT-2000	Fulfill one's dream of anywhere, anytime communication
Key Features	<ul style="list-style-type: none"> - High degree of commonality of design worldwide - Compatibility of services within IMT-2000 and with the fixed networks - High quality - Small terminal for worldwide use - Worldwide roaming capability - Capability for multimedia applications and a wide range of services and terminals
Important Component	<ul style="list-style-type: none"> - 2 Mbps for fixed environment - 384 kbps for indoor/outdoor and pedestrian environment - 144 kbps for vehicular environment
Standardization Work	- In progress (see Table 1.6)
Scheduled Service	<ul style="list-style-type: none"> - Started in October 2001 in Japan (W-CDMA) - Started in December 2001 in Europe - Started in January 2002 in South Korea - Started in October 2003 in USA - Started in April 2009 in China

TABLE 1.6

Fourth-Generation Wireless Systems and Services

IMT-Advanced	
Key Feature	<ul style="list-style-type: none"> - High speed of communication - High quality - Wide spectrum - Full integration of a variety of business - Great compatibility - Channel-dependent scheduling - Link adaptation - Mobile-IP utilized for mobility - IP-based femtocells
Access Technique	<ul style="list-style-type: none"> - FDD-LTE - TD-LTE
Important Component	<ul style="list-style-type: none"> - FDD-LTE: Uplink rate is 150 Mbps; Downlink rate is 40 Mbps - TD-LTE: Uplink rate is 100 Mbps; Downlink rate is 50 Mbps
Scheduled Service	<ul style="list-style-type: none"> - FDD-LTE started in December 2009 in Sweden - FDD-LTE started at the end of 2010 in the United States - FDD-LTE started in July 2011 in South Korea - TD-LTE started in December 2013 in China