1 Wireless communications systems

Wireless communications technology has become a key element in modern society. In our daily life, devices such as garage door openers, TV remote controllers, cellular phones, personal digital assistants (PDAs), and satellite TV receivers are based on wireless communications technology. Today the total number of users subscribing to cellular wireless services have surpassed the number of users subscribing to the wired telephone services. Besides cellular wireless technology, cordless phones, wireless local area networks (WLANs), and satellites are being extensively used for voice- as well as data-oriented communications applications and entertainment services.

In 1895, Guglielmo Marconi demonstrated the feasibility of wireless communications by using electromagnetic waves. In 1906, the first radio broadcast was done by Reginald Fessenden to transmit music and voice over the air. In 1907, the commercial trans-Atlantic wireless transmission was launched. In 1946, the first public mobile telephone systems were introduced in several American cities. The first analog cellular system, the Nordic Mobile Telephone System (NMT), was introduced in Europe in 1981. In 1983, the first cellular wireless technology, the advanced mobile phone system (AMPS), was deployed for commercial use. During the last two decades there has been significant research and development in wireless communications technology. In fact, today it has emerged as the most flourishing branch of development in the area of telecommunications.

The various wireless communications systems available today differ in terms of data rate of transmission, geographical coverage area, transmission power, and mobility support for users. Wireless communications systems can be broadly categorized as follows:

- *high-power wide area systems (or cellular systems)*, which support mobile users roaming over a wide geographic area;
- *low-power local area systems*, for example cordless telephone systems, which are implemented with relatively simpler technology;
- *low-speed wide area systems*, which are designed for mobile data services with relatively low data rates (e.g. paging systems);
- *high-speed local area systems*, which are designed for high speed and local communications (e.g. wireless LANs).

The first two categories are voice-oriented systems while the remaining two are data-oriented systems. Although different types of wireless systems have different

Table 1.1 Radio frequency bands.

	Designation	Frequency
ELF	Extremely low frequency	3 Hz–30 Hz
SLF	Superlow frequency	30 Hz–300 Hz
ULF	Ultralow frequency	300 Hz–3000 Hz
VLF	Very low frequency	3 kHz–30 kHz
LF	Low frequency	30 kHz–300 kHz
MF	Medium frequency	300 kHz–3000 kHz
HF	High frequency	3 MHz–30 MHz
VHF	Very high frequency	30 MHz–300 MHz
UHF	Ultrahigh frequency	300 MHz–3000 MHz
SHF	Superhigh frequency	3 GHz–30 GHz
EHF	Extremely high frequency	30 GHz–300 GHz

transmission rate, power, coverage, and mobility requirements, similar challenges exist for the design and implementation of these systems. These challenges include radio resource allocation/management and medium access control, rate control, handoff and mobility management, quality of service (QoS) provisioning, and security. This chapter intends to provide an introduction to the different wireless communications and networking technologies, to cover the basics of spectrum management, and the radio propagation characteristics and channel models for wireless communications, and finally to summarize the common research challenges in wireless communications systems.

1.1 Radio frequency bands and spectrum management

1.1.1 Radio frequency bands

Wireless communications systems are built based on the transmission of electromagnetic waves (i.e. radio waves) with frequencies in the range 3 Hz–300 GHz. These radio waves are transmitted and received through antennas which transform the radio frequency electrical energy to electromagnetic energy and vice versa. Radio waves with different frequencies have different propagation characteristics, each of which is suitable for a specific wireless application. For example, low-frequency radio waves are suitable for long-range communications and high-frequency radio waves are more suitable for short-range but high-speed wireless communications. The frequency of radio waves can be divided into different groups/bands as shown in Table 1.1.

Various wireless applications and services use different radio frequencies (Table 1.2). For example, 535 kHz–1.7 MHz is used for AM radio transmission, 54 MHz–88 MHz and 470 MHz–800 MHz are used for television (TV) signal transmission, and 88 MHz–108 MHz is used for FM broadcast.

1.1.2 Spectrum management

Interference can occur when radio waves are transmitted simultaneously from multiple sources over the same frequency. Frequency/spectrum management is required to

Table 1.2 Licensed spectrum allocations in the USA.

Service/system	Frequency
AM radio	535–1605 KHz
FM radio	88–108 MHz
Broadcast TV (channels 2–6)	54–88 MHz
Broadcast TV (channels 7–13)	174–216 MHz
Broadcast TV (UHF)	470–806 MHz
Broadband wireless	746–764 MHz, 776–794 MHz
3G wireless	1.7–1.85 GHz, 2.5–2.69 GHz
1G and 2G cellular	806–902 MHz
Personal communications systems	1.85–1.99 GHz
Wireless communications service	2.305–2.32 GHz, 2.345–2.36 GHz
Satellite digital radio	2.32–2.325 GHz
MMDS	2.15–2.68 GHz
Satellite TV	12.2–12.7 GHz
LMDS	27.5–29.5 GHz, 31–31.3 GHz
Fixed wireless services	38.6–40 GHz

control the transmission of radio waves to avoid interference among wireless users. Traditional spectrum management techniques, as defined by the Federal Communications Commission (FCC), are based on the command-and-control model. In this model, radio frequency bands are licensed to the authorized users by the government. The common method for allocation is referred to as a “spectrum auction.” In a spectrum auction, the government opens a radio frequency band for bidding and could specify a certain type of wireless technology/application for this particular radio frequency band (e.g. TV or cellular service). Any user/company interested in using this radio frequency band submits the bid (e.g. the amount of money it is willing to pay to the government to obtain the license). The government (i.e. the auctioneer) determines the winning user/company, which is generally the user/company offering the highest bid. The licensed user is authorized to use the radio frequency band under certain rules and regulations (e.g. etiquette for spectrum usage) specified by the government. The duration of the license issued to an authorized user is also determined by the government. While most of the spectrum is managed under this command-and-control scheme, there are some spectrum bands that are reserved for industrial, scientific, and medical purposes, referred to collectively as the industrial, scientific, and medical (ISM) radio band. This ISM band can also be used for data communication. However, since there is no control on this ISM band, the data communication could be interfered with by any ISM equipment. The allocation of this ISM band is shown in Table 1.3.

This command-and-control-based spectrum management framework can guarantee that the radio frequency spectrum will be exclusively licensed to an authorized user (i.e. licensee) who wins the radio frequency bidding and can use the spectrum without any interference. However, this command-and-control model can cause inefficient spectrum usage, as shown in the report from the spectrum Policy Task Force (SPTF) of the FCC in 2002 [4]. The spectrum management inefficiency arises due to the fact that an authorized user may not fully utilize the spectrum at all times in all locations. Also,

Table 1.3 Unlicensed spectrum allocations in the USA.

Band	Usage	Frequency
ISM band I	Cordless phones, 1G WLANs	902–928 MHz
ISM band II	Bluetooth®, 802.11b, 802.11g WLANs	2.4–2.4835 GHz
ISM band III	Wireless PBX	5.725–5.85 GHz
U-NII1 band I	Indoor systems, 802.11a WLANs	5.15–5.25 GHz
U-NII band II	Short-range outdoor systems, 802.11a WLANs	5.25–5.35 GHz
U-NII band III	Long-range outdoor systems, 802.11a WLANs	5.725–5.825 GHz

regulatory requirements put limitations on the wireless technology that can use the licensed spectrum, and this may prevent an authorized user from changing their wireless transmission techniques and services according to market demand.

To meet the spectrum demand of emerging wireless applications/services, there was a request to FCC to change the spectrum management policy to make it more flexible. The recommendations to change the spectrum management policy are as follows [5]: (1) improve flexibility of spectrum usage; (2) take all dimensions and related issues of spectrum usage into the policy; and (3) support and encourage efficient use of the spectrum. The objectives behind these recommendations were to improve both the technical and economic efficiency of spectrum management. From a technical perspective, spectrum management needs to ensure the lowest interference and the highest utilization of the radio frequency band. The economic aspects of spectrum management relate to the revenue and satisfaction of the spectrum licensee. To achieve economic efficiency, an economic model needs to be integrated into the spectrum management framework. Pricing is an important issue to achieve efficient spectrum management. The spectrum owners or service providers can compete or cooperate with each other in offering prices to the wireless service users to achieve the highest revenue. In this regard, service providers may be required to provide a quality-of-service (QoS) guarantee to users.

Different spectrum management models have been introduced in the literature for different radio frequency bands and different wireless applications [5]. These spectrum management models have improved the flexibility of spectrum usage and have also opened up new opportunities for the different wireless technologies to utilize the radio spectrum more efficiently. To exploit these opportunities, the wireless transceivers need to be more intelligent to access the radio spectrum. Such an intelligent wireless transceiver is referred to as a *cognitive radio*. The analysis and design of smart spectrum access techniques by cognitive radio is the main focus of this book.

1.2 Wireless protocols

In wireless communications, one of the most important components is the protocol. In this case, the communication system is divided into subsystems, i.e. layers. Different protocols are used in different layers for different tasks. Data is transferred among

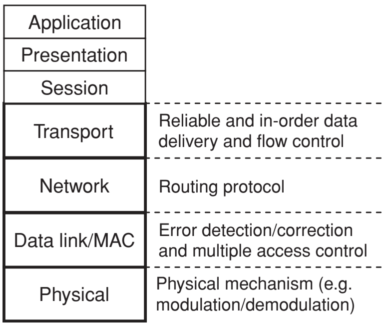

Figure 1.1 Protocol stack.

the layers and processed by the corresponding protocols, which specify the rules or conventions for such transfer (i.e. data transmission and reception). The protocol in a particular layer relies on the protocol in the lower layer to perform more primitive functions. Also, this protocol provides services to protocols in the higher layer. According to the open systems interconnection (OSI) model, the five important layers of wireless communications are as follows (Figure 1.1):

- *Physical layer*: Protocols in this layer provides a physical mechanism for transmitting signal bits between the transmitter and receiver. In wireless systems, protocols in this layer perform the modulation and demodulation of electromagnetic waves used for transmission.
- *Data-link layer*: Since the wireless links can often be unreliable, one function of the data-link layer is to perform error detection and/or correction. A part of the data-link layer, called the medium access control (MAC) sublayer, is responsible for allowing data packets to be sent over the shared media without undue interference with other transmissions. This aspect is referred to as multiple-access communications.
- *Networking layer*: Protocols in this layer (i.e. routing protocols) are responsible for determining the routing of data from the source to its destination. The Internet protocol (IP) is the default protocol at this layer to provide the routing function across multiple networks. Since the end systems can be mobile, and therefore the associations among the nodes continually changing, wireless systems place greater demand on the network layer.
- *Transport layer/host-to-host layer*: This layer is responsible for reliable and in-order data delivery on an end-to-end basis and flow control in the network to ensure that the network does not become congested. The most commonly used protocol in this layer is the transmission control protocol (TCP). TCP was primarily designed for wired networks for end-to-end transmission rate control. This protocol needs to be modified to achieve satisfactory performance in a wireless communication environment.
- *Application layer*: Protocols in this layer contain the logic needed to support the various user applications. For each different type of application, such as file transfer or Internet browsing, a separate module is required which is peculiar to that application.

There are three basic components in the physical layer, i.e. transmitter, channel, and receiver. The transmitter is responsible for taking the information bits from the information source and converting it into a form that is suitable for wireless transmission. The transmitter shapes and modulates the signal so that it can pass reliably through the channel, while efficiently using the limited transmission medium resources (i.e. the radio spectrum). The channel is a medium for transporting the signal produced by the transmitter to the receiver. In wireless systems, the channel impairments include channel distortion, which may take the form of multipath, i.e. constructive and destructive interference between many received copies of the same transmitted signal. The channel characteristics are usually time-varying, due to either mobility of the users or changes in the propagation environment. Interference and noise impact the quality of transmission in a wireless medium. This interference is produced (accidentally or intentionally) by other sources whose output signals occupy the same frequency band as or an adjacent band to the transmitted signal. On the other hand, receiver noise is produced by the electronic components in the receiver. After the signal is transmitted over the channel, the receiver receives it and produces an estimate of the transmitted signal (or information bit). In wireless systems, the receiver frequently estimates the time-varying nature of the channel in order to implement compensation techniques. The system also implements error detection and/or error correction techniques to improve the reliability of the wireless channel.

In the data-link layer, an error detection mechanism is used to detect the error in the received data which is caused by noise and interference. In addition, an error correction mechanism will provide an ability to correct the erroneous data. For error correction, an automatic repeat-request (ARQ) protocol and/or a forward error correction (FEC) coding mechanism can be used. With ARQ, the transmitter sends the data using an error detection code, for example the cyclic redundancy check (CRC) code. The receiver checks the received data for error, and requests retransmission if an error is detected. However, if there is no error detected, the receiver will send an acknowledgement (ACK) to inform the transmitter of successful data reception. With FEC, the transmitter encodes the data with an error correcting code (ECC). The coded data is transmitted to the receiver. The receiver checks the received data. If an error is detected, the receiver will attempt to correct the error in the original data by using the ECC.

The MAC protocol describes the method for multiple wireless users to share the channel. Four different methods for multiple-access communications are as follows:

- *Frequency-division multiple access (FDMA)*: The spectrum is shared by assigning specific frequency channels to specific users on either a permanent or a temporary basis.
- *Time-division multiple access (TDMA)*: All users are allowed to access all of the available spectrum, but users are assigned specific time intervals during which they can access it, on either a temporary or a permanent basis.
- *Code-division multiple access (CDMA)*: Users are allowed to use the available spectrum, but their signal must be spread (encrypted) with a specific code to distinguish it from other signals.

- *Space-division multiple access (SDMA)*: The spectrum is shared among the users by exploiting the spatial distribution of users' mobiles through the use of smart directional antennas that minimize the interference between users' mobiles.

1.3 Radio propagation characteristics and channel models

1.3.1 Radio propagation

For transmission of a wireless signal, radio frequency electrical energy from the transmitter is converted into electromagnetic energy by the antenna and radiated into the surrounding environment. For reception of a signal, electromagnetic energy impinging on the antenna is converted into radio frequency electrical energy and fed into the receiver. The quality of the received signal depends heavily on the radio propagation characteristics. This radio propagation is generally site-specific and can vary significantly depending on the terrain, frequency of operation, velocity of the mobile terminal, interference sources and other dynamic factors. Also, the radio propagation depends on the frequency of operation. At lower frequencies (<500 MHz) in the radio spectrum, the signal strength loss is less than that of higher frequency. However, due to the larger wavelengths, the antenna size for communications equipment operating in the lower frequency bands should be larger. On the other hand, at higher frequencies, it is possible to use low power transmitters (of about 1 W) to provide adequate signal coverage over, for example, a few floors of a multistorey building or a few kilometers outdoors in a line-of-sight (LOS) situation. The antenna sizes are also of the order of an inch, which means that the design of transmitters and receivers can be compact and requires lower power.

Radio propagation in open areas is very different from radio propagation in indoor and urban areas. In open areas across small distances or free space, the signal strength falls as the square of the distance. In other terrain, the signal strength often falls at a much higher rate as a function of distance depending on the environment and radio frequency. In urban areas, the shortest direct path (LOS path) between transmitter and receiver is usually blocked by buildings and other terrain features. Similarly, walls, floors, and other objects within buildings obstruct LOS communications. Such scenarios are called non-LOS (NLOS) or obstructed LOS (OLOS) scenarios, where the signal is usually carried by a multiplicity of indirect paths with various signal strengths. The signal strengths of NLOS and OLOS paths depend on the distance they have traveled, the obstacles they have reflected from or passed through, and the location of objects around the transmitter and the receiver. Because signals from the transmitter arrive at the receiver via a multiplicity of paths, with each taking a different time to reach the receiver, the resulting channel has an associated multipath delay spread that affects the reception of data. The maximum data rate that can be supported by a channel is affected by the multipath structure of the channel and the fading characteristics of the multipath components. The rate of fluctuations in the channel is referred to as the Doppler spread of the channel. This fluctuation is caused by the movement of the transmitter, receiver, or objects in between, and influences the signaling scheme and the receiver design.

The basic channel propagation mechanisms can be summarized as follows [6]:

- *Free-space or line-of-sight (LOS) propagation:* This mechanism corresponds to a clear transmission path between the transmitter and the receiver. Satellite communications generally rely on line-of-sight paths between the transmitter and satellite, and between the satellite and receiver.
- *Reflection:* This situation arises when electromagnetic waves are incident upon a surface with dimensions that are very large compared to the wavelength. Upon reflection or transmission, a ray attenuates by factors that depend on the frequency, the angle of incidence, and the nature of the medium (e.g. material properties, thickness, homogeneity, etc.). This phenomenon often dominates radio propagation in indoor applications.
- *Diffraction:* When electromagnetic waves are forced to travel through a small slit, they tend to spread out on the far side of the slit. This is referred to as diffraction. Due to diffraction, electromagnetic waves can bend over hills and around buildings to provide communications. Electromagnetic waves that are incident upon the edges of buildings, walls, and other large objects can be viewed as secondary sources. This can result in propagation into shadowed regions, since the diffracted field can reach the receiver, even though it is not in the line of sight of the transmitter. However, this secondary source suffers a much greater loss than that experienced via reflection or direct transmission. Consequently, diffraction is an important phenomenon outdoors, where signal transmission through buildings is virtually impossible. It is less important in indoor scenarios, where the diffracted signal is extremely weak compared to a reflected signal.
- *Scattering:* Irregular objects, such as walls with rough surfaces and furniture (indoors), and vehicles, foliage, and so on (outdoors), scatter rays in all directions in the form of spherical waves. Propagation in many directions results in reduced power levels, especially far from the scatterer. As a result, this phenomenon is not that significant unless the receiver or transmitter is located in a highly cluttered environment.

The importance of these three propagation mechanisms depends on the particular propagation scenario. As a result of reflection, diffraction, and scattering mechanisms, radio propagation can be roughly characterized by three nearly independent phenomenon: path loss variations with distance, slow log-normal shadowing, and fast multipath fading.

The channel can be characterized in the large and small scales. A large-scale propagation model characterizes signal strength over large transmitter–receiver separation distances and predicts the mean signal strength. As the mobile moves away from the transmitter, the local average received signal will gradually decrease and can be predicted by large-scale propagation models. A small-scale propagation model or fading model characterizes the rapid fluctuations of the received signal strength over very short travel distances (a few wavelengths) or short time durations (of the order of seconds). As a mobile moves over very small distances, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading since the received signal is a sum of many contributions coming from different directions. In small-scale fading, the received signal power may vary by as much as three or four orders of magnitude (30 or 40 dB) when the receiver is moved by only a fraction of a wavelength.

1.3.2 Channel models

Accurate characterization of the radio channel through key parameters and mathematical models is important for predicting signal coverage, achievable data rates, and the specific performance attributes of alternative signaling and reception schemes. This channel model can be used to analyze the interference in different systems, and determine the optimum locations for installing base station antennas.

Large-scale channel model

For large-scale radio propagation, channel models for wireless communications take one of two forms: physical models and statistical models. In physical models, the exact physics of the propagation environment is captured in which the site geometry has to be taken into consideration. Although this physical model provides the most reliable estimates of propagation behavior, it is computationally intensive. On the other hand, a statistical model is based on measuring the propagation characteristics in a variety of environments. The channel model is built by considering the measured statistics for a particular class of environments. These statistical models are easier to describe and to be used than the physical models, but do not provide the same accuracy.

In the physical approach, a model of the environment is built up which includes the terrain, buildings, and other features that may affect radio propagation. With this physical model, the possible propagation paths are determined. This process is referred to as ray tracing. For the different paths, the path losses between the transmitter and the receiver are estimated.

When the transmitter and the receiver have an LOS path between them, the free-space propagation model is used. With this model, the relationship between the transmit power and received power is given by

$$P_{\mathrm{r}}(d) = \frac{P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}} \lambda^2}{(4\pi d)^2 L},$$

where d is the separation between transmitter and receiver antennas (in meters), G_{t} is the transmitter antenna gain, G_{r} is the receiver antenna gain, L is the system loss factor not related to propagation (e.g. filter losses, antenna losses; $L \geq 1$), λ is the wavelength of the transmitted signal in meters, $G = \frac{4\pi A_{\mathrm{e}}}{\lambda^2}$, where A_{e} is the effective aperture of the antenna ($= \lambda^2/(4\pi)$, for isotropic antenna), $\lambda = \frac{c}{f}$ (c = light speed, m/s; f = carrier frequency, Hz). This model is valid for values of d which are in the far-field of the transmitting antenna. The far-field or Fraunhofer distance of a transmitting antenna is given by: $d_f = \frac{2D^2}{\lambda}$, D = Largest physical linear dimension of the antenna.

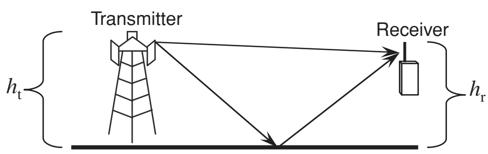

Figure 1.2 Two-ray channel model.

For the free-space propagation model, with $L = 1$, since $\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda^2}$, the signal attenuation (or path loss) is given by

$$\overline{P}_L(dB) = 10\log(A) + 20\log(d) - 20\log(\lambda),$$

where $A = \frac{(4\pi)^2}{G_t G_r}$. That is, for the same antenna dimensions and separation, the lower the carrier wavelenth λ (i.e. the longer the carrier frequency f), the higher is the free space path loss. Note that the received power in free space in terms of received power at a reference point d_0 is given by

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2, \quad d \geq d_0 \geq d_f.$$

A simple two-path model for an outdoor environment can be used to illustrate the effect of transmitting and receiving antenna heights. Here, the base station and the mobile terminal are both assumed to be at an elevation above the earth, which is modeled as a flat surface in between the base station and the mobile terminal (Figure 1.2). Usually there is an LOS component between the base station and the mobile terminal which carries the signal as in free space. There will be also another path over which the signal travels that consists of a reflection off the flat surface of the earth. The two paths travel different distances based on the height of the base station antenna, h_t, and the height of the mobile terminal antenna, h_r, and result in the addition of signals either constructively or destructively at the receiver.

The relationship between the transmit power and the received power for the two-ray model can be approximated by:

$$P_r(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}, \tag{1.1}$$

where P_r and P_t are respectively the receive and transmit power, G_r and G_t denote respectively the antenna gains of the receiver and transmitter, and d is the distance between the transmitter and receiver [6].

In the statistical approach, the propagation characteristics are empirically approximated on the basis of measurements in certain general types of environments, such as urban, suburban, and rural environments. The statistical approach is broken down into two components: a component based on the estimate of the average path loss and a component representing local variations. The average large-scale path loss for an arbitrary transmitter–receiver separation d is given by [6]:

$$\overline{P}_L(d) = \overline{P}_L(d_0) + 10n\log\frac{d}{d_0}, \tag{1.2}$$