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INTRODUCTION

Scientists and mathematicians of the nineteenth century laid the foundation of telecommunication and wireless technology, which has affected all facets of modern society. In 1864, James C. Maxwell put forth fundamental relations of electromagnetic fields that not only summed up the research findings of Laplace, Poisson, Faraday, Gauss, and others but also predicted the propagation of electrical signals through space. Heinrich Hertz subsequently verified this in 1887, and Guglielmo Marconi transmitted wireless signals across the Atlantic Ocean successfully in 1900. Interested readers may find an excellent discussion of the historical developments of radio frequencies (RFs) and microwaves in the *IEEE Transactions on Microwave Theory and Technique* (Vol. MTT-32, September 1984).

Wireless communication systems require high-frequency signals for the efficient transmission of information. Several factors lead to this requirement. For example, an antenna radiates efficiently if its size is comparable to the signal wavelength. Since the signal frequency is inversely related to its wavelength, antennas operating at RFs and microwaves have higher radiation efficiencies. Further, their size is relatively small and hence convenient for mobile communication. Another factor that favors RFs and microwaves is that the transmission of broadband information signals requires a high-frequency carrier signal. In the case of a single audio channel, the information bandwidth is about 20 kHz. If amplitude modulation (AM) is used to superimpose this information on a carrier, it requires at least this much bandwidth on one side of the spectrum. Further,

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TABLE 1.1 Frequency Bands Used in Commercial Broadcasting

	Channels	Frequency Range	Wavelength Range
AM	107	535–1605 kHz	186.92–560.75 m
TV	2–4	54–72 MHz	4.17–5.56 m
	5–6	76–88 MHz	3.41–3.95 m
FM	100	88–108 MHz	2.78–3.41 m
TV	7–13	174–216 MHz	1.39–1.72 m
	14–83	470–890 MHz	33.7–63.83 cm

commercial AM transmission requires a separation of 10-kHz between the two transmitters. On the other hand, the required bandwidth increases significantly if frequency modulation (FM) is used. Each FM transmitter typically needs a bandwidth of 200 kHz for audio transmission. Similarly, each television channel requires about 6 MHz of bandwidth to carry the video information as well. Table 1.1 shows the frequency bands used for commercial radio and television broadcasts.

In the case of digital transmission, a standard monochrome television picture is sampled over a grid of 512×480 elements called *pixels*. Eight bits are required to represent 256 shades of the gray display. To display motion, 30 frames are sampled per second; thus, it requires about 59 Mb/s ($512 \times 480 \times 8 \times 30 = 58{,}982{,}400$). Color transmission requires even higher bandwidth (on the order of 90 Mb/s).

Wireless technology has been expanding very fast, with new applications reported every day. In addition to the traditional applications in communication, such as radio and television, RF and microwave signals are being used in cordless phones, cellular communication, local, wide, and metropolitan area networks and personal communication service. Keyless door entry, radio-frequency identification (RFID), monitoring of patients in a hospital or a nursing home, and cordless mice or keyboards for computers are some of the other areas where RF technology is being used. Although some of these applications have traditionally used infrared (IR) technology, current trends favor RF, because RF is superior to infrared technology in many ways. Unlike RF, infrared technology requires unobstructed line-of-sight connection. Although RF devices have been more expensive than IR, the current trend is downward because of an increase in their production and use.

The electromagnetic frequency spectrum is divided into bands as shown in Table 1.2. Hence, AM radio transmission operates in the medium-frequency (MF) band, television channels 2 to 12 operate in the very high frequency (VHF) band, and channels 18 to 90 operate in the ultrahigh-frequency (UHF) band. Table 1.3 shows the band designations in the microwave frequency range.

In addition to natural and human-made changes, electrical characteristics of the atmosphere affect the propagation of electrical signals. Figure 1.1 shows

TABLE 1.2 IEEE Frequency Band Designations

Band Designation	Frequency Range	Wavelength Range (in Free Space)
VLF	3–30 kHz	10–100 km
LF	30–300 kHz	1–10 km
MF	300–3000 kHz	100 m–1 km
HF	3–30 MHz	10–100 m
VHF	30–300 MHz	1–10 m
UHF	300–3000 MHz	10 cm–1 m
SHF	3–30 GHz	1–10 cm
EHF	30–300 GHz	0.1–1 cm

TABLE 1.3 Microwave Frequency Band Designations

Frequency Bands	Old (Still Widely Used)	New (Not So Commonly Used)
500–1000 MHz	UHF	C
1–2 GHz	L	D
2–4 GHz	S	E
3–4 GHz	S	F
4–6 GHz	C	G
6–8 GHz	C	H
8–10 GHz	X	I
10–12.4 GHz	X	J
12.4–18 GHz	Ku	J
18–20 GHz	K	J
20–26.5 GHz	K	K
26.5–40 GHz	Ka	K

various layers of the ionosphere and the troposphere that are formed due to the ionization of atmospheric air. As illustrated in Figure 1.2(*a*) and (*b*), an RF signal can reach the receiver by propagating along the ground or after reflection from the ionosphere. These signals may be classified as *ground* and *sky waves*, respectively. The behavior of a sky wave depends on the season, day or night, and solar radiation. The ionosphere does not reflect microwaves, and the signals propagate line of sight, as shown in Figure 1.2(*c*). Hence, curvature of the Earth limits the range of a microwave communication link to less than 50 km. One way to increase the range is to place a human-made reflector up in the sky. This type of arrangement is called a *satellite communication system*. Another way to increase the range of a microwave link is to place repeaters at periodic intervals. This is known as a *terrestrial communication system*.

Figures 1.3 and 1.4 list selected devices used at RF and microwave frequencies. Solid-state devices as well as vacuum tubes are used as active elements in RF and

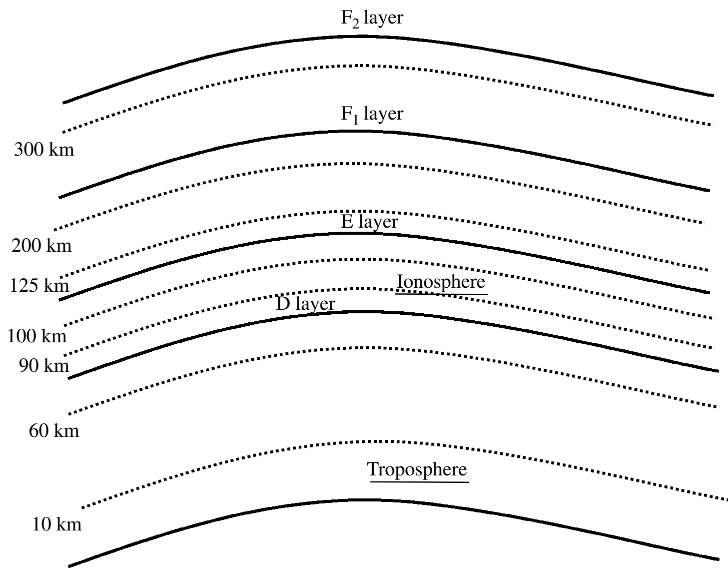


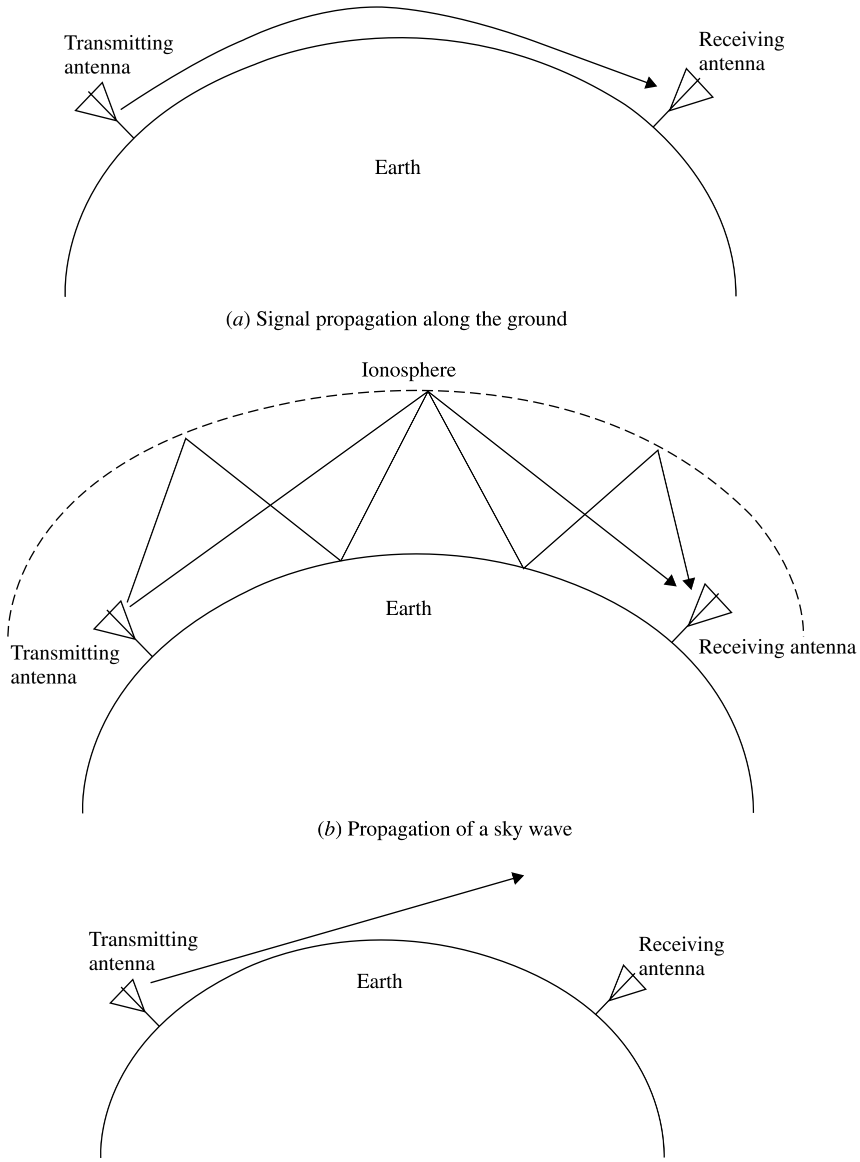
Figure 1.1 Atmosphere surrounding Earth.

microwave circuits. Predominant applications for microwave tubes are in radar, communications, electronic countermeasures (ECMs), and microwave cooking. They are also used in particle accelerators, plasma heating, material processing, and power transmission. Solid-state devices are employed primarily in the RF region and in low-power microwave circuits such as low-power transmitters for local area networks and receiver circuits. Some applications of solid-state devices are listed in Table-1.4.

Figure 1.5 lists some applications of microwaves. In addition to terrestrial and satellite communications, microwaves are used in radar systems as well as in various industrial and medical applications. Civilian applications of radar include air traffic control, navigation, remote sensing, and law enforcement. Its military uses include surveillance; guidance of weapons; and command, control, and communication (C^3). Radio-frequency and microwave energy are also used in industrial heating and for household cooking. Since this process does not use a conduction mechanism for the heat transfer, it can improve the quality of certain products significantly. For example, the hot air used in a printing press to dry ink affects the paper adversely and shortens the product's life span. By contrast, in microwave drying only the ink portion is heated, and the paper is barely affected. Microwaves are also used in material processing, telemetry, imaging, and hyperthermia.

1.1 MICROWAVE TRANSMISSION LINES

Figure 1.6 shows selected transmission lines used in RF and microwave circuits. The most common transmission line used in the RF and microwave range is the



(*a*) Signal propagation along the ground

(*b*) Propagation of a sky wave

(*c*) Line-of-sight propagation

Figure 1.2 Modes of signal propagation.

coaxial line. A low-loss dielectric material is used in these transmission lines to minimize signal loss. Semirigid coaxial lines with continuous cylindrical conductors outside perform well in the microwave range. To ensure single-mode transmission, the cross section of a coaxial line must be much smaller than the signal wavelength. However, this limits the power capacity of these lines. In

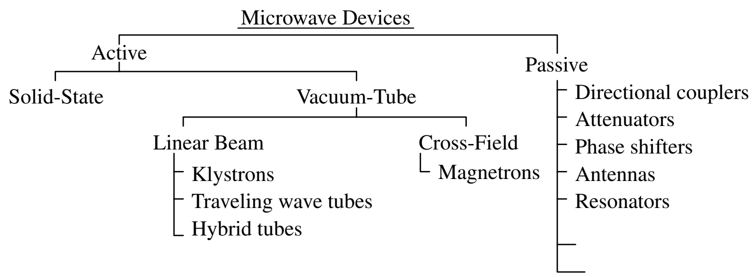


Figure 1.3 Microwave devices.

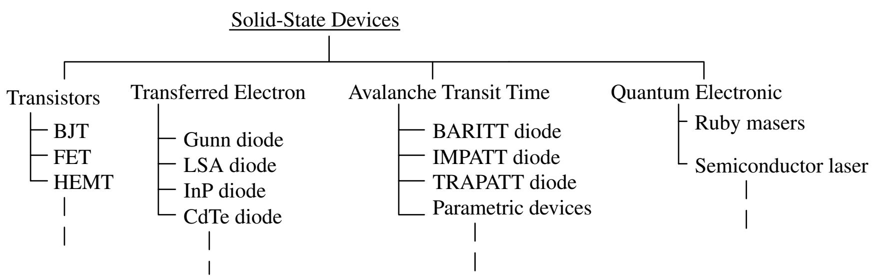


Figure 1.4 Solid-state devices used at RF and microwave frequencies.

TABLE 1.4 Selected Applications of Microwave Solid-State Devices

Devices	Applications	Advantages
Transistors	L-band transmitters for telemetry systems and phased-array radar systems; transmitters for communication systems	Low cost, low power supply, reliable, high-continuous-wave (CW) power output, lightweight
Transferred electron devices (TED)	C-, X-, and Ku-band ECM amplifiers for wideband systems; X- and Ku-band transmitters for radar systems, such as traffic control	Low power supply (12 V), low cost, lightweight, reliable, low noise, high gain
IMPATT diode	Transmitters for millimeter-wave communication	Low power supply, low cost, reliable, high-CW power, lightweight
TRAPATT diode	S-band pulsed transmitter for phased-array radar systems	High peak and average power, reliable, low power supply, low cost
BARITT diode	Local oscillators in communication and radar receivers	Low power supply, low cost, low noise, reliable

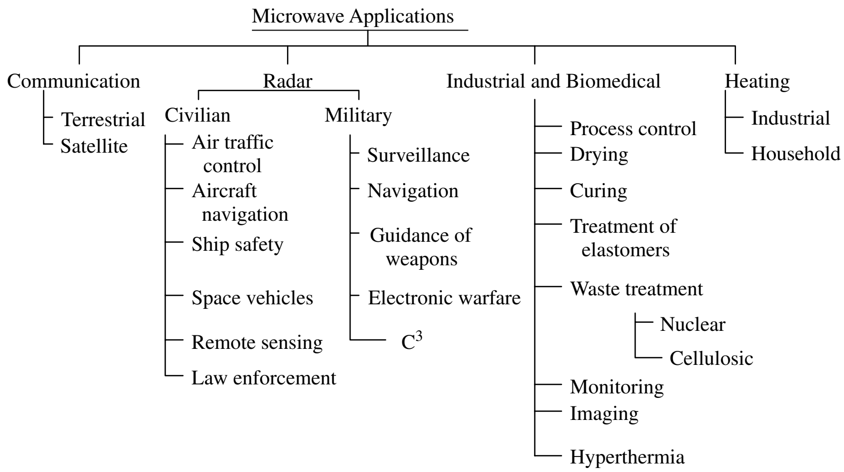


Figure 1.5 Some applications of microwaves.

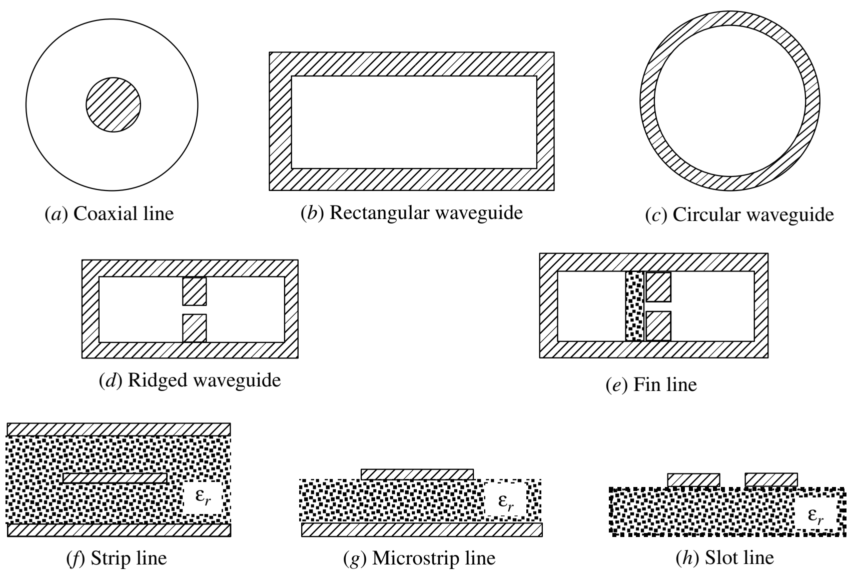


Figure 1.6 Transmission lines used in RF and microwave circuits.

high-power microwave circuits, waveguides are used in place of coaxial lines. Rectangular waveguides are commonly employed for connecting high-power microwave devices because these are easy to manufacture compared with circular waveguides. However, certain devices (e.g., rotary joints) require a circular cross section. In comparison with a rectangular waveguide, a ridged waveguide provides broadband operation. The fin line shown in Figure 1.6(*e*) is commonly used in the millimeter-wave band. Physically, it resembles a slot line enclosed in a rectangular waveguide.

The transmission lines illustrated in Figure 1.6(*f*) to (*h*) are most convenient in connecting the circuit components on a printed circuit board (PCB). The physical dimensions of these transmission lines depend on the dielectric constant ε_r of insulating material and on the operating frequency band. The characteristics and design formulas of selected transmission lines are given in the appendixes.

1.2 TRANSMITTER AND RECEIVER ARCHITECTURES

Wireless communication systems require a transmitter at one end to send the information signal and a receiver at the other to retrieve it. In one-way communication (such as a commercial broadcast), a transmitting antenna radiates the signal according to its radiation pattern. The receiver, located at the other end, receives this signal via its antenna and extracts the information, as illustrated in Figure 1.7. Thus, the transmitting station does not require a receiver, and vice versa. On the other hand, a transceiver (a transmitter and a receiver) is needed at both ends to establish a two-way communication link.

Figure 1.7 is a simplified block diagram of a one-way communication link. At the transmitting end, an information signal is modulated and mixed with a local oscillator to up-convert the carrier frequency. Bandpass filters are used before

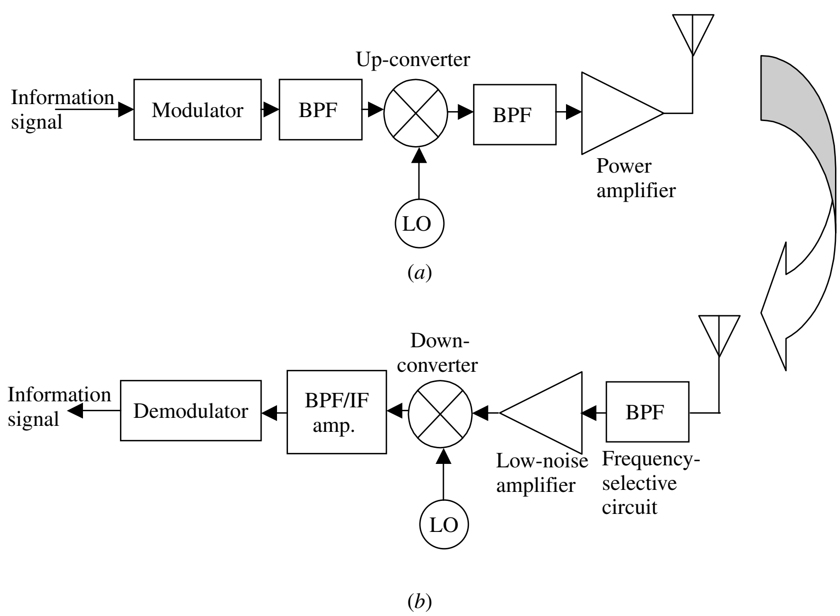


Figure 1.7 Simplified block diagram of the transmitter (*a*) and receiver (*b*) of a wireless communication system.

and after the mixer to stop undesired harmonics. The signal power is amplified before feeding it to the antenna. At the receiving end the entire process is reversed to recover the information. Signal received by the antenna is filtered and amplified to improve the signal-to-noise ratio before feeding it to the mixer for down-converting the frequency. A frequency-selective amplifier (tuned amplifier) amplifies it further, before feeding it to a suitable demodulator, which extracts the information signal.

In an analog communication system, the amplitude or angle (frequency or phase) of the carrier signal is varied according to the information signal. These modulations are known as amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM), respectively. In a digital communication system, the input passes through channel coding, interleaving, and other processing before it is fed to the modulator. Various modulation schemes are available, including on–off keying (OOK), frequency-shift keying (FSK), and phase-shift keying (PSK). As these names suggest, a high-frequency signal is turned on and off in OOK to represent the logic states 1 and 0 of a digital signal. Similarly, two different signal frequencies are employed in FSK to represent the two signal states. In PSK, the phase of the high-frequency carrier is changed according to the 1 or 0 state of the signal. If only two phase states (0° and 180°) of the carrier are used, it is called binary phase-shift keying (BPSK). On the other hand, a phase shift of 90° gives four possible states, each representing 2 bits of information (known as a *dibit*). This type of digital modulation, known as quadrature phase-shift keying (QPSK), is explained further below.

Consider a sinusoidal signal S_{mod}, as given by equation (1.2.1). Its angular frequency and phase are ω radians per second and ϕ, respectively:

$$S_{\text{mod}}(t) = \sqrt{2}\cos(\omega t - \phi) = \sqrt{2}(\cos\omega t\cos\phi + \sin\omega t\sin\phi) \qquad (1.2.1)$$

This can be simplified further as follows:

$$S_{\text{mod}}(t) = S_I\cos\omega t + S_Q\sin\omega t \qquad (1.2.2)$$

where

$$S_I = \sqrt{2}\cos\phi \qquad (1.2.3)$$

and

$$S_Q = \sqrt{2}\sin\phi \qquad (1.2.4)$$

The subscripts I and Q represent in-phase and quadrature-phase components of S_{mod}. Table 1.5 shows the values of S_I and S_Q for four different phase states together with the corresponding dibit representations. This scheme can be implemented easily for a polar digital signal (positive peak value representing logic 1 and the negative peak logic 0). It is illustrated in Figure 1.8. The demultiplexer simultaneously feeds one bit of the digital input S_{BB} to the top and the other to the bottom branch of this circuit. The top branch multiplies the signal by cos ωt

TABLE 1.5 QPSK Scheme

ϕ	S_I	S_Q	Dibit Representation
$\pi/4$	1	1	11
$3\pi/4$	−1	1	01
$5\pi/4$	−1	−1	00
$7\pi/4$	1	−1	10

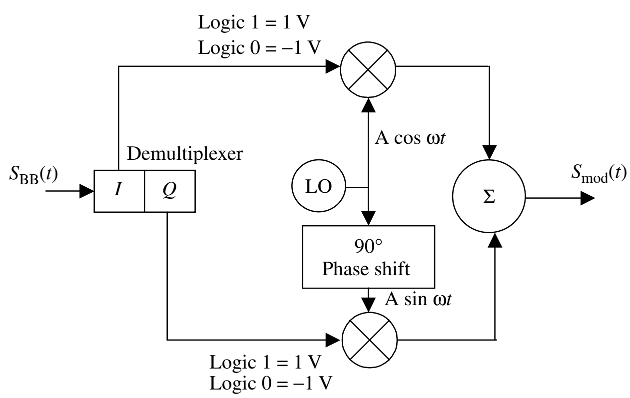


Figure 1.8 Block diagram of a QPSK modulation scheme.

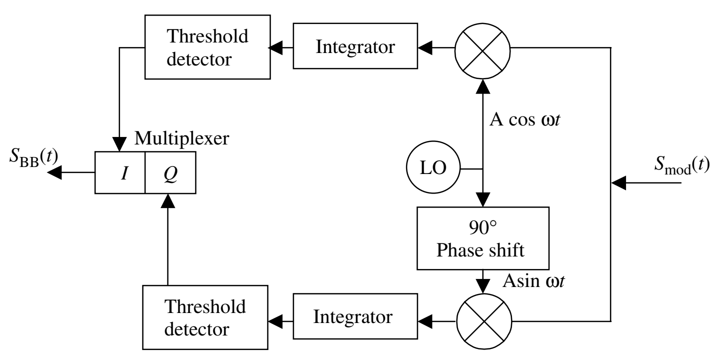


Figure 1.9 Block diagram of a QPSK demodulation scheme.

and the bottom signal by sin ωt. The outputs of the two mixers are then added to generate S_{mod}.

Demodulation inverts the modulation to retrieve S_{BB}. As illustrated in Figure 1.9, S_{mod} is multiplied by cos ωt in the top branch and by sin ωt in the bottom branch of the demodulator. The top integrator stops S_Q, and the bottom integrator, S_I. Two threshold detectors generate the corresponding logic states that are multiplexed by the multiplexer unit to recover S_{BB}. Chapter 2 provides an overview of wireless communication systems and their characteristics.