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Overview of Wireless Communications and Networking

This book aims at providing students at the senior level an in-depth understanding of end-to-end communications over an information transport platform consisting of a wireless segment and a wireline segment. It points out the obstacles that cause spectral limitation in the wireless propagation channel, the difficulty in maintaining service continuity as the user roams, the problems in bridging the wireless and wireline domains, and the techniques to overcome the difficulties in handling the end-to-end information transfer.

This chapter gives the reader an overview of the salient features of wireless communications and networking and the organization of the materials presented in the ensuing seven chapters.

1.1 HISTORICAL OVERVIEW OF WIRELESS COMMUNICATIONS

Long distance wireless transmission has a century-old history, dating from the time Guglielmo Marconi sent telegraphic signals over a distance of approximately 1800 miles from Cornwall, across the Atlantic Ocean, to St. John's, Newfoundland in 1901. Over the past century, wireless transmission has progressed through the development and deployment of radio, radar, television, satellite and mobile telephone technologies.

In the early years of wireless communications, radio was the most intensively deployed wireless technology, both in the public domain and by law enforcement establishments (e.g., police forces at all levels). Amplitude modulation (AM) of a radio frequency carrier was the transmission technique used until Edwin Armstrong demonstrated the feasibility of frequency modulation (FM) in 1935. Since the late 1930s, FM has been the main modulation method deployed for mobile communication systems worldwide.

The development of radar technology was escalated and matured during World War II when practically every university radar research laboratory in the United States, notably the University of Michigan at Ann Arbor and the Lincoln Laboratories at Massachusetts Institute of Technology (MIT), were converted to concentrate mainly on military applications, such as surveillance of the battle front in Europe. In the late 1940s and 1950s, commercial deployment of one-way and two-way radio and television systems flourished.

The growth of cellular radio and personal communication systems began to accelerate in the late 1970s. This growth was spurred on with the successive introduction of the first generation (1G), the second generation (2G), and the third generation (3G) cellular systems.

1.2 CHALLENGES IN WIRELESS COMMUNICATION NETWORKING

A wireless communication network offers a flexible information transport platform that allows mobile users to roam without suffering intolerable performance degradation. A wireless communication networking scenario is depicted in Figure 1.1. Here, a base station (BS) is the information distribution center for all mobile stations (MSs) within its signaling coverage area. The signal propagation medium between the MSs and the BS is wireless. The radio channel from an MS to its serving BS is called the uplink or reverse channel, and the radio channel from the BS to the MSs is called the downlink or forward channel. Base stations are connected to Mobile Switching

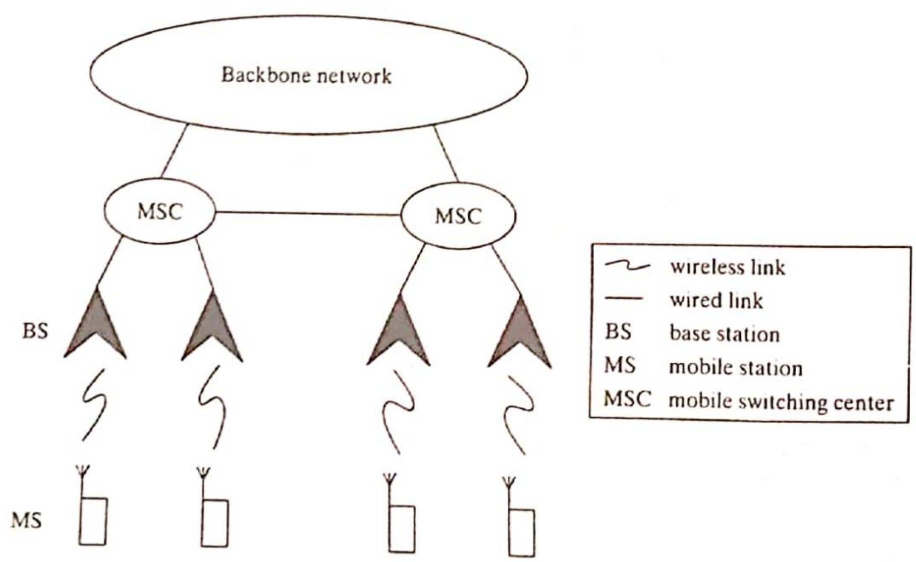

Figure 1.1 An illustration of wireless communications network.

Centers (MSCs) by wirelines to extend the geographical coverage of a single BS. Also, an MSC may be connected by wirelines to other MSCs and/or to a wired backbone network, e.g., an ATM (Asynchronous Transfer Mode) network or the Internet. In this way, a pair of communicating mobile users can be separated by a large distance. The key challenge is the creation of a viable information transport platform for the support of communications between mobile users. This platform is a hybrid connection of a front-end wireless network and a backbone wireline network.

Definition of Radio Cell A radio cell is a geographical area served by a single base station supporting the services of many mobile stations.

Depending on the size of the area covered, radio cells are categorized into picocells, microcells, and macrocells. The main problems in wireless communications come from (*a*) the hostile wireless propagation medium and (*b*) user mobility.

1.2.1 The Wireless Channel

The radio propagation channel exhibits many different forms of channel impairments, notably multipath delay spread, Doppler spread, intracell interference, intercell interference, fading, ambient noise, etc. Interference, distortion and noise can be differentiated into multiplicative and additive types as follows:

a. Multiplicative interference and distortion are normally signal-dependent, and include fading, intersymbol interference, etc. It causes attenuation, mutilation, etc., of the transmitted signal. The net result is a reduction in usable frequency spectrum. This form of disturbance cannot be suppressed by using filtering.
b. Additive noise is not as severe as multiplicative noise, but it still reduces signal detectability. Out-of-band noise can be suppressed by filtering, but in-band noise will still penetrate through the filter.

Effective and efficient transmitters and receivers are needed to combat interference and distortion. Transmitter/receiver design requires a good knowledge of the channel characteristics. Thus, a good understanding of the characteristics of the propagation channel is essential to allow for the design of effective transmitters, receivers, and communications protocols.

1.2.2 User Mobility

To provide communication services to a larger number of users using the limited radio spectrum, wireless systems are designed based on the cellular concept for frequency reuse. By dividing a large service area into small nonoverlapping (in an ideal case) cells and letting each base station communicate with all the mobile stations in the cell with low transmitter power, radio frequency spectrum can be reused in different cells subject to transmission quality satisfaction. As a mobile station moves from cell to cell, the serving base station changes. The process in which a mobile station switches its serving base station while crossing the cell boundary is referred to as *handoff management*. The process that tracks the user's movement, supports user roaming on a large scale, and delivers calls to the user at its current location is referred to as *location management*. As a result, the operation of a wireless network requires proper *mobility management* functions, which include both handoff management and location management.

While the information is represented and transmitted in the form of signal waveforms, communications between the sender and the receiver can be conveniently viewed as taking place in three conceptual layers: *physical, link* and *networking*. The physical layer involves the actual signal transmission and reception over the propagation channel. The link layer deals with the signals at the output of the cell-site (base station) receiver. Radio resource management functions such as power control, rate allocation and error control, and network resource management functions such as service scheduling and call admission control, can be exercised at the link layer. The networking layer comprises a protocol stack that includes handoff management, location management, traffic management and traffic control. As reflected by its title, the focus of this text is on elucidating and understanding the physical layer and the networking layer properties. The rationale behind this approach is that resource management and service scheduling strategies at the link layer are issues that aim at maximizing resource utilization and enhancing quality of service. Works in these areas are currently under intensive research.

1.3 WIRELESS COMMUNICATIONS STANDARDS

Wireless communications systems that have been in deployment for sometime are those of the first generation and second generation. Third generation systems are also currently under deployment, but continue to evolve. The first generation (1G) wireless communications systems use *frequency division multiple access* (FDMA) as the multiple access technology. FDMA is an analog transmission technique that is inherently narrowband. The second generation (2G) wireless systems use digital transmission. The multiple access technology is both *time division multiple access* (TDMA) and *code division multiple access* (CDMA). Although the second generation wireless systems offer higher transmission rates with greater flexibility than the first generation systems, they are nevertheless narrowband systems. The service offered by both 1G and 2G systems is predominantly voice. The third generation (3G) standard is based on CDMA as the multiple access technology. With a transmission rate of up to 2 megabits per second (Mbps), 3G systems are wideband, and are expected to support multimedia services.

For the first and second generations, the main initiatives have been originated in North America, Europe and Japan. Although all regions use similar technology, the systems differ in the location of the frequency band in the radio spectrum, the channel spacing, and the data transmission rate. ITU (International Telecommunications Union) has now adopted both the European IMT-2000 (International Mobile Telecommunications by the year 2000) and the North American cdma-2000 as third generation standards. IMT-2000 is a wideband direct-sequence CDMA (DS-CDMA) and cdma-2000 is a multicarrier CDMA (MC-CDMA) technology.

1.3.1 First Generation Cellular Systems

The first generation cellular systems use analog FM for speech transmission. The individual calls use different frequencies and share the available spectrum through FDMA.

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AMPS in America and Australia. America and Australia use the Advanced Mobile Phone System (AMPS) with a 25 MHz band in each uplink, from 824 to 849 MHz, and a 25 MHz band in each downlink, from 869 to 894 MHz. AMPS uses a channel spacing of 30 kHz, with a total capacity of 832 channels, and supports a data transmission rate of 10 kilobits per second (kbps).

ETACS in Europe. Europe uses the European Total Access Communications System (ETACS) with a 25 MHz band in the uplink, from 890 to 915 MHz, and a 25 MHz band in the downlink, from 935 to 960 MHz. ETACS uses a channel spacing of 25 kHz, with a total capacity of 1000 channels, and supports a data transmission rate of 8 kbps.

NTT in Japan. The first generation cellular system is the Nippon Telephone and Telegraph (NTT) system which employs a 15 MHz band in the uplink, from 925 to 940 MHz, and a 15 MHz band in the downlink, from 870 to 885 MHz, with a channel spacing of 25 kHz. The NTT system has a total capacity of 600 channels and supports a data transmission rate of 0.3 kbps.

The NTT system was later modified to increase its capacity from 600 to 2400 channels. This increase was achieved by decreasing the channel spacing from 25 kHz to 6.25 kHz. In addition, the data transmission rate of each channel was increased from 0.3 kbps to 2.40 kbps.

The radio interface technology of the first generation wireless cellular systems (AMPS in America, ETACS in Europe, and NTT in Japan) is tabulated in Table 1.1. As can be seen from this table, the systems differ in the location of the frequency bands, channel spacing, data rate, spectral efficiency and system capacity.

1.3.2 Second Generation Cellular Systems

The second generation cellular systems are completely digital, employing either TDMA or CDMA as the multiple access technology. The digital technology allows greater sharing of the radio hardware in the base station among the multiple users, and provides a larger capacity to support more users per base station per MHz of spectrum than analog systems. Digital systems offer a number of advantages over analog systems, including

Table 1.1 First Generation Analog Cellular Systems

Region	America	Europe	Japan
Parameter	AMPS	ETACS	NTT
Multiple access	FDMA	FDMA	FDMA
Duplexing	FDD	FDD	FDD
Forward channel	869–894 MHz	935–960 MHz	870–885 MHz
Reverse channel	824–849 MHz	890–915 MHz	925–940 MHz
Channel spacing	30 kHz	25 kHz	25 kHz
Data rate	10 kbps	8 kbps	0.3 kbps
Spectral efficiency	0.33 bps/Hz	0.33 bps/Hz	0.012 bps/Hz
Capacity	832 channels	1000 channels	600 channels

a. natural integration with the evolving digital wireline network,
b. flexibility for supporting multimedia services,
c. flexibility for capacity expansion,
d. reduction in RF (radio frequency) transmit power,
e. encryption for communication privacy, and
f. reduction in system complexity.

Advantage of Digital System over Analog

As stated previously, the second generation cellular systems use either TDMA or CDMA access technology. While the CDMA standard is strictly North American, in the form of IS-95, TDMA deployment is regionally based (i.e., Europe, North America, or Japan). In Europe, it is the Pan-European GSM (Groupe Special Mobile or Global System for Mobile Communications) and DCS 1800 (Digital Cellular System). In North America, it is IS-54 and IS-136, and in Japan it is PDC (Personal Digital Cellular) systems. The different second generation standards have the following specifications.

GSM in Europe. The channel time in TDMA is partitioned into frames, each containing eight time-slots. Each time-slot is of 0.57 ms duration. Each user transmits periodically in every eighth slot and receives in the corresponding slot. (Each slot is a channel.) The modulation scheme is Gaussian filtered minimum shift keying (GMSK).

IS-54 in North America. In the frequency domain, the channel spacing is 30 kHz, the same as that of AMPS. The modulation scheme is $\pi/4$ shifted differential quadrature phase shift keying (DQPSK) with a channel rate of 48.6 kbps. In the time domain, one TDMA frame contains six time slots supporting three full-rate users or six half-rate users, each slot having a duration of approximately 6.67 ms. The speech codec rate is 7.95 kbps or 13 kbps with error protection. The capacity of each frequency channel is three times that of AMPS.

PDC in Japan. The system is TDMA-based with three slots multiplexed onto each carrier (similar to IS-54). In the frequency domain, the channel spacing is 25 kHz. The modulation scheme is $\pi/4$-shifted DQPSK with a transmission rate of 42 kbps. The speech codec operates at a full rate of 6.7 kbps or 11.2 kbps with error protection.

IS-95 in North America. IS-95 is a CDMA-based standard. Users share a common channel for transmission within a cell. Users in adjacent cells also use the same radio channel. In other words, the frequency spectrum is reused from cell to cell. The system is designed to be compatible with the existing analog system AMPS; the allocated frequency band is 824-849 MHz for the uplink using offset quadrature phase shift keying (OQPSK) and 869-894 MHz for the downlink using QPSK. The spreading code chip rate is 1.2288 megachips per second (Mcps). The spreading factor is 128, with the maximum user data rate of 9.6 kbps. Forward and reverse links use different spreading processes. Rake receivers are used at both the base station and mobile station to resolve and to combine multipath components.

The radio interface technology of the second generation digital systems is tabulated in Table 1.2.

In cellular communications, location management is critically important. IS-41, with a two-tiered network architecture for location management, is a companion standard to IS-54 in North America. GSM in Europe performs location management using MAP (Mobile Applications Part), which is also a two-tiered network architecture.

Table 1.2 Second Generation Digital Cellular Systems

Region	U.S.	Europe	Japan	U.S.
Parameter	IS-54	GSM	PDC	IS-95
Multiple access	TDMA/FDD	TDMA/FDD	TDMA/FDD	CDMA
Modulation	$\pi/4$ DQPSK	GMSK	$\pi/4$ DQPSK	QPSK/OQPSK
Forward channel	869-894 MHz	935-960 MHz	810-826 MHz	869-894 MHz
Reverse channel	824-849 MHz	890-915 MHz	940-956 MHz	824-849 MHz
Channel spacing	30 kHz	200 kHz	25 kHz	1,250 kHz
Data/chip rate	48.6 kbps	270.833 kbps	42 kbps	1.2288 Mcps
Speech codec rate	7.95 kbps	13.4 kbps	6.7 kbps	1.2/2.4/4.8/9.6 kbps

1.3.3 Third Generation Wireless Communications Networks

Third generation standardization activities were initiated in Europe and in North America under the respective names IMT-2000 and cdma-2000. IMT-2000 is wideband direct-sequence code division multiple access (DS-CDMA), while cdma-2000 is multicarrier code division multiple access (MC-CDMA). ITU has adopted the recommendations of both IMT-2000 and cdma-2000 under the banner of Harmonized Global 3G (G3G). Both IMT-2000 and cdma-2000 use frequency division duplex (FDD) to support two-way transmissions with frequency isolation. TDD (time division duplex) has also been suggested as a third 3G mode. The gist of harmonization is that both ANSI-41 and GSM MAP based services should be fully supported in the Radio Access Network with all 3G CDMA modes.

It is likely that the third generation cellular systems will be equipped with the infrastructure to support Personal Communications Systems (PCS). The network infrastructure support will likely include

a. public land mobile networks (PLMNs),
b. Mobile Internet Protocol (Mobile IP),
c. wireless asynchronous transfer mode (WATM) networks, and
d. low earth orbit (LEO) satellite networks.

Impact of High Transmission Rate. The most prominent features of 3G, compared with 2G, are the higher transmission rate and the support of multimedia services. The higher transmission rate means that the bandwidth of the signal will be large compared with the coherence bandwidth of the propagation channel. When the signal bandwidth is large compared with the coherence bandwidth of the channel, different frequency components of the signal will experience different fading characteristics (i.e., different parts of the signal spectrum will be affected differently by channel fading). Techniques to combat frequency selective fading need to be used in order to attain an acceptable error rate at the output of the cell-site receiver. A basic approach to combat frequency selective fading is to partition the signal into contiguous frequency bands, each of which is narrow compared with the coherence bandwidth of the channel. Each of the signal components is then modulated onto a different subcarrier and the signal components are sent over the channel in parallel. In this way, each of the signal components will experience non-frequency-selective fading, i.e., the fading is uniform across a given component's frequency band. This can be achieved by converting the high rate serial data sequence into a number of lower rate parallel sequences, and then modulating each onto a subcarrier. An effective method to achieve this is orthogonal frequency division multiplexing (OFDM). OFDM, as a signaling method, will be described in detail later in the text.

Mobiles can be located anywhere within the footprint of a base station. If every mobile transmits at the same power level, the signal received at the cell-site receiver from the mobile(s) closest to it will be the strongest. This is referred to as the near–far problem, and the power levels need to be controlled to smooth out the near–far effect. Power control, rate allocation and service scheduling are radio resource management functions. The primary purpose in managing the radio resources is to maximize system utilization. Strategies to effectively mechanize these functions are challenging research issues, which are not addressed in this text.

System Capacity and Impact of User Mobility. The capacity of cellular systems is enlarged through efficient employment of the available bandwidth (i.e., frequency reuse). To support higher transmission rates in 3G systems, the limited bandwidth of the systems needs to be reused more often.

Although decreasing the cell size allows for a higher degree of frequency reuse to increase system capacity, the tradeoff for this benefit is that mobile users tend to move in and out of cells much more frequently. To maintain service continuity, the connection of a mobile user must be handed off from the serving base station to base station of the target cell. Also, once handoff is complete, the mobile needs to identify its current location within the cellular array so that messages can be delivered to it in its new location. As a result, a reduction in the cell size translates to a larger overhead for mobility management (i.e., handoff management and location management) in the network. This text provides a lucid discussion of handoff and location management issues, and approaches to construct handoff and location management algorithms.

1.3.4 Coverage Extension

Wireless systems have limited geographical coverage. A backbone network such as the Internet is needed to extend the geographical coverage. Interworking of a wireless domain with a wireline domain introduces many challenging issues, chief among which is the problem of delivering information to the mobile as it roams around the extended network. These issues and the methods to handle information delivery in an efficient manner are discussed and treated later in the text.

1.3.5 Types of Wireless Communication Networks

Depending on whether or not there is a fixed infrastructure, wireless systems can be categorized as cellular systems or ad hoc networks. A cellular system has a fixed infrastructure in the form of a base station, which performs central administration for the system. Cellular networks provide the information transport platform for wireless local area networks (WLANs) and wireless wide area networks (WWANs). Wireless LAN standards activities have been spearheaded by IEEE 802.11, while wireless WAN standards activities have been led by ANSI (American National Standards Institute) and ITU (International Telecommunications Union).

Ad hoc networks have no fixed infrastructure and the network architecture is configurable. Every node (mobile) in the ad hoc network can set up as, and play the role of, a base station in that it can directly transmit to and receive from other nodes in the network. The main focus of this book is with cellular networks, but a bird's eye view into the operational features of ad hoc networks is also given.

1.4 ORGANIZATION OF THIS TEXT

With the overview of challenging issues in wireless communications and networking presented in this chapter, in-depth discussions of channel characterization, transmitter/receiver design, cellular network architecture, multiple access technologies, mobility management, and traffic management in extended networks are provided in Chapters 2 through 8. The rationale behind the material presented in each of these chapters is concisely summarized next.

Characterization of the Wireless Channel (Chapter 2). Because of impairments in the wireless channel, signal transmission through the wireless propagation medium presents a set of very challenging problems. Impairments in the wireless channel include multipath delay spread, Doppler spread, fading, path loss, shadowing, interference and ambient noise, etc. Knowledge of the channel characteristics will facilitate transmitter and receiver design. In the absence of this knowledge, ways to characterize the propagation channel are critically important.

Bandpass Transmission Techniques for Mobile Radio (Chapter 3). To minimize the effects of signal attenuation and signal distortion, the information-bearing baseband signal needs to be suitably modulated onto an appropriate carrier frequency, or a set of subcarrier frequencies. With high transmission rates, the bandwidth of the transmitted signal will likely exceed the coherence bandwidth of the wireless channel, resulting in frequency-selective fading. Transmission techniques such as OFDM, having the ability to render the fading channel non-frequency-selective, are important to mobile radio communications. With severe channel impairments, residual errors are unavoidable. Error probabilities of different modulation schemes that provide appropriate measures of system performance need to be analyzed and evaluated.

Receiver Techniques for Fading Dispersive Channels (Chapter 4). Optimum reception of transmitted signals over fading dispersive channels subject to a suitably chosen criterion is key to optimum receiver design. With the wireless channel exhibiting impairments such as intersymbol interference, Doppler spread and multipath delay spread, techniques such as diversity reception, linear combining, channel equalization, etc., are crucial to optimal signal reception at the cell-site receiver.

Fundamentals of Cellular Communications (Chapter 5). The area covered by a single base station is limited. The area coverage can be extended by (*a*) linking cells in a two-dimensional array and (*b*) wiring the cell-sites to an MSC and then to a backbone network as illustrated in Figure 1.1.

An array structure offers reuse of the same frequency in neighboring cells. However, frequency reuse can cause interference from adjacent cells. Therefore, effective strategies to manage the available resources are needed.

Multiple Access Techniques (Chapter 6). There is no interference if only one mobile transmits to the base station (cell-site receiver). If two or more mobiles transmit to the same cell-site receiver simultaneously, collision(s) can occur leading to destructive interference. Therefore an effective multiple access control scheme to enhance spectral efficiency and capacity is needed.

Mobility Management in Wireless Networks (Chapter 7). A wireless network has the capability to support user roaming. To achieve this roaming feature, it is necessary to introduce efficient and effective methods for (*a*) call admission control, (*b*) handoff, and (*c*) location management.

Wireless/Wireline Interworking (Chapter 8). While the wireless system offers the flexibility for user roaming, a backbone network such as the Internet is needed to support global communications. The interworking of a wireless segment with a wireline segment to extend the geographical coverage is imperative for future personal communication service (PCS) networks. The interworking of wireless/IP-based networks introduces some challenging issues in terms of maintaining network integrity, maximization of network utilization, and provision of quality of service in end-to-end network information delivery.