Chapter 1

Introduction and overview

This book provides a tutorial introduction to digital mobile wireless networks. The field is so vast, and changing so rapidly, that no one book could cover the field in all its aspects. This book should, however, provide a solid foundation from which an interested reader can move on to topics not covered, or to more detailed discussions of subjects described here. Much more information is available in the references appended throughout the book, and the reader is urged to consult these when necessary. There is a host of journals covering current work in the field, many of them referenced in this book, which will provide the reader with up-to-date research results or tutorial overviews of the latest developments.

Note the use of the word *digital* in the first line above. The earliest wireless networks used analog communication, as we shall see in the historical section following. We shall provide a brief description of one of these analog networks, AMPS, that is currently still deployed, later in that section. But the stress in this book is on modern digital wireless networks. There are, basically, two types of digital wireless networks currently in operation worldwide. One type is the class of cellular networks, carrying voice calls principally, but increasingly carrying data and multimedia traffic as well, as more cell phones or other cell-based mobile terminals become available for these applications. These digital wireless networks are now ubiquitous, being available worldwide to users with cell phones, although, as we shall see, different cellular systems are not compatible with one another. The second type of digital wireless networks is the class of local- and personal-area networks. Much of this book is devoted to the first type, digital cellular networks. A number of the topics covered, however, are equally applicable to both types of network, as will become apparent to readers of this book. In addition, Chapter 12 provides a comprehensive introduction to local- and personal-area networks, focusing on the increasingly widespread "Wi-Fi" networks of the local-area type, and "Bluetooth" as an example of the personal-area type.

Consider cellular networks, to be described in detail in the chapters following. In these networks, user cell phones connect to so-called base stations, each covering a geographic "cell." The base stations are, in turn, connected to the wired telephone network, allowing user calls, in principle, to be transmitted to any desired location, worldwide. The first cellular networks to be developed were analog, as we shall see in the historical section following. They were succeeded by digital cellular networks, the ones now most commonly used throughout the world. The analog networks are still used, however, to provide a backup when a digital cellular connection cannot be made. This is particularly the case in North America where a number of competing and incompatible digital cellular networks may preclude a connection to be made in a given geographic area or region. The analog networks are often referred to as "first-generation" cellular networks; the currently deployed digital networks are referred to as "second-generation" networks. As noted above, the stress in this book is on digital cellular networks, although some of the tutorial material in the chapters following applies to any type of cellular network, as well as to local-area and personal-area networks, as stated above. There are three principal types of second-generation networks in operation throughout the world: GSM, D-AMPS or IS-136, and IS-95. We provide a detailed description of these three networks in Chapters 6 and 8.

Much work has gone on in recent years to upgrade the second-generation networks to so-called "third-generation" networks. These networks are designed to transmit data in a *packet-switched* mode, as contrasted to second-generation networks, which use circuit-switching technology, in exact conformity with digital wired telephone networks. We discuss the third-generation networks in detail in Chapter 10. The distinction between *circuit switching* and *packet switching* is made clear in that chapter.

1.1 Historical introduction

It is of interest to precede our detailed study of mobile wireless communications in this book with a brief historical survey of the field. Much of the emphasis in the material following is on work at Bell Laboratories, covering developments in the United States. Further details appear in Frenkiel (2002) and Chapter 14 of O'Neill (1985). A brief discussion of European activities in mobile wireless communications from 1981 on concludes this section. Details appear in Paetsch (1993).

Ship-to-shore communication was among the first applications of mobile telephony. Experimental service began on coastal steamers between Boston and Baltimore in the United States in 1919; commercial service using AM technology at 4.2 and 8.7 MHz began in 1929. This was roughly the same period at which AM radio broadcasting began to capture the public's attention. Note the wavelengths at these frequencies are about 70 and 35 meters, respectively, making ships suitable vehicles for carrying antennas of these lengths. Ships were also suitable for the size and weight of the radio equipment required to be carried, as well as being able to provide the power required. Police communication was begun at about the same time. In 1928, the Detroit police department introduced land mobile communications using small, rugged radios. By 1934, 5000 police cars from 194 municipal and 58 police systems in the US had been equipped for, and were using, mobile

Frenkiel, R. 2002. "A brief history of mobile communications," *IEEE Vehicular Technology Society News*, May, 4–7.

O'Neill, E. F. 1985. *A History of Engineering and Science in the Bell System: Transmission Technology (1925–1975)*, ed. E. F. O'Neill, AT&T Bell Laboratories.

Paetsch, M. 1993. *Mobile Communications in the US and Europe: Regulation, Technology, and Markets*, Boston, MA, Artech House.

radio communications. These early mobile communications systems used the frequency band at 35 MHz. It soon became apparent, however, that communication to and from automobiles in urban areas was often unsatisfactory because of deleterious propagation effects and high noise levels. Propagation effects in urban environments were an unknown quantity and studies began at Bell Laboratories and elsewhere. Propagation tests were first carried out in 1926 at 40 MHz. By 1932, tests were being conducted at a number of other frequencies over a variety of transmission paths with varying distances, and with effects due to such phenomena as signal reflection, refraction, and diffraction noted. (Such tests are still being conducted today by various investigators for different signal propagation environments, both indoor and outdoor, and at different frequency bands. Chapter 2 provides an introduction to propagation effects as well as to models used in representing these effects.) In 1935, further propagation tests were carried out in Boston at frequencies of 35 MHz and 150 MHz. Multipath effects were particularly noted at this time. The tests also demonstrated that reliable transmission was possible using FM rather than the earlier AM technology. These various tests, as well as many other tests carried out over the years following, led to the understanding that propagation effects could be understood in their simplest form as being the combination of three factors: an inverse distance-dependent average received power variation of the form $1/d^n$, n an integer greater than the usual free-space factor of 2; a long-term statistical variation about the average received power, which is now referred to as shadow or log-normal fading; a short-term, rapidly varying, fading effect due to vehicle motion. These three propagation effects are discussed and modeled in detail in Chapter 2 following.

The advent of World War II interrupted commercial activity on mobile wireless systems, but the post-war period saw a rapid increase in this activity, especially at higher frequencies of operation. These higher frequencies of operation allowed more user channels to be made available. In 1946, the Federal Communications Commission, FCC, in the USA, granted a license for the operation of the first commercial land-mobile telephone system in St Louis. By the end of the year, 25 US cities had such systems in operation. The basic system used FM transmission in the 150 MHz band of frequencies, with carrier frequencies or channels spaced 120 kHz apart. In the 1950s the channel spacing was reduced to 60 kHz, but, because of the inability of receivers to discriminate sufficiently well between adjacent channels, neighboring cities could only use alternate channels spaced 120 kHz apart. A 50-mile separation between systems was required. High towers covering a range of 20–30 miles were erected to provide the radio connections to and from mobile users. Forty channels or simultaneous calls were made available using this system. The FCC divided these radio channels equally between the local telephone companies (Telcos) and newly established mobile carriers, called Radio Common Carriers (RCCs). These early mobile systems were manual in operation, with calls placed through an operator. They provided half-duplex transmission, with one side of a connection only being able to communicate at any one time: both parties to a connection used the same frequency channel for the air or radio portion of the connection, and a "push-to-talk" procedure was required for the non-talking party to "take over" the channel. With the number of channels available set at 40, the system could accommodate 800–1000 customers in a given area, depending on the length of calls. (Clearly, as user conversations increase in length, on the average, the number of customers that can be accommodated must be reduced. We shall quantify this obvious statement later in this book, in discussing the concept of "blocking probability.") As the systems grew in popularity, long waiting lists arose to obtain a mobile telephone. These systems thus tended to become somewhat "elitist," with priorities being established for people who desired to become customers; priority might be given to doctors, for example.

The introduction of new semi-conductor devices in the 1960s and the consequent reduction in system cost and mobile phone-power requirement, as well as the possibility of deploying more complex circuitry in the phones, led to the development of a considerably improved mobile telephone service called, logically enough, IMTS, for Improved Mobile Telephone Service. Bell Laboratories' development of this new service was carried on from 1962 to 1964, with a field trial conducted in 1965 in Harrisburg, PA. This service had a reduced FM channel spacing of 30 kHz, it incorporated automatic dialing, and operated in a full-duplex mode, i.e., simultaneous operation in each direction of transmission, with each side of a conversation having its own frequency channel. A mobile phone could also scan automatically for an "idle" channel, one not currently assigned to a user. This new system could still only accommodate 800–1000 customers in a given area however, and long waiting lists of as many as 25 000 potential customers were quite common! In addition, the limited spectrum made available for this service resulted, quite often, in users experiencing a "system busy" signal, i.e. being blocked from getting a channel. The "blocking probability" noted above was thus quite high.

Two solutions were proposed as early as 1947 by Bell Laboratories' engineers to alleviate the sparse mobile system capacity expected even at that time: one proposal was to move the mobile systems to a higher frequency band, allowing more system bandwidth, and, hence, more user channels to be made available; the second proposal was to introduce a cellular geographic structure. The concept of a cellular system is quite simple, although profound in its consequences. In a cellular system, a given region is divided into contiguous geographic areas called *cells*, with the total set of frequency channels divided among the cells. Channels are then reused in cells "far enough apart" so that interference between cells assigned the same frequencies is "manageable." (We shall quantify these ideas in Chapter 3.) For example, in one scheme we shall investigate in Chapter 3, cells may each be assigned one-seventh of the total number of channels available. This appears, at first glance, to be moving in the wrong direction – reducing the number of channels per cell appears to *reduce* the number of users that might be simultaneously accommodated! But, if the area covered by each cell is small enough, as is particularly possible in urban areas, frequencies are reused over short-enough distances to more than compensate for the reduction in channels per cell. A problem arising we shall consider in later chapters, however, is that, as mobile users "roam" from cell to cell, their on-going calls must be assigned a new frequency channel in each cell entered. This process of channel reassignment is called "handoff" (an alternative term used, particularly in Europe, is "handover"), and it must appear seamless to a user carrying on a conversation. Such a channel reassignment also competes with new calls attempting to get a channel in the same cell, and could result in a user disconnection from an ongoing call, unless special measures are taken to either avoid this or reduce the chance of such an occurrence. We discuss the concept of "handoff dropping probability," and suggested means for keeping it manageable, quantitatively, in Chapter 9, and compare the tradeoffs with respect to "new-call blocking probability."

We now return to our brief historical discussion. In 1949 the Bell System had requested permission from the FCC to move mobile telephone operations to the 470–890 MHz band to attain more channels and, hence, greater mobile capacity. This band was, at that time, intended for TV use however, and permission was denied. In 1958 the Bell System requested the use of the 764–840 MHz band for mobile communications, but the FCC declined to take action. By this time, the introduction of the cellular concept into mobile systems was under full discussion at Bell Laboratories. By 1968, the FCC had decided to allocate spectral capacity in the vicinity of 840 MHz for mobile telephony, and opened the now-famous "Notice of Inquiry and Notice of Proposed Rule-Making," Docket 18262, for this purpose. The Bell System responded in 1971, submitting a proposal for a "High-Capacity Mobile Telephone System," which included the introduction of cellular technology. (This proposed system was to evolve later into AMPS, the Advanced Mobile Phone Service, the first-generation analog cellular system mentioned earlier.) A ten-year conflict then began among various parties that felt threatened by the introduction by the Bell System of a mobile service in this higher frequency range. The broadcasters, for example, wanted to keep the frequency assignment for broadcast use; communication manufacturers felt threatened by the prospect of newer systems and the competition that might ensue; the RCCs feared domination by the Bell System; fleet operators wanted the spectrum for their private mobile communications use. It was not until 1981 that these issues were resolved, with the FCC finally agreeing to allocate 50 MHz in the 800–900 MHz band for mobile telephony. (Actually, a bandwidth of 40 MHz was allocated initially; 10 MHz additional bandwidth was allocated a few years later.) Half of this band of frequencies was to be assigned to local telephone companies, half to the RCCs. By this time as well, the widespread introduction of solid-state devices, microprocessors, and electronic telephone switching systems had made the processes of vehicle location and cell handoff readily carried out with relatively small cells.

During this period of "skirmishing and politicking" (O'Neill, 1985) work continued at Bell Laboratories on studies of urban propagation effects, as well as tests of a cellular-based mobile system in an urban environment. A technical trial for the resulting AMPS system was begun in Chicago in 1978, with the first actual commercial deployment of AMPS taking place in that city in 1983, once the FCC had ruled in favor of moving ahead in 1981. (Note, however, that the AT&T divestiture took place soon after, in 1984. Under the Modification of Final Judgment agreed to by AT&T, the US Justice Department, and the District Court involved with the divestiture, mobile operations of the Bell System were turned over to the RBOCs, the seven Regional Bell Operating Companies established at that time.)

The AMPS system is generally called a first-generation cellular mobile system, as noted above, and is still used, as noted earlier, for cell-system backup. It currently covers two 25 MHz-wide bands: the range of frequencies 824–849 MHz in the uplink or reverse-channel direction of radio transmission, from mobile unit to the base station; 869–894 MHz in the downlink or forward-channel direction, from base station to the mobile units. The system uses analog-FM transmission, as already noted, with 30 kHz allocated to each channel, i.e. user connection, in each direction. The maximum frequency deviation per channel is 12 kHz. Such a communication system, with the full 25 MHz of bandwidth in each direction of transmission split into 30 kHz-wide channels, is called a frequency-division multiple access (FDMA) system. (This frequency-division strategy, together with TDMA, time-division multiple access, and CDMA, code-division multiple access, will be discussed in detail in Chapter 6.) This means 832 30 kHz frequency channels are made available in each direction. In the first deployments of AMPS in the US, half of the channels were assigned to the RBOCs, the Regional Bell Operating Companies, and half to the RCCs, in accordance with the earlier FCC decision noted above. One-seventh of the channels are assigned to a given cell, also as already noted. Consider, for example, a system with 10-mile radius cells, covering an area of about 300 sq. miles. (Cells in the original Chicago trials were about 8 miles in radius.) Twenty-five contiguous cells would therefore cover an area of 7500 sq. miles. Consider a comparable non-cellular system covering about the same area, with a radius of about 50 miles. A little thought will indicate that the introduction of cells in this example increases the system capacity, the number of simultaneous user connections or calls made possible, by a factor of 25/7, or about 3.6. The use of smaller cells would improve the system capacity even more.

Despite the mobile capacity improvements made possible by the introduction of the cellular-based AMPS in 1983, problems with capacity began to be experienced from 1985 on in major US cities such as New York and Los Angeles. The Cellular Telecommunications Industry Association began to evaluate various alternatives, studying the problem from 1985 to 1988. A decision was made to move to a digital time-division multiple access, TDMA, system. This system would use the same 30 kHz channels over the same bands in the 800–900 MHz range as AMPS, to allow some backward compatibility. Each frequency channel would, however, be made available to three users, increasing the corresponding capacity by a factor of three. (TDMA is discussed in Chapter 6.) Standards for such a system were developed and the resultant system labeled IS-54. More recently, with revised standards, the system has been renamed IS-136. It is often called D-AMPS, for digital-AMPS, as well. This constitutes one of the three second-generation cellular systems to be discussed in this book. These second-generation digital systems went into operation in major US cities in late 1991. A detailed discussion of IS-135 is provided in Chapters 6 and 8.

In 1986, QUALCOMM, a San Diego communications company that had been developing a code-division multiple access, CDMA, mobile system, got a number of the RBOCs, such as NYNEX and Pacific Bell, to test out its system, which, by the FCC rules, had to cover the same range of frequencies in the 800–900 MHz band as did AMPS and D-AMPS. This CDMA system, labeled IS-95, was introduced commercially in the US and in other countries in 1993. This system is the second of the second-generation systems to be discussed in this book. It has been adopted for the 2 GHz PCS band as well. (We shall have little to say about the 2 GHz band, focusing for simplicity in this book on the 800–900 MHz band.) In IS-95, the 25 MHz-wide bands allocated for mobile service are split into CDMA channels 1.25 MHz wide. Code-division multiple access is discussed in detail in Chapter 6, and, again, in connection with third-generation cellular systems, in Chapter 10. Details of the IS-95 CDMA system are provided in Chapters 6 and 8.

Note that, by the mid and late 1990s, there existed two competing and incompatible second-generation digital wireless systems in the United States. If one includes the later adoption of the 2 GHz PCS band for such systems as well, there is clearly the potential for a great deal of difficulty for mobile users in maintaining connectivity while roaming far from home in an area not covered well by the designated mobile carrier. Dual-mode cell phones are used to help alleviate this problem: they have the ability to fall back on the analog AMPS system when experiencing difficulty in communicating in a given area. The situation in Europe was initially even worse. The first mobile cellular systems were introduced in the Scandinavian countries in 1981 and early 1982. Spain, Austria, the United Kingdom, Netherlands, Germany, Italy, and France followed with their own systems in the period 1982–1985. These systems were all analog, but the problem was that there were eight of them, all different and incompatible. This meant that communication was generally restricted to one country only. The problem was, of course, recognized early on. In 1981 France and Germany instituted a study to develop a second-generation digital system. In 1982 the Telecommunications Commission of the European Conference of Postal and Telecommunication Administrations (CEPT) established a study group called the *Groupe Speciale Mobile* (GSM) to develop the specifications for a European-wide second-generation digital cellular system in the 900 MHz band. By 1986 the decision had been reached to use TDMA technology. In 1987 the European Economic Community adopted the initial recommendations and the frequency allocations proposed, covering the 25 MHz bands of 890–915 MHz for uplink, mobile to base station, communications, and 935–960 MHz for downlink, base station to mobile, communications. By 1990 the first-phase specifications of the resultant system called GSM (for either Global System for Mobile Communications or the GSM System for Mobile Communications) were frozen. In addition, that same year, at the request of the United Kingdom, work on an adaptation of GSM for the 1.8 GHz band, DCS1800, was begun. Specifications for DCS1800 were frozen a year later, in 1992. The first GSM systems were running by 1991 and commercial operations began in 1992. GSM has since been deployed throughout Europe, allowing smooth roaming from country to country. A version of GSM designed for the North American frequency band has become available for North America as well. This, of course, compounds the incompatibility problem in the United States even more, with three different second-generation systems now available and being marketed in the 800–900 MHz range, as well as systems available in the 2 GHz PCS band. Canada, which initially adopted IS-136, has also seen the introduction of both IS-95 and GSM.

Japan's experience has paralleled that of North America. NTT, Japan's government-owned telecommunications carrier at the time, introduced an analog cellular system as early as 1979. That system carried 600 25 kHz FM duplex channels in two 25 MHz bands in the 800 MHz spectral range. Its Pacific Digital Cellular (PDC) system, with characteristics similar to those of D-AMPS, was introduced in 1993. It covers the same frequency bands as the first analog system, as well as a PCS version at 1.5 GHz. The IS-95 CDMA system, marketed as CDMAOne, has been introduced in Japan as well.

As of May 2003, GSM was the most widely adopted second-generation system in the world, serving about 864 million subscribers worldwide, or 72% of the total digital mobile users throughout the world (GSM World). Of these, Europe had 400 million subscribers, Asia Pacific had 334 million subscribers, Africa and the Arab World had 28 million subscribers each, and North America and Russia had 22 million subscribers each. IS-95 CDMA usage was number two in the world, with 157 million subscribers worldwide using that type of system. D-AMPS had 111 million subscribers, while PDC, in Japan, had 62 million subscribers.

1.2 Overview of book

With this brief historical survey completed, we are ready to provide a summary of the chapters to come. As noted above, propagation conditions over the radio medium or air space used to carry out the requisite communications play an extremely significant role in the operation and performance of wireless mobile systems. Multiple studies have been carried out over many years, and are still continuing, of propagation conditions in many environments, ranging from rural to suburban to urban areas out-of-doors, as well as a variety of indoor environments. These studies have led to a variety of models emulating these different environments, to be used for system design and implementation, as well as simulation and analysis. Chapter 2 introduces the simplest of these models. The discussion should, however, provide an understanding of more complex models, as well as an entrée to the most recent literature on propagation effects. In particular, we focus on a model for the statistically varying received signal power at a mobile receiver, given signals from the base station transmitted with a specified power. This model incorporates, in product form, three factors summarizing the most significant effects experienced by radio waves traversing the air medium. These three factors were mentioned briefly earlier. The first term in the model covers the variation of the average signal power with distance away from the transmitter. Unlike the case of free-space propagation, with power varying inversely as the square of the distance, the transmitted signal in a typical propagation environment is found to vary inversely as a greater power of the distance. This is due to the effect of obstacles encountered along the signal propagation path, from base station to mobile receiver, which serve to reflect, diffract, and scatter the signal, resulting in a multiplicity of rays arriving at the receiver. A common example, which we demonstrate in Chapter 2 and use in later chapters, is variation as $1/(\text{distance})^4$, due to the summed effect of two rays, one direct from the base station, the other reflected from the ground.

The second term in the model we discuss in Chapter 2 incorporates a relatively large-scale statistical variation in the signal power about its average value, sometimes exceeding the average value, sometimes dropping below it. This effect, covering distances of many wavelengths, has been found to be closely modeled by a log-normal distribution, and is often referred to as shadow or log-normal fading. The third term in the model is designed to incorporate the effect of small-scale fading, with the received signal power varying statistically as the mobile receiver moves distances the order of a wavelength. This type of fading is due to multipath scattering of the transmitted signal and is referred to as Rayleigh/Rician fading. A section on random channel characterization then follows. We also discuss in Chapter 2 the rate of fading and its connection with mobile velocity, as well as the impact of fading on the information-bearing signal, including the condition for frequency-selective fading. This condition occurs when the delay spread, the differential delays incurred by received multipath rays, exceeds a data symbol interval. It results in signal distortion, in particular in inter-symbol interference. Chapter 2 concludes with a discussion of three methods of mitigating the effects of multipath fading: equalization techniques designed to overcome inter-symbol interference, diversity procedures, and the RAKE receiver technique used effectively to improve the performance of CDMA systems.

Chapter 3 focuses on the cellular concept and the improvement in system capacity made possible through channel reuse. It introduces as a performance parameter the signal-to-interference ratio or SIR, used commonly in wireless systems as a measure of the impact of interfering transmitters on the reception of a desired signal. In a cellular system, for example, the choice of an acceptable lower threshold for the SIR will determine the reuse distance, i.e., how far apart cells must be that use the same frequency. In discussing two-dimensional systems in this chapter we focus on hexagonal cellular structures. Hexagons are commonly used to represent cells in cellular systems, since they tessellate the two-dimensional space and approximate equi-power circles obtained when using omni-directional antennas. With the reuse distance determined, the number of channels per cell is immediately found for any given system. From this calculation, the system performance in terms of blocking probability may be found. This calculation depends on the number of mobile users per cell, as well as the statistical characteristics of the calls they make. Given a desired blocking probability, one can readily determine the number of allowable users per cell, or the cell size required. To do these calculations, we introduce the statistical form for blocking probability in telephone systems, the Erlang distribution. (We leave the actual derivation of the Erlang distribution to Chapter 9, which covers performance issues in depth.) This introductory discussion of performance in Chapter 3, using SIR concepts, focuses on average signal powers, and ignores the impact of fading. We therefore conclude the chapter with a brief introduction to probabilistic signal calculations in which we determine the probability the received signal power will exceed a specified threshold. These calculations incorporate the shadow-fading model described earlier in Chapter 2.

Chapter 4 discusses other methods of improving system performance. These include dynamic channel allocation (DCA) strategies for reducing the call blocking probability as well as power control for reducing interference. Power control is widely used in cellular systems to ensure the appropriate SIR is maintained. As we shall see in our discussions of CDMA systems later in the book, in Chapters 6, 8, and 10, power control is critical to their appropriate performance. In describing DCA, we focus on one specific algorithm which lends itself readily to an approximate analysis, yet is characteristic of many DCA strategies, so that one can readily show how the use of DCA can improve cellular system performance. We, in fact, compare its use, for simple systems, with that of fixed-channel allocation, implicitly assumed in the discussion of cellular channel allocations in Chapter 3. Our discussion of power control algorithms focuses on two simple iterative algorithms, showing how the choice of algorithm can dramatically affect the convergence rate. We then show how these algorithms can be written in a unified form, and can, in fact, be compared with a simple single-bit control algorithm used in CDMA systems.

Chapter 5 continues the discussion of basic system concepts encountered in the study of digital mobile wireless systems, focusing on modulation techniques used in these systems. It begins with a brief introductory section on the simplest forms of digital modulation, namely phase-shift keying (PSK), frequency-shift keying (FSK), and amplitude-shift keying or on–off keyed transmission (ASK or OOK). These simple digital modulation techniques are then extended to quadrature-amplitude modulation (QAM) techniques, with QPSK and 8-PSK, used in third-generation cellular systems, as special cases. A brief introduction to signal shaping in digital communications is included as well. This material should be familiar to anyone with some background in digital communication systems. The further extension of these techniques to digital modulation techniques such as DPSK and GMSK used in wireless systems then follows quite readily and is easily described. The chapter concludes with an introduction to orthogonal frequency-division multiplexing (OFDM), including its implementation using Fast Fourier Transform techniques. OFDM has been incorporated in high bit rate wireless LANs, described in Chapter 12.

In Chapter 6 we describe the two major multiple access techniques, time-division multiple access (TDMA) and code-division multiple access (CDMA) used in digital wireless systems. TDMA systems incorporate a slotted repetitive frame structure, with individual users assigned one or more slots per frame. This technique is quite similar to that used in modern digital (wired) telephone networks. The GSM and D-AMPS (IS-136) cellular systems are both examples of TDMA systems. CDMA systems, exemplified by the second-generation IS-95 system and the third-generation cdma2000 and WCDMA systems, use pseudo-random coded transmission to provide user access to the cellular system. All systems utilize FDMA access as well, with specified frequency assignments within an allocated spectral band further divided into time slots for TDMA transmission or used to carry multiple codes in the case of CDMA transmission. We provide first an introductory discussion of TDMA. We then follow with an introduction to the basic elements of CDMA. (This discussion of CDMA is deepened later in the book, specifically in describing IS-95 in Chapter 8 and the third-generation CDMA systems in Chapter 10.) We follow this introduction to CDMA with some simple calculations of the system capacity potentially provided by CDMA. These calculations rely, in turn, on knowledge of the calculation of bit error probability. For those readers not familiar with communication theory, we summarize classical results obtained for the detection of binary signals in noise, as well as the effect of fading on signal detectability. Error-probability improvement due to the use of diversity techniques discussed in Chapter 2 is described briefly as well.

These calculations of CDMA capacity using simple, analytical models enable us to compare, in concluding the chapter, the system-capacity performance of TDMA and CDMA systems. We do stress that the capacity results obtained assume idealized models of cellular systems, and may differ considerably in the real-world environment. The use of system models in this chapter and others following do serve, however, to focus attention on the most important parameters and design choices in the deployment of wireless systems.

Chapter 7, on coding for error detection and correction, completes the discussion of introductory material designed to provide the reader with the background necessary to understand both the operation and performance of digital wireless systems. Much of this chapter involves material often studied in introductory courses on communication systems and theory. A user with prior knowledge of coding theory could therefore use the discussion in this chapter for review, while focusing on the examples provided of the application of these coding techniques to the third-generation cellular systems discussed later in Chapter 10. We begin the discussion with an introduction to block coding for error correction and detection. We focus specifically on so-called cyclic codes used commonly in