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OVERVIEW OF WIRELESS NETWORKS

1.1 INTRODUCTION

The second half of the twentieth century witnessed enormous transformations in electronic communications, including the development of data transmission over legacy telephone networks, the introduction of packet-data networks, the development of high-speed local area networks (LANs), and the development of mobile wireless communications networks, most notably cellular networks, paging systems, and even mobile satellite systems. By the start of the current century, cellular and paging services had come into widespread use in support of business communications and personal communications as well. The early analog cellular networks were rapidly supplanted by digital networks affording increased traffic capacity and capable of supporting an expanding menu of data-oriented services. In this first decade of the new century, we

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are seeing rapidly increasing interest in higher-rate forms of wireless data communication, including multimedia transmission to and from portable phones, and wireless access to the Internet from laptop computers. The technology underlying these wireless communications developments is the specific focus of this book.

The worldwide growth of the wireless communications industry has been truly phenomenal. At this writing, there are more than 1 billion cellular telephone users throughout the world, and the aggregate annual revenue of the wireless industry exceeds the revenues of the wired-telephone service industry. About 10 years ago, Internet access began expanding from the business environment to include the home environment, and this soon generated annual revenues comparable to those of traditional telephone service and wireless service. Currently, the *information exchange industry*, defined to include both wired and wireless phone services as well as Internet access, enjoys annual revenues of several trillion dollars and is by far the largest industry in the world.

Underlying this rapid development of all communications services and networks has been the ongoing evolution of digital technology, particularly large-scale integration and microprocessor chip technology. The digital revolution enabled transformation of the core of a traditional telephone network to a digital infrastructure providing greater reliability, increased capacity, and an ever-widening array of services to customers. About 10 years ago, digital technology began to have an impact on mobile wireless services and networks, increasing network capacities and capabilities as well as lowering the cost and increasing the battery life of mobile devices. An interesting and important aspect of the burgeoning worldwide wireless communications industry has been the rebirth of wireless LAN (WLAN) technology, driven by the steadily increasing popularity of laptop computers, the demand for wireless Internet access, and the expanding deployment of wireless access points on campuses and, increasingly, in public commercial venues.

Many of the wireless technology developments of the past decade have focused on improved physical (PHY) layer and medium access control (MAC) layer designs. The technical core of these protocol layers comprises digital signal processing (DSP) techniques and technology, to which most of this book is directed.

In this chapter we provide an overview of wireless information networks. We describe the basic elements of a wireless network and the key technical issues to be considered in the design of these networks. We also discuss the market sectors constituting the wireless industry and the trends apparent in voice- and data-oriented networks. In the final section of the chapter we outline the remaining chapters of the book.

1.1.1 Elements of a Wireless Network

An information network is an infrastructure that interconnects telecommunication devices to provide them with means for exchanging information. Telecommunication devices are terminals that allow users to run applications that communicate with other terminals through the information network infrastructure. The basic elements of an information network infrastructure are switches or routers that are connected by point-to-point links. Switches include fixed- and variable-rate voice-oriented circuit switches, low-speed (X.25) and high-speed (frame relay) data-oriented packet switches (routers), and ATM switches. The point-to-point links include a variety of fiber links, coaxial cables, twisted-wire pairs, and wireless connections.

To support transmission of voice, data, and video, several wired information network infrastructures have evolved throughout the past century. Wireless networks allow a mobile telecommunication terminal to access these wired information network infrastructures. At first glance it may appear that a wireless network is only an antenna site connected to one of the switches in the wired infrastructure, enabling a mobile terminal to be connected to the backbone network. In reality, in addition to the antenna site, a wireless network may also need its own mobility-aware switches and base station control devices in order to support mobility, that is, enabling a mobile terminal to change its point of connection to the network. Thus, a wireless network has a fixed infrastructure with mobility-aware switches and point-to-point connections, similar to other wired infrastructures, as well as antenna sites and mobile terminals.

Important examples of wireless networks are cellular telephone networks and wireless Internet access networks, which we discuss in greater detail in Section 1.2. There, we show how these networks extend the structure and services of existing wired networks to support either voice- or data-oriented wireless services

1.1.2 Key Technical Issues for Wireless Networks

As we can see in the two examples mentioned above, a wireless network includes not only the wireless terminals and radio-frequency (RF) links to fixed antennas, but also network elements and functions needed to support both interoperation with the existing fixed-wired networks and mobility for the wireless user. The set of characteristics of the wireless connection between the mobile terminal and a base station, including all the PHY- and MAC-layer details of access method, modulation, coding, and transmission formats, is commonly referred to as the *air interface*. Thus, we can say that the key technical issues for wireless networks are networking issues and air-interface design issues. Although these two sets of issues are not totally independent of each other, they are largely independent and can be treated separately. As we shall see in subsequent sections of the book, the networking issues relate primarily to interoperability between the wireless and wired infrastructures and to support of user mobility. On the other hand, air-interface issues relate primarily to the quality of service provided to wireless users and to efficiency in the use of available RF bandwidth.

1.1.3 Four Market Sectors

The market for wireless networks has evolved within four different segments that can be divided logically into two classes: the voice-oriented market and the data-oriented market. The *voice-oriented market* has evolved around wireless connection to the public switched telephone network. These services evolved further into local and wide area markets. The local voice-oriented market is based on low-power, low-mobility devices with a higher quality of voice, including cordless telephone, personal communication services (PCSs), wireless private branch exchanges, and wireless Telepoint. The voice-oriented wide-area market evolved around cellular mobile telephone services using terminals with higher power consumption, comprehensive coverage, and lower quality of voice. Figure 1.1*a* compares several features of these two sectors of the voice-oriented market.

The wireless *data-oriented market* evolved around the Internet and computer-communication network infrastructure. Data-oriented services can be divided into local

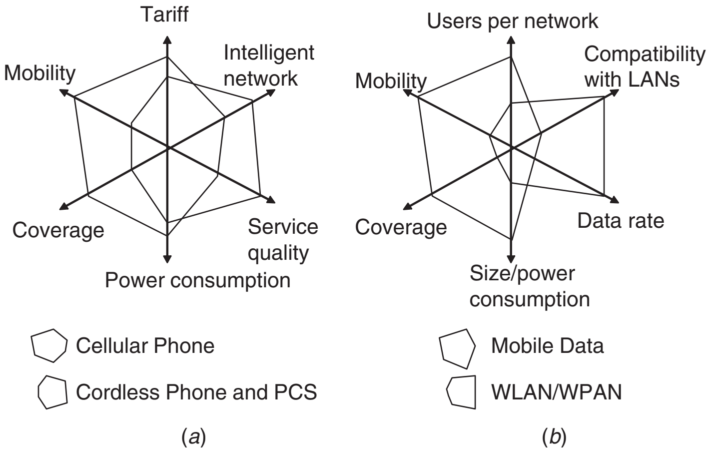

FIGURE 1.1 Wireless market sector comparisons: (*a*) voice-oriented networks; (*b*) data-oriented networks.

broadband and ad hoc markets on the one hand, and wide-area mobile data markets on the other. The wide-area wireless data market provides Internet access for mobile users. Local broadband and ad hoc networks include wireless LANs and wireless personal area networks (WPANs) that provide high-speed Internet access. The local and ad hoc networks will also support evolving ad hoc wireless consumer product markets. Figure 1.1*b* illustrates several differences among the local- and wide-area wireless data networks.

1.2 NETWORK ARCHITECTURE AND DESIGN ISSUES

Next we describe the principal system architectures for wireless networks and outline the key design issues that must be addressed in the design of these networks. These architectures and design issues are dealt with in detail in the remainder of the book.

1.2.1 Network Architectures

Here we consider two prominent examples of wireless networks: cellular telephone and wireless Internet.

Cellular Telephone. Figure 1.2 depicts wireless telephone service as an extension of the familiar *public-switched telephone network* (PSTN). The PSTN, designed to provide wired telephone services, is augmented with a wireless fixed infrastructure to support communication with mobile terminals. The mobile terminals communicate with the wireless fixed infrastructure via RF links to fixed antennas, each antenna connected to or integral with a *base station*. The PSTN infrastructure comprises switches, point-to-point connections, and computers used for operation and maintenance of the network.

The fixed infrastructure of the cellular telephone service has its own mobility-aware switches, point-to-point connections, and other hardware and software elements that

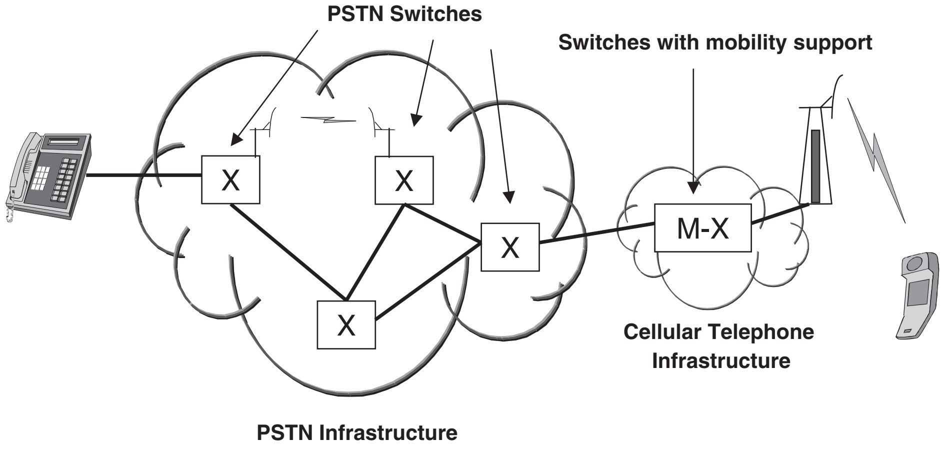

FIGURE 1.2 Cellular telephone infrastructure as an extension of the PSTN.

are needed for operation and maintenance of the mobile network. A wireless telecommunication device (e.g., a cordless telephone) can connect to the PSTN infrastructure by replacing the wire attachment with radio transceivers. However, for the wireless device to change its point of connection, switches in the PSTN must be able to support mobility. Switches in the PSTN infrastructure were not originally designed to support mobility. To solve this problem, a cellular telephone service provider adds its own fixed infrastructure with mobility-aware switches. The fixed infrastructure of the cellular telephone service provider is an interface between the base stations and the PSTN infrastructure that implements the functionality to support mobility. Just as a wired telephone service network needs added infrastructure to allow a mobile telephone to connect to the PSTN, a *wireless data network* needs its own added infrastructure to support wireless Internet access. Consider the next example.

Wireless Internet. Figure 1.3 shows the traditional wired data infrastructure together with an additional wireless data infrastructure that allows wireless connection to the Internet. The traditional data network consists of routers, point-to-point connections, and computers for operation and maintenance. The elements of a wireless network include mobile terminals, access points, mobility-aware routers, and point-to-point connections. This new infrastructure has to implement all the functionalities needed to support mobility.

The difference between the cellular telephone and wireless Internet examples is that the wireless network in Fig. 1.2 is a connection-based voice-oriented network, whereas the wireless network in Fig. 1.3 is a connectionless data-oriented network. A *connection-oriented operation* needs a setup procedure to connect the communicating terminals, and after the connection is established, a certain quality of service (QoS) is guaranteed to the user throughout the communication session. In *connectionless operation* there is no setup procedure and terminals are always connected to the network, in the sense that the communication session remains intact, but the QoS is not guaranteed. Instead, each protocol data unit (e.g., datagram or packet) is communicated between network access points on a best-effort basis. Common examples of connectionless protocols are the *Internet Protocol* (IP) and the *User Datagram Protocol* (UDP), both of

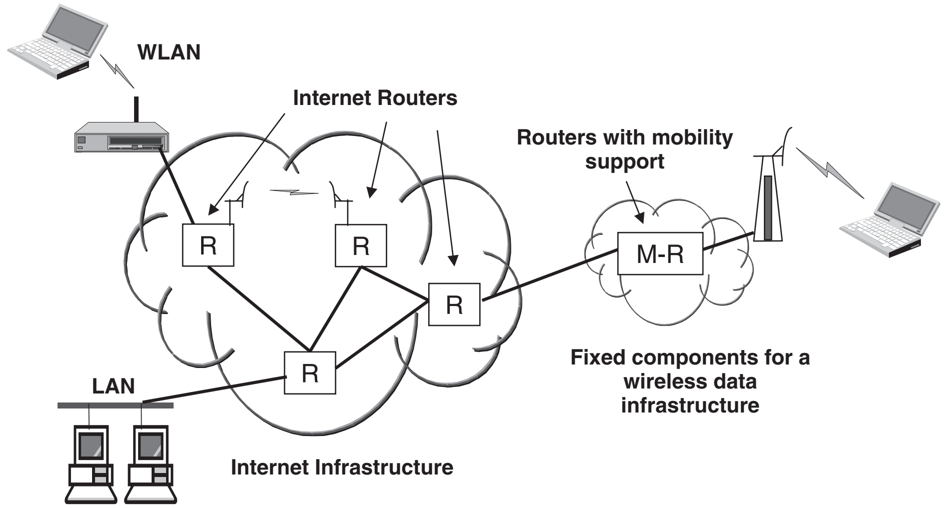

FIGURE 1.3 Wireless connectivity to the Internet.

which are used to support the *Transmission Control Protocol* (TCP), a transport-layer connection-oriented protocol, which in turn supports higher-layer protocols such as *Hypertext Transfer Protocol* (HTTP) and *Simple Mail Transfer Protocol* (SMTP). TCP is connection-oriented because a TCP session is set up and maintained for the full duration of a higher-layer session such as a Web-access session.

1.2.2 Wireless Versus Wired Networks

There are a number of fundamental differences between wired and wireless networks, essentially all stemming from the inherent characteristic of wireless communications (i.e., the replacement of fixed subscriber equipment connections by radio links). This freedom from the wired "tether" provides enormous advantages for customers of communications services but also introduces some new problems not encountered in traditional wired networks.

Perhaps the most important characteristic of wireless networking is that a radio link connecting the user's device to a wired network infrastructure is inherently less reliable than a fixed wired connection. This characteristic should be obvious and will be familiar to users of cellular phones who have experienced signal breakup and dropped connections on cellular phone calls. This inherent relative unreliability of radio links leads to a need for considerably more complexity in the physical-layer design than is required in traditional wired networks. Also, there is a need for *connection management* techniques as part of the solution to the radio-link reliability problem.

Another important characteristic of wireless communications is the fundamental limitation on the availability of frequency spectrum. For systems that operate in licensed frequency bands (cellular telephone service is the primary example), each service provider operates its network within a fixed band of frequencies, and means must be provided to manage the sharing of allocated bandwidth among a large number of users. Furthermore, as the service provider's subscriber volume grows, there must be means for expanding the overall capacity of the service network in an efficient manner to accommodate the growth in demand for service.

The bandwidth limitation problem also gives rise to the need for complexity in the design of source coding techniques (speech coding in the case of voice service, and other compression techniques in the case of multimedia transmission) so as to reduce the amount of bandwidth needed for each user channel signal while maintaining a prescribed level of signal quality as perceived by the user.

A very practical issue for users of mobile wireless devices is the necessary reliance on batteries, with the need for periodic recharging. This issue has led to the clever application of *power management* techniques in the design of mobile devices, so as to extend talk time and recharging cycles.

The inherent advantage of wireless networking—mobility for the user—adds complexity to the network design to manage changing the connection point to the fixed network infrastructure, including changes over both small and large geographical areas. This calls for greater complexity in *registration* and *call routing* techniques than are needed in wired networks, and a need for the use of both permanent and temporary addressing to support mobility.

Finally, the use of wireless transmission creates a vulnerability of the user's communications to eavesdropping and fraudulent intrusion into the network. Because of these problems, considerable attention has been given to providing *security* and *privacy* for wireless communications networks. Security provisions include such techniques as *authentication* to prevent unauthorized access to networks. Privacy provisions include the *encryption* of transmitted digital streams to prevent eavesdropping.

1.2.3 Elements of a Wireless Network Architecture

It is useful to consider the elements of a wireless network in four categories: services, infrastructure, protocols, and network engineering.

Services. From the perspective of the user of the network, the principal aspect of the network is the service or set of services the network is designed to support. In fact, the various industry efforts that lead to interoperability standards invariably begin with agreements among participants as to the array of services to be provided by the intended network standard, and considerable attention is given to the detailed features of those services and the specific ways in which the user's equipment will interact with the network in the operation of the service. Of course, the basic types of services are voice and data services.

In some networks, the voice services might comprise a menu of selectable digital data rates, the higher data rates providing a higher received voice quality at the cost of higher bandwidth requirement, accompanied by an appropriate tariff differential.

Data services may be provided in various forms, the simplest, called *data-bearer service*, being simple transport of data with minimal specification of data format at the mobile data port. Data service offerings might include a choice of transparent (T) or nontransparent (NT) data in either synchronous (clock-driven) or nonsynchronous (start/stop character-driven) formats. Transparent data service will employ forward-error correction coding at a fixed transmission rate in the channel. Nontransparent service will employ error-detection coding and retransmission of faulty data blocks so as to ensure greater accuracy in the delivered user data. Other options might include circuit-switched (connection-oriented) data versus packet (connectionless) service. Other, application-specific data services, such as Group-3 Facsimile service, will typically be offered with a set of optional data rates.

Short messaging service (SMS) is available in many cellular networks for transmission and reception of short text messages displayed on a small screen. The SMS messages are embedded in the control channels of the cellular network, which enables rapid delivery. A service that is growing rapidly, called *text messaging*, is built on SMS. As the demand for wireless multimedia service grows, data services are being provided at increasingly high data rates.

System Infrastructure. Provisioning of the various services in a wireless network in turn places requirements on hardware and software that must be included in the elements connecting the wireless service customer with the fixed networks. We need to consider two categories of system elements: the mobile terminal and the fixed wireless infrastructure that makes connection with the fixed network.

The mobile terminal is the user's device for sending and receiving signals over a wireless link. For a user requiring only basic voice service, the mobile terminal is the familiar cellular phone, nowadays probably a CDMA digital phone in the United States or a GSM phone in Europe and many other regions of the world. Many cellular phones are designed with a standardized data port for connecting to a portable computer or other data terminal. In supporting data connectivity, the cellular phone is functioning as a wireless modem interfacing baseband data (e.g., ASCII-formatted) with the wireless network. Currently, this wireless modem function is typically implemented in a circuit card to be plugged into a socket on a laptop computer, or even a card already mounted inside the laptop. As wireless networks evolve to support increasing capability for multimedia transmission, a variety of new mobile devices are appearing in the marketplace to support sending and receiving multimedia images.

Signals from the mobile user terminal arrive at an antenna that provides an RF interface to the fixed wireless infrastructure, and that infrastructure in turn provides an interface to the fixed wired infrastructure. In the case of cellular systems, the fixed wired infrastructure will typically be a public-switched telephone network (PSTN) or a public-switched data network (PSDN). In the case of WLAN systems, the fixed network will typically be a wired Ethernet LAN in an office building, office complex, or university campus.

In the case of cellular systems, the fixed wireless infrastructure includes antennas, radio base stations (BSs), mobile switching centers (MSCs), and terrestrial lines (typically, coaxial cable or optical fiber) to make connections among BSs and MSCs as well as between MSCs and the PSTN. The fixed wireless infrastructure will also include computers and a variety of instrumentation needed for operation and maintenance of the cellular network. All of the equipment and software in place, from the antennas to the PSTN connections, will be owned and operated by the cellular service provider. Currently, a cellular service company might have to deploy 50 to 100 BSs to provide satisfactory signal coverage over a major metropolitan area.

Functional partitioning between network equipment elements may vary from one manufacturer's equipment to another's, but in current cellular networks, the BS will typically include not only RF transmission and reception equipment but also speech coder/decoders (*codecs*). In such a configuration, all transmissions between the BS and the PSTN are in digital form. In such a configuration, the BS will also typically include *interworking functions* (IWFs), also called *modem emulators*, to modulate and demodulate the data streams in support of wireless data services. The MSCs include mobile-aware switches that provide for the setup and routing of call connections to and from mobile terminals and also handle the hand-off of call connections from one BS to another as mobile users move about the cellular service area. The MSCs also include the other hardware and software elements that are needed for mobile network operation, maintenance, and troubleshooting.

Wired Backbones for Wireless Networks. Since wireless networks depend heavily on the wired infrastructures to which they connect, in this section we provide a brief overview of the important wired infrastructures. The most commonly used wired infrastructures for wireless networks are PSTN, Internet, and hybrid fiber coax (HFC), originally designed for voice, data, and cable TV distributions applications, respectively. Figure 1.4 provides an overall picture of these three networks and how they relate to other wired and wireless networks. (A more detailed discussion of this topic can be found in [Pah02a].)

The main sources of information transmitted through telecommunication devices are voice, data, and video. Voice and video are analog in nature, whereas data traffic is digital. The dominant voice application is telephony, that is, a bidirectional symmetric real-time conversation. To support telephony, telephone service providers have developed a network infrastructure that establishes a connection for a telephone call

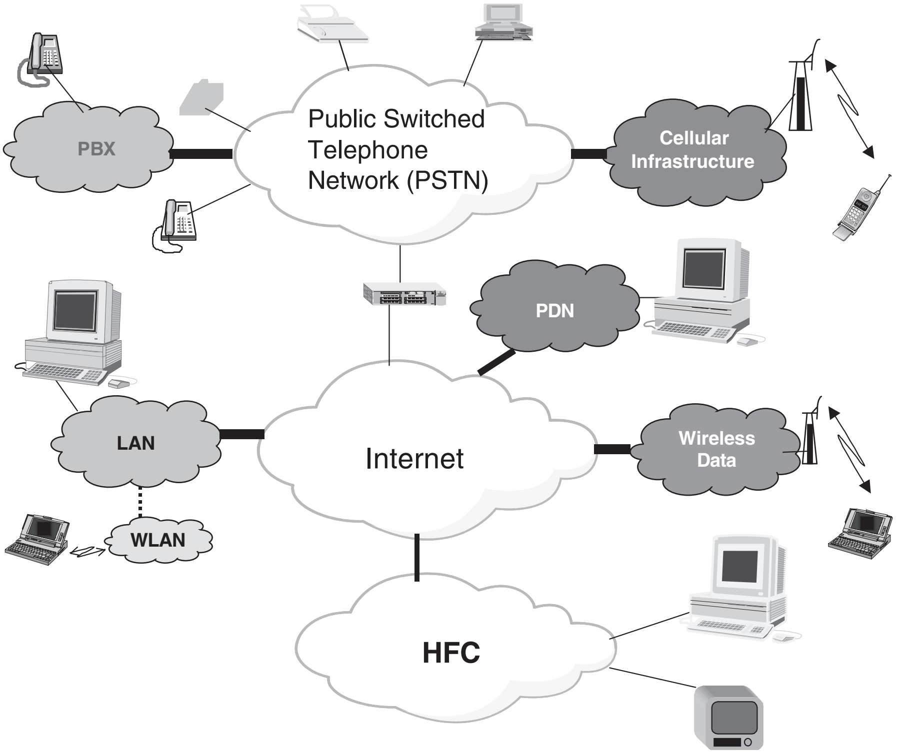

FIGURE 1.4 Interconnection of PSTN, Internet, and HFC.

during the dialing process and disconnects it after completion of the conversation. This network is referred to as the public switched telephone network (PSTN). As shown at the top of Fig. 1.4, the cellular telephone infrastructure provides wireless access to the PSTN. Another network attached to the PSTN is the *private branch exchange* (PBX), a local telephone switch owned privately by a business enterprise. This private switch allows privacy and flexibility in implementing additional services in an office environment. The PSTN physical connection to homes is twisted-pair wiring that is also used for broadband xDSL services. The core of the PSTN is a huge digital transmission system that allocates a 64-kb/s channel for each direction of a telephone conversation. Other network providers often lease the PSTN transmission facilities needed to interconnect their nodes.

The infrastructure developed for video applications is cable television, shown in the lower part of Fig. 1.4. This network broadcasts wideband video signals to residential premises. A cable goes from an end office to a residential neighborhood, and all customers are fed from the same cable. The set-top boxes leased by cable companies provide selectivity of channels, depending on the customer's service subscription. The end offices, where groups of distribution cables arrive, are connected to one another with fiber lines. For this reason, the cable TV network is also called *hybrid fiber coax* (HFC). Nowadays, cable distribution is also used for broadband residential access to Internet.

The data network infrastructure was developed for bursty data applications and evolved into the Internet, which supports Web access, e-mail, FTP, and Telnet applications as well as multimedia (voice, video, and data) sessions with a wide variety of session characteristics. The middle part of Fig. 1.4 shows the Internet and its relation to other data networks. From a user point of view, data-oriented networks are always connected, but they use the transmission resources only when a burst of information is to be transferred. Sessions of popular data communications applications such as Web browsing or FTP are often asymmetric, and a short upstream request burst results in downstream transmission of a large amount of data. Symmetric sessions such as IP telephony over data networks (termed *voice over IP*, or VoIP) are also becoming popular, providing an alternative to traditional telephony. Residential Internet access is a logical access that is physically implemented on other media, such as cable TV wiring or copper telephone lines. Distribution of the Internet in office areas is usually through Ethernet local area networks (LANs). Wireless LANs in offices are usually connected to the Internet through the wired LANs. Nowadays all other private data networks (PDNs), such as those used by banks or airline reservation agencies, are also connected to the Internet. The Internet also serves as the backbone for wireless data services.

Protocol Layering. Wireless communications networks, and cellular networks in particular, must accomplish many complex functions in order to establish call connections to and from mobile users, to implement the services to which each user has subscribed, to manage user authentication, and to provide mobility for wireless user terminals. As we have noted above, these tasks are performed in a number of mobile and fixed elements. At the same time, these networks must provide smooth interoperability among hardware and software elements supplied by a variety of manufacturers. In complex systems such as these, designers have found it beneficial to organize systems designs according to the concepts of *protocol layering*. Perhaps the best known model for protocol layering is the Open System Interconnect (OSI) seven-layer reference model, adopted as an international standard in 1978. In the OSI model, the lowest layer, layer 1, the physical layer, provides a physical medium for the flow of information across a link. The highest layer in the model, layer 7, the application layer, provides services to users of the network. In the intermediate five layers, the services provided move progressively away from the physical medium toward network- and application-related functions.

The basic concept of protocol layering is to manage the complexity of a network design by segmenting the system functions into a set of *layers*, each layer built on the ones below it. Each protocol layer can be described as performing specific *services* for the higher layers while isolating the higher layers from the details of how the services are actually implemented. The set of rules by which information is processed and formatted in any give layer constitutes a *protocol* for that layer. This assures, for example, that two pieces of equipment performing functions in the same layer can interoperate properly at that layer. A set of layers and their protocols is commonly referred to as a *network architecture*. A list of protocols used in a chosen system, one protocol per layer or sublayer, is referred to as a *protocol stack* [Gar00].

In all of the wireless networks we consider in this book, the system functions are organized according to some version of protocol layering. From one network standard to another, the functional segmentation into layers may be somewhat different. However, the functional segmentation will be the same for all hardware and software elements manufactured to each particular standard. For example, the GSM network architecture consists of five layers: transmission, radio resource management, mobility management, communication management, and operation, administration, and maintenance [Mou92, Meh97, Hei99]. As a second example, the IEEE 802.11 family of standards encompasses two layers: MAC and PHY [O'Ha99].

Traffic Engineering and Deployment. The cost of equipping and deploying a wireless communications network can vary widely depending on the type of network and the application for which it is intended. A WLAN might be installed in a business office or in a university campus building for a few thousand dollars. On the other hand, a cellular telephone network built to serve a metropolitan area might incur costs of tens of millions of dollars. However, regardless of the wireless technology employed or the intended application, principles of sound network engineering apply: The network should be designed to provide good signal coverage to wireless terminals over the intended floor, campus, or geographic service area with a reasonable expenditure of capital for equipment and installation.

In the case of a WLAN installation, *access points* (sometimes called *base stations*) will typically be installed on ceilings or high on walls in locations chosen to provide unobstructed signal coverage for some set of wireless terminals, such as desktop or laptop computers. Multiple access points will be installed to cover the total population of wireless terminals, typically with overlapping coverage areas to avoid gaps in coverage.

In the deployment of a cellular telephone network, the general principle of good network engineering is the same as for a WLAN deployment—install a number of cell sites in such a way as to provide unbroken signal coverage for mobile users over the geographic area in which the cellular company offers service. The cost of equipping and installing a single cell site might well be on the order of $1 or 2 million, including acquisition of real estate, and thus it is important that the cell site layout be designed to make optimum use of capital investment.

A key element in the planning of a wireless network is a specification of the traffic the network will be designed to handle. In the case of a WLAN design, we would want to know the number of wireless terminals and some statistics for the amount and type of traffic to be generated by the terminals. We would want to know the profile of short-message traffic, long file transfers, and so on, and the frequency of these transmissions. In other words, we would like to have a *traffic model* as a starting point for planning the network. With a traffic model in hand, and a specification of the traffic capacity of an access point, we can determine the number of access points to be provided. Then specifying the distribution of wireless user terminals will allow us to position the access points appropriately.

In the case of a cellular network deployment, the considerations are much the same, but with the important difference that users are highly mobile and that communication traffic patterns can change significantly from day to day and even from hour to hour. Commuters caught in a traffic jam or in a severe rainstorm will generate an unusually high volume of calls as they try to contact their co-workers or family members to revise their schedules. Fans at a Sunday afternoon football game will generate high volumes of communication traffic in the vicinity of the stadium. Another traffic characteristic specific to the cellular case is the relatively high frequency of call handoffs as users move about the service area. This contrasts with the typical relatively less frequent handoffs experienced in the WLAN environment. Thus, the efficient engineering of a cellular network must take account not only of average statistics of generated traffic but also of the potentially high variability of the traffic. Once again, a traffic model is needed, and the traffic model in the cellular case is likely to be considerably more complex than in the WLAN case. We shall have more to say about wireless network deployment in subsequent sections.

1.2.4 Technical Aspects of a Wireless Infrastructure

Next, we consider important issues that must be addressed in the design and operation of the wireless network infrastructure. These issues are often considered under the heading *network engineering*, as they are issues concerning the design and operation of the network as a whole.

Network Deployment Planning. In the preceding section we briefly discussed traffic engineering as a key element in network planning. With a traffic model, both temporal and geographic, as a starting point, the network engineer can begin to plan the layout of the access points or cell sites that will carry the wireless traffic to and from the fixed wired backbone network. This aspect of network planning is typically performed with the aid of *signal coverage prediction models*.

Signal coverage prediction models, usually based on a combination of radio-wave propagation theory and experimental measurements, provide the designer with a means of estimating the optimum placement of access points or cell sites for covering the intended area of user terminals with acceptable signal quality. A tutorial description of signal coverage in a wireless network with multiple access points or cell sites will typically illustrate signal coverage with a diagram of abutting hexagons or perhaps circles with some overlapping coverage areas. Those are both highly idealized descriptions that do not accurately represent the real world of wireless signal propagation and coverage. Even in a relatively benign office layout, planning for a WLAN installation must take account of the types and locations of office furniture and equipment, office partitions, walls, doorways, and so on, all of which can affect signal coverage. In a factory setting, even more complex situations might be encountered, with various metal surfaces, manufacturing machinery, and so on, all affecting signal propagation throughout the building. In the case of cellular telephone networks covering large service areas, signal coverage prediction models must take account of a wide range of factors, including terrain type (flat, hilly, mountainous), land use (rural, suburban development, city high-rise, urban canyon), and special situations such as roadways on high bridges and over-water propagation paths.

Some of the more sophisticated cellular network planning tools are elaborate software packages that incorporate time-varying traffic models, population distributions, cellular antenna types, optional propagation models, and call-handoff models in order to make accurate estimates of received signal quality for customers situated in various sectors of a service region. Even very sophisticated network planning tools can provide only an estimate of network performance, and a network engineer may well also conduct *drive tests* in selected regions of the service area in order to verify or refine computer-generated performance estimates.

Mobility and Location Management. An important requirement that users will place on wireless networks is mobility, freedom for the wireless user to maintain a reliable wireless connection while moving about an area that is relevant to the application. In the case of a WLAN system, users may want the capability to move their wireless terminals to different locations in an office building, factory, or campus without having to reregister with the network. Here, users are not likely to move about rapidly, and the problem is a relatively simple one. However, in the case of WANs such as cellular telephone networks, mobility is the *raison d'etre* of the technology and is the principal differentiator between traditional wired telephone networks and wireless networks. Users expect to be able to move about freely on foot, by automobile, or even traveling on trains, while enjoying seamless connectivity for their wireless communication. They also expect to be able to migrate from one cellular company's coverage region to another's, placing and receiving calls reliably in any region.

In traditional wired telephone networks, the subscriber's telephone is always wired to the same central office (CO) switch, and the network directs every incoming call to the subscriber's line using his or her telephone number. Outgoing calls are always made through the same local CO to which the subscriber is permanently connected. However, in a cellular network, the cell site to which the user connects when receiving a call depends on the user's physical location at that moment. In order for a subscriber to receive a call, the network must determine the cell in which the user is currently located. This is the essence of the *location management* problem, and this problem has been solved in cellular networks by designing location awareness into both the wireless and wired portions of a wireless network infrastructure.

An important facet of location management is *call handoff*, the process in which a user's call connection is transferred seamlessly from one serving cell to another as the user moves about the service area. This comes under the heading of what is known as *mobility management* in cellular systems. This is accomplished by a combination of signal strength measurements made in the releasing and the receiving cells, and coordination of frequency channels in the two cells, typically done under the control of a mobile switching center (MSC). Once again, this calls for a considerable amount of complexity in the design of the wired and wireless segments of the wireless network infrastructure.

Related to call handoff is the process of *roaming*, by which a user who has subscribed to particular services in his or her home area can travel to another service provider's region and use the same services. This feature greatly enhances the value of a wireless service to a subscriber by lessening geographic restrictions on his or her access to services. Roaming capabilities in cellular networks have been achieved by cooperation among service providers and among manufacturers, largely in the venue of standards bodies. Roaming requires the adoption of a standardized air interface, standardization of phone-type identification, and cooperation among the operators for transfer of location data between home and visited networks. Cooperation is also required in administrative areas such as transfer of calling charges and subscription information.

Radio Resource and Power Management. A characteristic of any wireless network is that it must operate within a strictly defined spectrum allocation. Radio spectrum is a limited resource, and regulatory agencies set specific spectrum allocations for different services. For example, a cellular network operator has a license for 25 MHz of bandwidth, 12.5 MHz for each direction of full-duplex communication. With a typical cellular reuse factor of 7, about 3.6 MHz of bandwidth is available for two-way traffic in each cell, and this bandwidth must be shared among active users in the cell. The bandwidth available is far less than what would be required if all subscribers in the network were to demand call connections simultaneously. This is in marked contrast to a wired telephone network, in which we may always add new subscribers to the network by installing additional local loops. (To be sure, there is an issue in equipping a wired telephone network in sizing the central office switches and the long-haul switches to ensure enough connections through the switches to meet expected call demand.) Thus, to ensure efficient sharing of the allocated spectrum, RF channels must be assigned and released dynamically, on a per-call basis.

Furthermore, directing a call from the wired network to a specific mobile subscriber is not a trivial procedure. Cellular networks reserve a portion of the allocated bandwidth for *control channels*, which are utilized in establishing and managing call connections. Paging messages are transmitted from cell sites, and a paging/response protocol is used to let the network determine which cell is currently the best one by which to reach the called subscriber. Only when this location determination has been made is an RF channel assigned for the call. All of these functions of assigning and managing the limited number of available RF channels come under the heading of *radio resource management*.

Another important element of radio resource management is *power management*. A cellular network is designed to operate under interference-limited conditions. That is, the dominant source of signal degradation in the network is interference from other active users of the network. With frequency reuse, the signal power radiated from a given cell is held to a sufficiently low level that the same subset of frequencies can be used simultaneously in another cell a reuse-separation distance away. In some cellular networks, power control is performed in both the base stations and the mobile phones. Power control at both ends of the wireless link helps to hold radiated power to a level sufficient to maintain good-quality communication without unduly increasing the overall interference level in the network.

Security. Although the use of wireless communications relieves the user of the wired tether to the public telephone network, with the enormous advantage of freedom of movement, the wireless medium also makes the user's communications vulnerable to eavesdropping and even fraudulent intrusion. In fact, when standards were being developed for digital wireless networks, a major benefit recognized for digital transmission was the facility it provided for the implementation of authentication and encryption techniques. All of the digital wireless interoperability standards have included procedures for authentication of users entering the network. With respect to the privacy problem, WLANs utilize spread-spectrum transmission, which has an inherent resistance to casual eavesdropping. Cellular networks based on CDMA are also using spread spectrum, providing inherently private transmission. In other cellular networks, such as GSM, encryption is provided in some operators' networks as a selectable feature. For communications that are particularly sensitive, some users may employ application-layer end-to-end encryption and use a wireless data service to carry encrypted traffic across the network. In this case, the user does not rely on the wireless network to provide security or privacy.

1.2.5 Technical Aspects of the Air Interface

If we examine the evolution of successive generations of wireless networks of any given type, say WLAN or WAN, the principal differences appearing from one generation to another lie in the details of the air-interface design, encompassing physical (PHY)- and medium access control (MAC)–layer designs. There is good reason for this: Improvements and new developments in PHY- and MAC-layer designs have yielded the most significant enhancements in communication quality and spectrum utilization in these networks. To assess the technical issues underlying the various alternatives for PHY- and MAC-layer designs and why certain choices have been made in the evolution of air-interface standards, it is necessary to begin with a good understanding of the RF medium for each type of wireless system. The fundamental characteristics of an RF transmission medium are summarized next.

Path Loss. As an RF signal radiates from a transmitting antenna to a receiving antenna, there is propagation path loss that attenuates the signal strength, the strength generally decreasing with distance along the path. In an idealized configuration, the loss could be calculated simply as free-space loss, which increases with the square of distance. However, in practical applications, the propagation path is rarely describable by the free-space model, and many other factors must be taken into account. Different factors will be important in different types of systems. For WLAN applications, where the spatial scale is on the order of room and building dimensions, one must account for structural elements and their properties as reflectors and absorbers of signal energy. For WANs such as cellular telephone networks, an even wider array of factors must be considered, and path loss is often difficult to compute theoretically. The path loss will typically be influenced by terrain type, land use, and sometimes by unique topological or architectural elements situated on or near a particular path. In all wireless networks, path loss also depends on the types of antennas used at both the mobile and fixed ends of the wireless link.

Multipath. For wideband signals as used in WLANs and some cellular networks, time dispersion, called *multipath*, must also be accounted for in modeling the propagation medium. As with path loss, multipath characteristics can vary widely from one type of network to another. Specific characteristics will vary with operating frequency, application setting (indoor versus outdoor), antenna coverage patterns, and structural or topological details of the coverage area. Furthermore, the ways in which multipath characteristics are described and measured will vary depending on the bandwidths of signals employed in each type of network. Given the wide variance among multipath characterizations for different types of networks, designers have tended to develop multipath modeling methods and databases that are specific to the individual types of networks under consideration. In some instances, standards-setting bodies have formalized sets of multipath models that manufacturers and service providers have agreed to use in development, testing, and evaluation of new wireless products. The chief example here is the Joint Technical Committee (JTC) of GSM, which has evolved standardized sets of multipath models, commonly termed *JTC models*, applicable to a variety of cellular propagation environments.

Fading. The third fundamental characteristic of an RF transmission medium is the presence of time variations in the strength of received signals, an effect usually referred to as *fading*. Signal fading can arise from a wide variety of causes, all of them related to dynamics of the propagation medium. Movements of WLAN terminals, or even movements of people, chairs, or doors, in the vicinity of WLAN signal paths, can cause variations in received signal strength. In a busy application environment such as a factory floor, there may be almost-constant movement of workers, vehicles, equipment, and materials, and all of these movements are potential sources of signal fading on WLAN paths.

In a cellular network, an obvious source of signal fading is the mobility of wireless users. When a cell phone is being operated in a moving automobile, or even by a pedestrian walking on a city street, the characteristics of the propagation path to the serving base station are changing constantly. Even if the wireless user is temporarily motionless, the movement of nearly vehicular traffic can result in signal fading.

Signal fading effects are closely related to multipath, discussed above, and in fact, most fading effects are due to the time-varying interaction of multipath signal components. That is, the time-dispersed signal components are typically affected individually by amplitude and phase fluctuations, and when these components are received together, there is an observed variation in the composite signal, commonly termed *multipath fading*. The multipath-fading phenomenon had been well understood for decades prior to the design of modern wireless networks, since it is a fundamental characteristic of long-distance radio propagation in HF, VHF, and UHF frequency bands (3 MHz to 3 GHz). The long-standing interest in utilizing digital transmission techniques in those high-frequency bands led, beginning in the 1950s, to development and refinement of signal-processing techniques such as *diversity combining*, spread-spectrum *RAKE receivers*, and *adaptive equalization* as means of ameliorating the effects of multipath fading in digital communication [Pri58]. Thus, those earlier developments were brought to bear in the PHY-layer designs of modern wireless networks, and there continues to be active research on new and better techniques for dealing with the multipath fading characteristics of wireless channels. Current examples of the fruits of this research include *orthogonal frequency-division multiplexing* (OFDM), *turbo equalization*, and *space-time coding* [Han02].

PHY- and MAC-Layer Alternatives. Most of the research in wireless networking technology in the past two decades has been directed toward advancements in PHY- and MAC-layer designs. Research on these aspects of wireless air interfaces has yielded steady improvements in performance quality and reliability as well as in the efficiency of utilization of spectrum. High quality of service builds customer satisfaction and healthy growth of the industry. Improved spectrum utilization translates directly into increased traffic capacity in the network, enabling greater per-user cost efficiency in the installation and operation of the network. The progression of successive generations of WLAN and WAN standards and products has in fact been characterized largely by advancements in PHY- and MAC-layer techniques.

A key element of PHY-layer design is the modulation technique, and the spectral efficiency afforded by each technique is critical. Thus, we have seen a steady progression of increasingly spectrum-efficient modulations in wireless networks. Access methods used in WANs have evolved from simple *frequency-division multiplexing* (FDM), through embedded digital control channels, to *code-division multiple access* (CDMA). The legacy analog cellular systems had utilized simple *frequency modulation* (FM) with *frequency-division multiplexing* (FDM) of user channels, a design much the same as had been used for decades in *land-mobile radio* (LMR) systems for taxicab fleets and public safety departments. The earliest digital cellular designs (second-generation cellular) saw the introduction of digital modulation techniques such as GMSK and $\pi/4$-QPSK together with *time-division multiplexing* of multiple digital traffic channels into TDMA frames, with various forms of control information embedded on a per-frame basis. TDMA transmissions were frequency-multiplexed into a FDM-TDMA signal design. The development of IS-95 for U.S. CDMA introduced spread-spectrum PSK modulation with code division as the access method, the combined techniques providing significant capacity enhancements relative to TDMA. Third-generation WAN standards will continue to build on CDMA designs, with higher-bandwidth signals and higher-data-rate services.

Since the 1997 adoption of IEEE 802.11 as the first international standard for WLANs, this standard, together with its subsequent modifications, had dominated the WLAN products industry. The initial 802.11 standard specifies a MAC layer and three PHY-layer options: (1) direct-sequence spread spectrum (DSSS) with both differential binary PSK (DBPSK) and differential quaternary PSK supported, (2) frequency-hopping spread spectrum (FHSS) with Gaussian FSK (GFSK) in either two- or four-level formats, and (3) infrared transmission using pulse position modulation (PPM), with two data rates supported. The 802.11–1997 MAC-layer protocol comprises two sublayers, the lower sublayer providing three access options. The basic access mechanism here is *carrier-sense multiple access with collision avoidance* (CSMA/CA).

Three enhancements of 802.11 have been standardized, designated as IEEE 802.11b and 802.11a, both ratified in 1999, and 902.11g, adopted in 2003. The 802.11a enhancement, which provides data rates up to 54 Mb/s, incorporates *orthogonal frequency-division multiplexing* (OFDM). The OFDM scheme divides the high-data-rate stream into several lower-rate streams. The lower-rate streams are then transmitted simultaneously on multiple subcarriers, producing longer symbol durations in the subchannels, thereby lessening the effect of multipath distortion. The OFDM technique is also employed in the HIPERLAN2 standard.

The IEEE 802.11b enhancement extends the 802.11 PHY layer using high-rate DSSS (HRDSSS). The 802.11b extension provides a modulation mode at 11 Mb/s using *complementary code keying* (CCK). The IEEE 802.11g extension operates at radio frequencies between 2.400 and 2.4835 GHz, the same band as that used by 802.11b. However, the 802.11g specification employs OFDM, the modulation scheme used in 802.11a to obtain higher data speed. Computers or terminals set up for 802.11g can fall back to speeds of 11 Mb/s.

The early mobile data networks ARDIS, Mobitex, and CDPD used PHY-layer modulation techniques that were much like those used in the digital cellular standards then under development. ARDIS used 4-ary FSK, whereas Mobitex and CDPD used GMSK. Since a high demand for those mobile data services never developed, there was little motivation to develop new PHY-layer designs for increased capacity. The MAC-layer protocols used in those original mobile data networks were relatively simple contention-based protocols, including data-sense multiple access (DSMA), slotted ALOHA, and digital-sense multiple access, which is closely related to CSMA with collision detection (CSMA/CD). In time, these mobile data services were subsumed under the cellular data services offered by the major cellular operators.

1.3 KEY TRENDS IN WIRELESS NETWORKING

Now that we have outlined the key characteristics of wireless information networks, it will be useful to summarize the trends to be observed in the continuing evolution of wireless technology. Let us look separately at voice- and data-oriented networks.

1.3.1 Voice-Oriented Networks

From the first-generation starting point of legacy analog cellular networks, second-generation voice-oriented networks introduced a digital air interface, in part to facilitate the introduction of digital data services and other new features and services, but also to expand network capacity over that provided by the legacy analog networks. The introduction of CDMA and third-generation wideband CDMA then provided improved voice quality and system capacity and also met the growing demand for higher data rates. As fourth-generation designs develop and evolve, we will probably see introduction of the use of space-time diversity techniques and multiple-input multiple-output (MIMO) antennas in the air interface, paving the way for further quality and capacity improvements beyond the third-generation systems.

1.3.2 Data-Oriented Networks

The 1997 ratification of the IEEE 802.11 standard was a major milestone in the WLAN industry. The 10-year standardization effort not only produced an international standard assuring product compatibility among WLAN manufacturers, but the project also provided good solutions to some difficult problems that had to be faced in creating wireless extensions to the then-ubiquitous wired LANs. The 802.11 standard dealt with mobility, link reliability management, power management, interference minimization, and security. While the initial standard did not provide data rates as high as then-standard 10-Mb/s Ethernet over wired LANs, the 1- to 2-Mb/s wireless rates met the needs of many users, who welcomed the mobility afforded by WLAN technology despite the data-rate limitations. The demand for higher data rates was inevitable, of course, and subsequently, the IEEE was able to issue the 802.11a (rates up to 54 Mb/s), 802.11b (rates up to 11 Mb/s), and 802.11g (rates up to 54 Mb/s) enhancements, based on the solid foundation of 802.11, the higher data rates achieved through use of the OFDM and CCK modulation schemes. Now appearing on the horizon is *ultrawideband* (UWB) pulse transmission, which offers promise of further increases in data rates and coexistence of even larger numbers of simultaneous users.

1.3.3 Where Is the Complexity?

As we indicated earlier, the complexity of radio propagation and its variability from one deployment situation to another pose major challenges in the design of efficient wireless information networks. The fundamental design objective will be to provide good signal coverage and reliable, high-quality service on each link. Thus, the designer must focus on air-interface performance, which in turn places emphasis on PHY- and MAC-layer designs. Because of this, research must continue to address a variety of complex signal-processing techniques, including new time, space and frequency diversity techniques, with the objective of achieving steadily higher data rates, better service quality, and increased spectrum utilization.

Related technologies are being pursued as well, including wireless positioning and optical communications. Wireless positioning is a particular example of new technology that is affected critically by the complexity of the radio propagation environment, and we can expect that increasingly sophisticated propagation modeling techniques will be required as this area of application becomes more important.

1.4 OUTLINE OF THE BOOK

The book is organized into four parts, each focused on a different aspect of wireless information networks.

Part I, Chapters 1 and 2, provides an introduction to wireless information networks. In Chapter 1 we provide an overview of wireless networks, principal design issues, and current trends in the evolution of these networks, and in Chapter 2 we outline the evolution of the wireless industry.

Part II, Chapters 3 to 6, deals with characterization of radio propagation, channel measurement and modeling for narrowband signaling, measurement of wideband channel characteristics, and computer simulation of radio channels. Both indoor and outdoor wireless channels are considered.

Part III, Chapters 7 to 10, deals with modem design, addressing many details of the underlying signal-processing functions employed in wireless networks. Chapter 7 deals with narrowband modem technology, Chapter 8 deals with diversity and coding techniques used to improve communication reliability in wireless channels, Chapter 9 deals with broadband modem technologies, and Chapter 10 deals with spread-spectrum and UWB systems.

Part IV, Chapters 11 to 15, deals with MAC-layer design, ultrawideband communications, geolocation technology, and optical wireless networks, and provides a current summary of important standards and systems.

QUESTIONS

(a) Consider a digital cellular network giving customers wireless access to the PSTN using their cell phones. What essential functions must be performed by the cellular equipment in carrying a voice signal arriving from the PSTN to a customer's cell phone?

(b) Why do all digital cellular systems employ methods of speech compression?

(c) Describe the phenomenon of multipath fading, and describe a few scenarios in which this effect can be expected in a wireless call connection in a wide-area cellular network. Next, describe a few scenarios applicable to indoor communication over a wireless LAN.

(d) How would you distinguish the traffic characteristics observed in a voice-oriented wireless network from those of a data-oriented network?

(e) Why is accurate modeling of radio-wave propagation important in the planning of a cellular service network?

(f) What technical and economic factors are most likely to cause a shift in dominance among competing digital cellular standards?

(g) Digital cellular standards include specifications of interfaces between major elements of each system. Why are these interface specifications important to (1) cellular network operators, (2) cellular equipment manufacturers, and (3) cellular service customers?

(h) What advantage do you see in the fact that all versions of the IEEE 802.11 standards for WLANs share the same MAC-layer protocol?

(i) What in your view is the major factor accounting for the resurgence in popularity of WLAN networking?

(j) Discuss and compare the issues involved in expanding capacity in the PSTN versus expanding capacity of a cellular network.