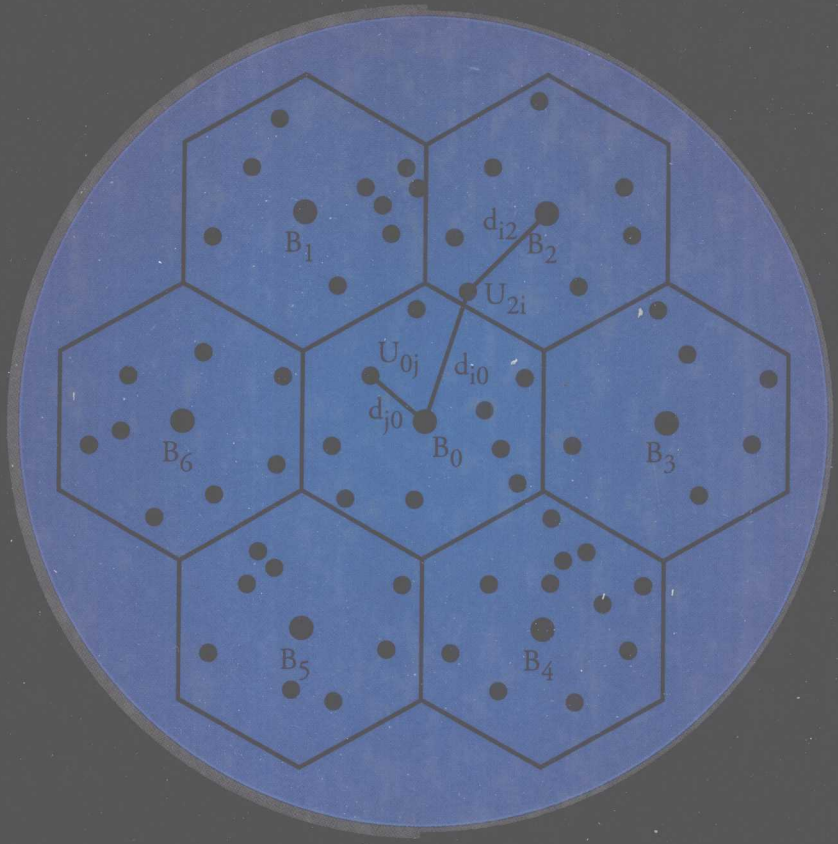
WIRELESS

communications

Principles & Practice



Theodore S. Rappaport

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Principles and Practice

Theodore S. Rappaport

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Preface

The purpose of this text is to initiate the newcomer to cellular radio and wireless personal communications, one of the fastest growing fields in the engineering world. Technical concepts which are at the core of design, implementation, research, and invention of wireless communication systems are presented in an order that is conducive to understanding general concepts, as well as those specific to particular cellular and personal communication systems and standards. This text is based upon my experiences as an educator, researcher, and consultant, and is modeled from an academic course developed for electrical engineering students as well as a self-study course for practicing engineers and technicians, developed at the request of the Institute of Electrical and Electronics Engineers (IEEE). References to journal articles are used liberally throughout this text to enable the interested reader to delve into additional reading that is always required to master any field. However, for handbook or classroom use, or for those who find it difficult to pursue outside reading, this text has been written as a complete, self-contained teaching and reference book. Numerous examples and problems have been provided to help the reader solidify the material.

This book has been designed for the student or practicing engineer who is already familiar with technical concepts such as probability, communication theory, and basic electromagnetics. However, like the wireless communications industry itself, this book combines material from many different technical disciplines, so it is unlikely that any one person will have had introductory courses for all of the topics covered. To accommodate a wide range of backgrounds, important concepts throughout the text are developed from first principles, so that readers learn the foundations of wireless communications. This approach

makes it possible to use this book as a handbook within industry, or as a teaching tool in a classroom setting.

The material and chapter sequence in this text have been adapted from an entry-level graduate course which I first taught in 1991 at the Virginia Polytechnic Institute and State University. Chapter 1 demonstrates the rapid growth of cellular radio throughout the world and provides a glimpse into the future. Chapter 2 covers cellular radio concepts such as frequency reuse and handoff, which are at the core of providing wireless communication service to subscribers on the move using limited radio spectrum. Chapter 2 also demonstrates how interference between mobiles and base stations affects the capacity of cellular systems. Chapter 3 presents radio propagation path loss and log-normal shadowing and describes different ways to model and predict the large-scale effects of radio propagation in many operating environments. Chapter 4 covers small-scale propagation effects such as fading, time delay spread, and Doppler spread, and describes how to measure and model the impact that signal bandwidth and motion have on the instantaneous received signal through the multipath channel. Radio wave propagation has historically been the most difficult problem to analyze and design for, since unlike a wired communication system which has a constant, stationary transmission channel (i.e., a wired path), radio channels are random and undergo shadowing and multipath fading, particularly when one of the terminals is in motion.

Chapter 5 provides extensive coverage of the most common analog and digital modulation techniques used in mobile communications and demonstrates trade-offs that must be made in selecting a modulation method. Issues such as receiver complexity, modulation and demodulation implementation, bit error rate analysis for fading channels, and spectral occupancy are presented. Channel coding, adaptive equalization, and antenna diversity concepts are presented in Chapter 6. In portable radio systems where people communicate while walking or driving, these methods may be used individually or in tandem to improve the quality (that is, reduce the bit error rate) of digital mobile radio communications in the presence of fading and noise.

Chapter 7 provides an introduction to speech coding. In the past decade there has been remarkable progress in decreasing the needed data rate of high quality digitized speech, which enables wireless system designers to match end-user services to network architectures. Principles which have driven the development of adaptive pulse code modulation and linear predictive coding techniques are presented, and how these techniques are used to evaluate speech quality in existing and proposed cellular, cordless, and personal communication systems are discussed. Chapter 8 introduces time, frequency, and code division multiple access, as well as more recent multiple access techniques such as packet reservation and space division multiple access. Chapter 8 also describes how each access method can accommodate a large number of mobile users and

demonstrates how multiple access impacts capacity and the network infrastructure of a cellular system. Chapter 9 describes networking considerations for wide area wireless communication systems, and presents practical networking approaches that are in use or have been proposed for future wireless systems. Chapter 10 unites all of the material from the first nine chapters by describing and comparing the major existing and proposed cellular, cordless, and personal communication systems throughout the world. The trade-offs made in the design and implementation of wireless personal communications systems are illuminated in this final chapter. The compilation of the major wireless standards makes Chapter 10 particularly useful as a single source of information for a wide range of systems.

Appendices which cover trunking theory, noise calculations, and the Gaussian approximation for spread spectrum code division systems provide details for those interested in solving practical wireless communications problems.

For industry use, Chapters 1—4 and 8 will benefit working engineers in the cellular system design and radio frequency (RF) testing/maintenance/measurement areas. Chapters 5—7 are tailored for modem designers and digital signal processing (DSP) engineers new to wireless. Chapters 9 and 10 should have broad appeal to network operators and managers, as well as working engineers.

To use this text at the undergraduate level, the instructor may wish to concentrate on Chapters 1—5, or Chapters 1—4, and 8, leaving the other chapters for treatment in a second semester undergraduate course or a graduate level course. Alternatively, traditional undergraduate courses on communications or network theory may find in Chapters 1, 2, 3, 5, 7, 8, and 9 useful material that can be inserted easily into the standard curriculum. In using this text at the graduate level, I have been successful in covering most of the material in Chapters 1—8 during a standard half-year semester. In Chapters 9 and 10, I have attempted to cover important but rarely compiled information on practical network implementations and worldwide standards.

Without the help and ingenuity of several former Virginia Tech graduate students, this text could not have been written. I am pleased to acknowledge the help and encouragement of Rias Muhamed, Varun Kapoor, Kevin Saldanha, and Anil Doradla – students I met in class while teaching the course *Cellular Radio and Personal Communications*. Kevin Saldanha also provided camera ready copy for this text (which turned out to be no small task!). The assistance of these students in compiling and editing materials for several chapters of this text was invaluable, and they were a source of constant encouragement throughout the project. Others who offered helpful suggestions, and whose research efforts are reflected in portions of this text, include Scott Seidel, Joe Liberti, Dwayne Hawbaker, Marty Feuerstein, Yingie Li, Ken Blackard, Victor Fung, Weifang Huang, Prabhakar Koushik, Orlando Landron, Francis Dominique, and Greg Bump. Zhi-

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From the academic perspective, a number of faculty in the wireless communications field provided useful suggestions which I readily incorporated. These reviewers include Prof. J. Keith Townsend of North Carolina State University and Prof. William H. Tranter of the University of Missouri-Rolla. Professors Jeffrey Reed and Brian Woerner of Virginia Tech also provided excellent recommendations from a teaching perspective. I am grateful for the invaluable contributions from all of these individuals. Also, I wish to thank the numerous faculty, students, and practicing engineers from around the world who have provided valuable feedback and who are using this book in classrooms and short courses.

I am pleased to acknowledge the support of the National Science Foundation, the Defense Advanced Research Project Agency, and the many sponsors and friends of the Mobile & Portable Radio Research Group, who have supported our research and educational activities in wireless communications since 1990. It is from the excellent faculty at Purdue University, particularly my advisor, Clare D. McGillem, that I formally learned about communications and how to build a research program. I consider myself fortunate to have been one of the many graduate students who was stimulated to pursue a dual career in engineering and education upon graduation from Purdue.

Finally, it is a pleasure to acknowledge my family and students, who put up with my preoccupation on this project, Barbara Coburn and Jill Cals of the IEEE, who championed the IEEE self-study course on the same subject, and Karen Gettman and Camille Trentacoste of Prentice Hall, who commissioned this work and helped me bring this text to you.

Theodore S. Rappaport

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CHAPTER 1

Introduction to Wireless Communication Systems

The ability to communicate with people on the move has evolved remarkably since Guglielmo Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English channel. That was in 1897, and since then new wireless communications methods and services have been enthusiastically adopted by people throughout the world. Particularly during the past ten years, the mobile radio communications industry has grown by orders of magnitude, fueled by digital and RF circuit fabrication improvements, new large-scale circuit integration, and other miniaturization technologies which make portable radio equipment smaller, cheaper, and more reliable. Digital switching techniques have facilitated the large scale deployment of affordable, easy-to-use radio communication networks. These trends will continue at an even greater pace during the next decade.

1.1 Evolution of Mobile Radio Communications

A brief history of the evolution of mobile communications throughout the world is useful in order to appreciate the enormous impact that cellular radio and personal communication services (PCS) will have on all of us over the next several decades. It is also useful for a newcomer to the cellular radio field to understand the tremendous impact that government regulatory agencies and service competitors wield in the evolution of new wireless systems, services, and technologies. While it is not the intent of this text to deal with the techno-political aspects of cellular radio and personal communications, techno-politics are a fundamental driver in the evolution of new technology and services, since radio spectrum usage is controlled by governments, not by service providers, equipment manufacturers, entrepreneurs, or researchers. Progressive involvement in

technology development is vital for a government if it hopes to keep its own country competitive in the rapidly changing field of wireless personal communications.

Wireless communications is enjoying its fastest growth period in history, due to enabling technologies which permit wide spread deployment. Historically, growth in the mobile communications field has come slowly, and has been coupled closely to technological improvements. The ability to provide wireless communications to an entire population was not even conceived until Bell Laboratories developed the cellular concept in the 1960s and 1970s [Nob62], [Mac79], [You79]. With the development of highly reliable, miniature, solid-state radio frequency hardware in the 1970s, the wireless communications era was born. The recent exponential growth in cellular radio and personal communication systems throughout the world is directly attributable to new technologies of the 1970s, which are mature today. The future growth of consumer-based mobile and portable communication systems will be tied more closely to radio spectrum allocations and regulatory decisions which affect or support new or extended services, as well as to consumer needs and technology advances in the signal processing, access, and network areas.

The following market penetration data show how wireless communications in the consumer sector has grown in popularity. Figure 1.1 illustrates how mobile telephony has penetrated our daily lives compared with other popular inventions of the 20th century. Figure 1.1 is a bit misleading since the curve labeled "mobile telephone" does not include nontelephone mobile radio applications, such as paging, amateur radio, dispatch, citizens band (CB), public service, cordless phones, or terrestrial microwave radio systems. In fact, in late 1990, licensed noncellular radio systems in the U.S. had over 12 million users, more than twice the U.S. cellular user population at that time [FCC91]. Figure 1.1 shows that the first 35 years of mobile telephone saw little market penetration due to high cost and the technological challenges involved, but how, in the past decade, cellular telephone has been accepted by consumers at rates comparable to the television, and the video cassette recorder.

In 1934, 194 municipal police radio systems and 58 state police stations had adopted amplitude modulation (AM) mobile communication systems for public safety in the U.S. It was estimated that 5000 radios were installed in mobiles in the mid 1930s, and vehicle ignition noise was a major problem for these early mobile users [Nob62]. In 1935, Edwin Armstrong demonstrated frequency modulation (FM) for the first time, and since the late 1930s, FM has been the primary modulation technique used for mobile communication systems throughout the world. World War II accelerated the improvements of the world's manufacturing and miniaturization capabilities, and these capabilities were put to use in large one-way and two-way consumer radio and television systems following the war. The number of U.S. mobile users climbed from several thousand in 1940 to