978-1-107-10249-1 — Radio Resource Management in Wireless Networks
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Part I

Basics of Wireless Networks

1 Introduction

1.1 Basics of a Wireless Communication System

Wireless connectivity is one of the most prominent features of modern communications. A basic wireless communication system consists of three main components: transmitter, wireless medium, and receiver. The transmitter transforms the information into physical signals and transmits it over a transmission medium. The wireless medium, which is also called the communication channel, carries the signal, e.g., the free space carries the electromagnetic waves. The receiver receives physical signals from the medium and converts them into information. Usually, the medium corrupts and distorts the transmitted signal. The aim of any communication system is to obtain the transmitted information at the receiver with the lowest possible error rate. Figure 1.1 depicts the block diagram of a digital communication system. For successful multiuser communication, specific network structures and protocols need to be employed.

1.1.1 Electromagnetic Spectrum and Frequency Range

To transmit information over free space, electromagnetic waves are used. The properties of electromagnetic waves vary with frequency, and each frequency band is suitable for certain applications. The natural electromagnetic spectrum consists of a wide range of frequencies, starting from a few Hz up to 10^{22} Hz. Figure 1.2 lists the frequency bands in the electromagnetic spectrum along with the corresponding applications.

Wireless communication is usually possible in a specific frequency range called the radio frequency (RF) band. The RF band consists of frequencies as low as 30 MHz up to 30 GHz. One advantage of RF band is, for most of the part of this band, relatively small antennas can be used to receive and transmit electromagnetic signals. When impinging on the earth's atmosphere, the RF signals penetrate the ionosphere and the earth's curvature does not hinder the transmission. The low-frequency RF signals, i.e., shortwave signals, are reflected by the ionosphere and thus can be used to broadcast signals.

While military use of the RF spectrum may vary in different countries, the International Telecommunications Union (ITU) allocates and standardizes the commercial spectrum worldwide. The commercial spectrum bands can be divided into licensed and unlicensed bands. The licensed bands are usually allocated to the operators through an

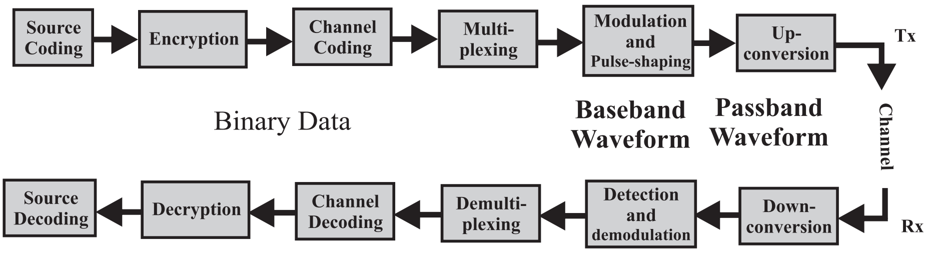

Figure 1.1 Block diagram of a digital wireless communication system.

auction process by the government authority (e.g., Federal Communications Commission [FCC] in the United States), and they are used exclusively by the corresponding operators. As an example, Table 1.1 lists the licensed commercial frequency allocation in the USA [3]. The unlicensed bands on the other hand are free and can be used

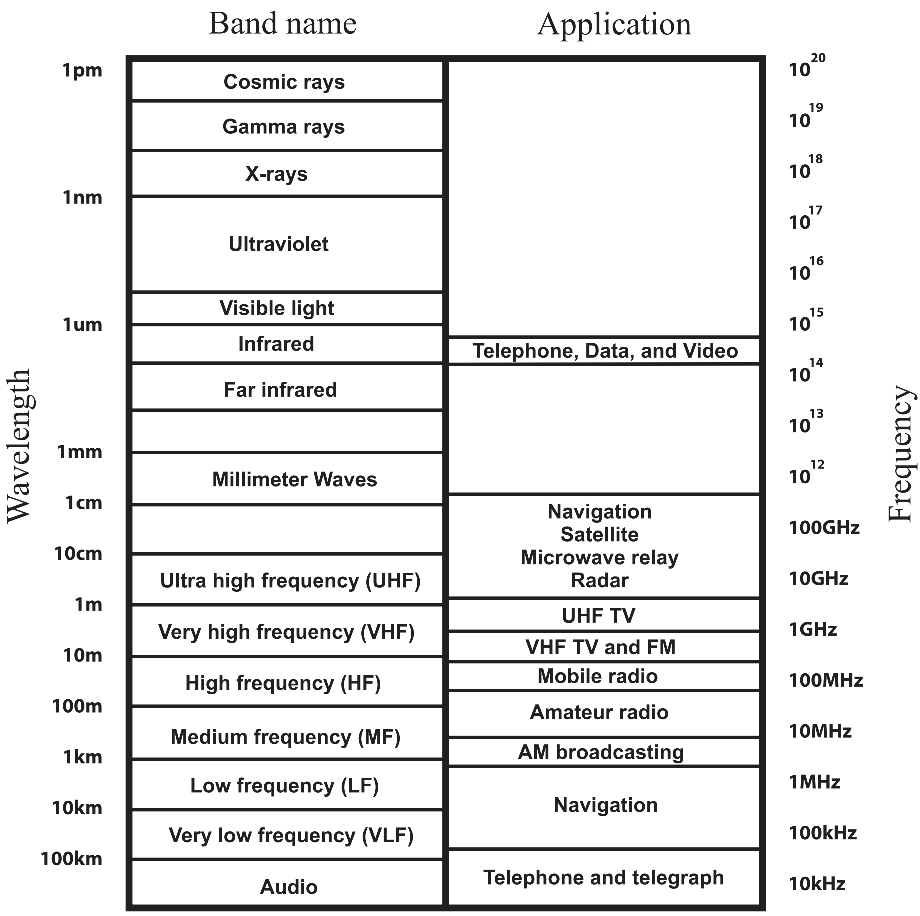

Figure 1.2 Electromagnetic spectrum.

Table 1.1 Licensed Commercial Frequency Allocation in the United States

Application	Frequency Range
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
4G wireless (LTE, LTE-A)	1850–1910 MHz (uplink), 1930–1990 MHz (downlink), 1710–1755 MHz (uplink), 2110–2155 MHz (downlink), 824–849 MHz (uplink), 869–894 MHz (downlink), 699–716 MHz (uplink), 729–746 MHz (downlink), 777–787 MHz (uplink), 746–756 MHz (downlink), 788–798 MHz (uplink), 758–768 MHz (downlink), 704–716 MHz (uplink), 734–746 MHz (downlink), 1850–1915 MHz (uplink), 1930–1995 MHz (downlink)
3G wireless	746–764 MHz, 776–794 MHz 1.7–1.85 MHz, 2.5–2.69 MHz
1G and 2G cellular	806–902 MHz
2G cellular	1.85–1.99 GHz
Wireless comm. services	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

by anyone under some regulations. Many wireless systems including Wi-Fi, Bluetooth, WiMax, and cordless phones use the unlicensed bands. Due to the high number of independent systems, the unlicensed spectrum bands almost always face interference. The licensed and unlicensed spectrum allocations in the United States for different wireless standards are shown in Figure 1.3 [3]. In Table 1.1, LMDS stands for *Local Multipoint Distribution Service*, and MMDS stands for *Multichannel Multipoint Distribution Service*. For the evolving fifth-generation (5G) systems, in the United States, the following new spectrum bands are being considered for potential use: 27.5–29.5 GHz, 37–40.5 GHz, 47.2–50.2 GHz, 50.4–52.6 GHz, and 59.3–71 GHz.

1.1.2 Signal Characterization

The information must be converted to physical signals for transmission. In this section we briefly define the signal power, energy, and spectral representation.

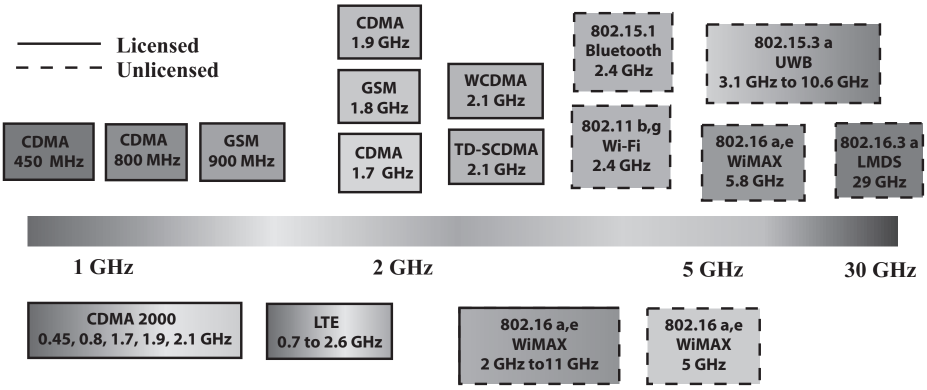

Figure 1.3 Licensed and unlicensed spectrum allocation in the United States.

Signal Power and Energy

A signal is a function that carries information. It can be a function of one or several independent variables such as time, location, etc. Given a signal $x(t)$, the amount of energy a signal carries is called the signal energy and is defined as

$$E = \int_{-\infty}^{+\infty} |x(t)|^2 dt. \tag{1.1}$$

The dimension of $|x(t)|^2$ is not necessarily consistent with the definition of energy in physics, but this nomenclature is widely used in electrical engineering and its related fields including wireless communications. While equation 1.1 calculates the total energy of a signal, the energy contained in a specific time interval can be calculated by modifying the integral limits. For example, the energy contained in the interval $[t_1, t_2]$ is obtained as $\int_{t_1}^{t_2} |x(t)|^2 dt$. In the discrete-time system, the energy of signal $x[n]$ where n is an integer is defined as

$$E = \sum_{n=-\infty}^{+\infty} |x[n]|^2. \tag{1.2}$$

For many signals, the energy could approach infinity. Therefore, the signal energy may not give any useful information. In this case, the signal power is a useful measurement. The signal power is the density of energy along the independent variable. For example, the energy density of $x(t)$ at time instance t equals $|x(t)|^2$, which is the *instantaneous* power of the signal. Usually we are interested in the average power. The average power of signal $x(t)$ is formally defined as

$$P = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 dt. \tag{1.3}$$

For a periodic signal, the right-hand side of the equation 1.3 reduces to $\frac{1}{T}\int_{-T/2}^{T/2}|x(t)|^2dt$, where T is the period of the signal. In a discrete-time system, the average power of signal $x[n]$, where n is an integer, is defined as

$$P = \lim_{N\to\infty}\frac{1}{2N+1}\sum_{n=-N}^{N}|x[n]|^2 \tag{1.4}$$

where N is the fundamental period of the discrete-time signal.

A signal with finite energy and zero power is generally referred to as an energy signal, e.g., $x(t) = \text{sinc}(t)$, and a signal with infinite energy and finite power is referred to as a power signal, e.g., $x(t) = \sin(t)$. Note that both power and energy of a signal may be infinite, e.g., $x(t) = e^t$.

The following two units are generally used for signal power: dBW (decibel-watt) and dBm (decibel-milliwatt). The power in dBW is given by $P_{dBW} = 10\log_{10}\frac{P_W}{1W}$. The power in dBm is given by $P_{dBm} = 10\log_{10}\frac{P_{mW}}{1mW}$. For example, if a transmitter transmits 50 watts of power, the transmit power is equivalent to $10\log_{10}50 = 17$ dBW, or $10\log_{10}(50\times10^3) = 47$ dBm. In general, the decibel is a measure of the ratio between two signal levels, which can be used to denote relative magnitudes or changes in magnitude. This can be expressed mathematically as $G_{(dB)} = 10\log_{10}\frac{P_{out}}{P_{in}}$, where G_{dB} = gain (in decibels), P_{in} = input power level, and P_{out} = output power level.

Frequency Spectrum of a Signal

It is very useful to represent a signal by its frequency contents to understand the contribution of each frequency component in the construction of the signal. The Fourier transform is the most powerful tool for frequency-domain analysis of a signal. The Fourier transform pair of signal $x(t)$ is defined as

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}dt \tag{1.5}$$

$$x(t) = \int_{-\infty}^{+\infty} X(f)e^{+j2\pi ft}df \tag{1.6}$$

where $X(f)$ is the Fourier transform of $x(t)$. Note that $X(f)$ represents the contribution of frequency f in construction of signal $x(t)$. For discrete-time signals, the Fourier transform pair is defined as

$$X(e^{j2\pi f}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j2\pi fn} \tag{1.7}$$

$$x[n] = \int_{2\pi} X(e^{j2\pi f})e^{+j2\pi fn}df \tag{1.8}$$

where the argument $e^{j2\pi f}$ asserts the periodicity of $X(e^{j2\pi f})$ with period 2π.

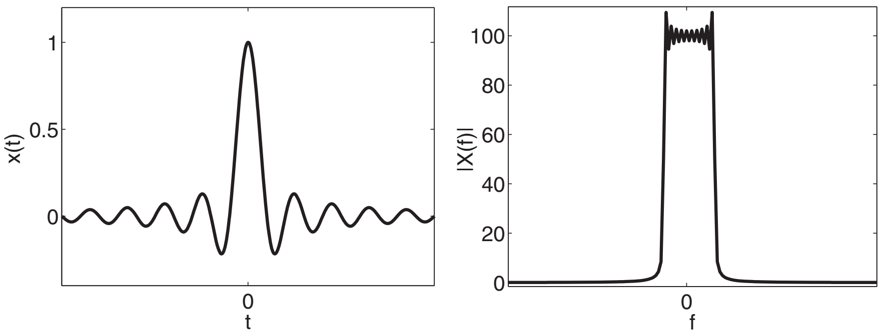

Figure 1.4 Signal $x(t)$ and the amplitude of its Fourier transform $X(f)$.

The amplitude $|X(f)|$ is a measure of contribution of frequency f in the signal. Moreover, the power spectral density of a deterministic (i.e., not random) signal can be defined as $|X(f)|^2$, which represents the amount of power delivered by frequency f. Figure 1.4 shows a signal and the amplitude of its Fourier transform.

The *power spectral density* (PSD) of a power signal is given by $\mathcal{P}_x(f) = \lim_{T_0 \longrightarrow \infty} \frac{1}{T_0} |X_{T_0}(f)|^2$. In terms of this PSD, the normalized average signal power is $P = \int_{-\infty}^{\infty} \mathcal{P}_x(\omega) d\omega$ (or $P = \int_{-\infty}^{\infty} \mathcal{P}_x(f) df$).

Bandwidth of a Signal

The *absolute bandwidth* of a signal is defined as the range of frequencies over which the signal has a non-zero power spectral density. For example, the absolute bandwidth of a rectangular pulse is infinity. A more commonly used measure is the first *null-to-null bandwidth*, which is equal to the main spectral lobe.

1.1.3 Modulation

A physical sinusoidal electromagnetic wave, called the carrier, can carry the information. The process of embedding the information in the carrier is called modulation. When modulated, the properties of the carrier such as amplitude and phase are changed according to the information at hand. The modulation schemes can be divided into two categories: analog and digital.

Digital modulation enables digital communication, which has numerous advantages over its analog counterpart. In analog communication, the transmitted messages are analog waveforms embedded in the carrier phase or amplitude. However, in digital communication, messages are in the form of bit streams embedded in the carrier which are decoded at the receiver. Based on the decoded binary bit stream, the receiver *reconstructs* the transmitted message (e.g., bit streams). This is in contrast to analog communication where the receiver can only amplify the noise-corrupted received message waveform. This fundamental difference enables digital communication systems to work under arbitrary error rates. The other striking difference between analog and digital

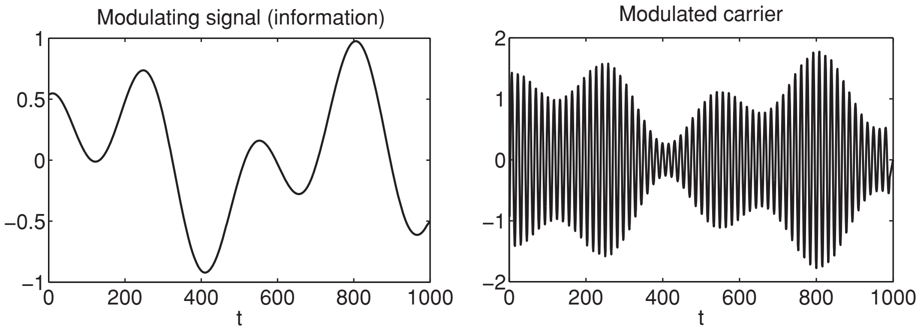

Figure 1.5 Modulating signal (information) and the modulated carrier in AM.

communications is the immense difference in information rate. Through digital techniques, the information rate in modern digital communications can be orders of magnitude higher than that in analog communications.

An important concept in modulation is baseband/passband conversion. Due to the large wavelength, low-frequency signals that are referred to as baseband cannot be transmitted using practical antennas. The signal is therefore transferred to RF frequencies. The frequency contents of the signal remain unchanged but only shifted in frequency. The resultant signal is referred to as a passband signal. Baseband-to-passband conversion and passband-to-baseband conversion are called up-conversion and down-conversion, respectively.

Mathematically, a signal $x(t)$ is called a *baseband* signal if $X(f) \approx 0$, $|f| > B$ for some $B > 0$. It is said to be a *passband* signal if $X(f) \approx 0$, for $|f \pm f_c| > B$. The time domain relationship between a baseband signal $x(t) = x_I(t) + jx_Q(t)$ (which is also called the *complex envelope* of a real-valued passband signal) and its passband signal $s(t)$ is given by $s(t) = Re\{x(t)e^{j2\pi f_c t}\}$ (which implies $s(t) = x_I(t)\cos 2\pi f_c t - x_Q(t)\sin 2\pi f_c t$). $x_I(t)$ and $x_Q(t)$ are also referred to as the in-phase [I] component and the quadrature [Q] component, respectively, of the passband signal $s(t)$, and f_c is a frequency reference generally chosen in or around the band occupied by $S(f)$.

Analog Modulation

In analog modulation, the information is in the form of a continuous signal, e.g., a voice signal. This signal is called the modulating signal. The main analog modulation schemes are amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). In AM, FM, and PM, the amplitude, frequency, and phase of the carrier fluctuate according to the modulating signal. Figure 1.5 demonstrates AM, for example. Denoting the message (modulating) signal by $x(t)$, the transmitted AM signal on carrier frequency f_c is given by $s(t) = [1 + mx(t)]\cos(2\pi f_c t)$, where m is called the modulation index and $0 < m < 1$.

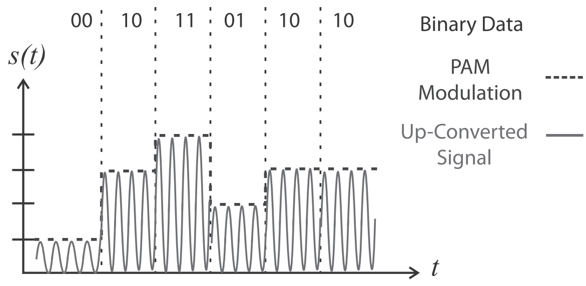

Figure 1.6 4-PAM modulated signal.

Digital Modulation

Modern wireless communications rely on digital modulation techniques. In digital modulation, the information is in the form of symbols that carry one or more bits. The information symbols are usually complex numbers whose amplitude and phase determine the amplitude and phase of the carrier signal. We now briefly overview some of the most common digital modulation schemes. The modulating bit stream is assumed to be 001011011010 for each modulation scheme.

PAM

Pulse amplitude modulation (PAM) is a digital modulation scheme based on varying the amplitude. In PAM, k bits are represented by 2^k possible amplitudes. For example, with 4-PAM, $k = 2$ and $2^k = 4$ different amplitude levels are possible, representing 00, 01, 10, or 11. Figure 1.6 shows a 4-PAM modulated bit stream where the baseband and up-converted passband signals are shown.

PSK

Phase-shift keying (PSK) modulation is based on changing the phase of the carrier. In PSK, k bits are represented by 2^k possible complex numbers whose phases determine the phase of the carrier. For example, with $k = 3$, eight different phases are possible, each representing a 3-bit stream. It is useful to show the PSK symbols in a complex plane: a representation which is called the signal constellation. Figure 1.7 depicts the signal constellations for 2-PSK, 4-PSK, and 8-PSK. 2-PSK and 4-PSK are often referred to as

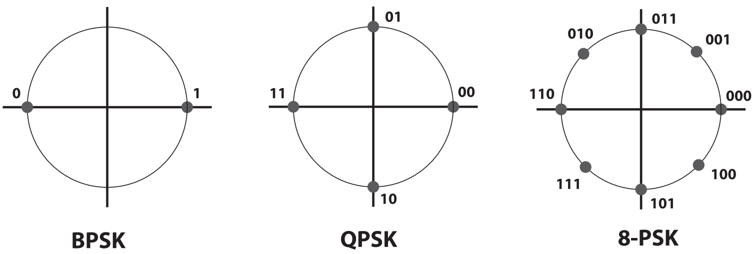

Figure 1.7 Signal constellation of PSK symbols on the complex plane.

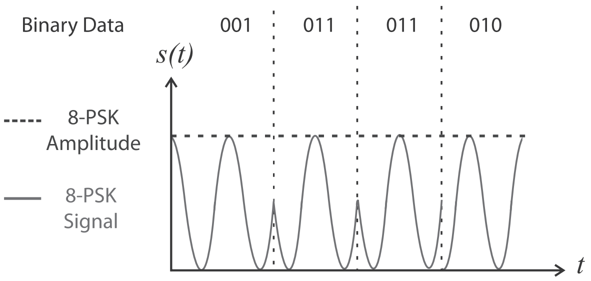

Figure 1.8 8-PSK modulated signal.

binary PSK (BPSK) and quadrature PSK (QPSK), respectively. BPSK is also a special case of PAM. Each signal constellation has a corresponding phase for the carrier. Note that the bit streams are mapped to the PSK symbols such that adjacent symbols differ only in one bit, and in this way the bit error rate is minimized. Figure 1.8 shows an 8-PSK modulated bit stream where the phase of the PSK signal is determined according to Figure 1.7.

QAM

Quadrature amplitude modulation (QAM) is based on changing the amplitude and phase of the carrier. In QAM, k bits are represented by 2^k possible complex numbers whose phase and amplitude determine the phase and amplitude of the carrier. For example, with $k = 4$, 16 different complex symbols are possible, each representing a 4-bit stream. Figure 1.9 depicts the signal constellation for 4-QAM, 8-QAM, and 16-QAM. Note that 2-QAM and 4-QAM are identical to BPSK and QPSK. Each symbol determines the phase and amplitude of the carrier. Note that the grid of QAM symbols is designed to achieve certain goals such as minimum power or minimum error rate. Figure 1.10 shows an 8-QAM modulated bit stream where the phase and amplitude of the QAM signal is determined according to Figure 1.9.

FSK

Frequency-shift keying (FSK) modulation is based on changing the frequency of the carrier. In FSK, k bits are represented by 2^k possible frequencies. Therefore, each bit

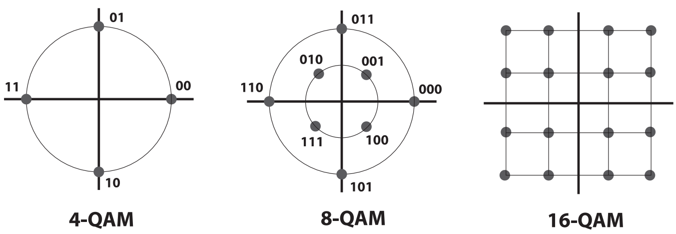

Figure 1.9 Signal constellation of QAM symbols on the complex plane.