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Introduction to Wireless Systems

This chapter presents a brief overview of wireless communications and cellular phone systems to lay the foundation for discussing the book's remaining chapters. It covers the basic functional blocks of a wireless communication system, radio systems classifications (simplex, half-duplex, and full-duplex), radio transceivers of wireless systems, cellular phone systems including first-generation (1G), second-generation (2G), third-generation (3G), fourth-generation (4G), and fifth-generation (5G) New Radio wireless technologies. Further topics cover the air interface technologies, including frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA), terahertz (THz) communications for next-generation 6G wireless technology, multiple-input multiple-output (MIMO) technology, the basic concept of modulation, time and frequency-domain signals, and frequency spectrum allocation. These topics are discussed in further detail in the references list at the end of the chapter. The chapter also provides review questions to help the reader understand the covered topics, and suggested readings that present the up-to-date research activities that are related to the topics of this chapter.

1.1 Chapter Objectives

On reading this chapter, the reader will be able to:

- Draw a block diagram of a wireless communication model and explain the function of each block.
- Compare and contrast full-duplex, simplex, and half-duplex radio systems.
- Explain the difference between 1G, 2G, 3G, 4G, and 5G wireless technologies.
- Explain the applications of frequency range 1 (FR1) and frequency range 2 (FR2) of 5G NR (new radio) wireless technology.
- Explain the advantages and challenges of using THz frequency in the future 6G wireless technology.
- Explain the advantages of MIMO wireless systems.
- Briefly explain the difference between amplitude modulation (AM) and frequency modulation (FM) and why modulation is needed.
- Illustrate the time-domain and frequency domain of a sinusoidal signal.
- Explain the differences between FDMA, TDMA, and CDMA wireless access technologies.

- Explain why radio transceivers' front end uses circulators and radiofrequency (RF) switches.
- Illustrate and explain the frequency spectra of an OFDM signal.

1.2 Overview of Wireless Communications

Wireless communication [1–8] is a global industry people depend on in many ways for effective business, efficiency in service (e.g., education, health, security, etc.), as well as for critical situations (e.g., lifeline emergencies), which makes it indispensable to public safety. Wireless technology was first introduced in 1901 when Guglielmo Marconi successfully achieved the first transatlantic communication. Radio broadcasting began in the 1920s and used vacuum-tube technology in transmitters and receivers. The invention of integrated circuits in 1958 enabled the design and development of small-size wireless communication systems.

The primary function of a wireless communication system is to send information, such as voice, video images, data, or other physical variables (e.g., temperature, speed, pressure, etc.), from the information source to the information destination through a radio channel (i.e., free-space transmission medium). Figure 1.1 shows a simplified block diagram of a wireless communication model.

In Figure 1.1, the source block represents a transducer that converts physical variables into electrical signals. These electrical signals are also called baseband signals that can be processed (e.g., encoding, interleaving, etc.) in the transmitter chain. Microphones and cameras are transducers that convert sound and visual images to baseband signals. Baseband signals cannot be transmitted directly over the air because such a transmission requires large antennas. To transmit baseband signals over the air, they must be combined with a higher frequency called carrier frequency, and this process is called modulation. The modulated signal gets amplified and applied to the antenna, which acts as an interface between the transmitter's output and the free space. The antenna converts the RF signals to radio waves (i.e., electromagnetic waves) that propagate over the air at the speed of light (3×10^8 m/s). Antennas and radio wave propagation are discussed in detail in Chapter 7.

At the receiver end of a wireless link, the antenna converts the radio waves into electrical signals that get down-converted to an intermediate frequency (IF) and baseband. Finally, the transducers convert the baseband signals back to the original physical variables that were sent by the transmitter.

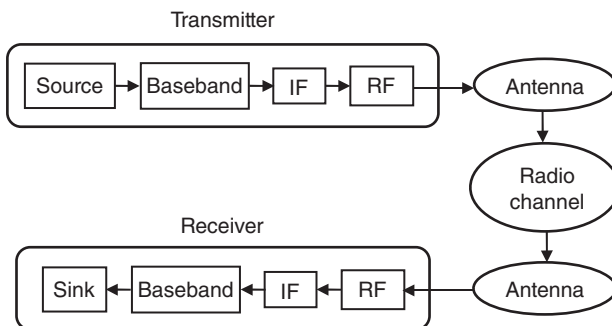


Figure 1.1 Simplified block diagram of a wireless communication model.

1.3 Radio Systems Classification

Radio communications systems are classified into simplex, half-duplex, and full-duplex. In a simplex system, communication is one-way from the transmitter to the receiver, as in radio and TV broadcasting. In a full-duplex system, transmission and reception coincide (thus creating a two-way communication) as in mobile phones. In a half-duplex radio system, the receiver and transmitter alternate (i.e., take turns). Figure 1.2 illustrates half-duplex and full-duplex transmission between two wireless systems *A* and *B*.

1.3.1 Radio Transceivers

Radio transceivers transmit and receive radio signals in wireless communication systems such as cellular phones, radars, two-way radios, and electronic navigation systems. In radio transceivers, the transmitter and the receiver share the same antenna and are packaged in the same enclosure.

When the transmit frequency differs from the receive frequency, a duplexer is used to enable the use of a single antenna for both transmit and receive operations. Figure 1.3 shows a simplified block diagram of an RF transceiver that uses a duplexer.

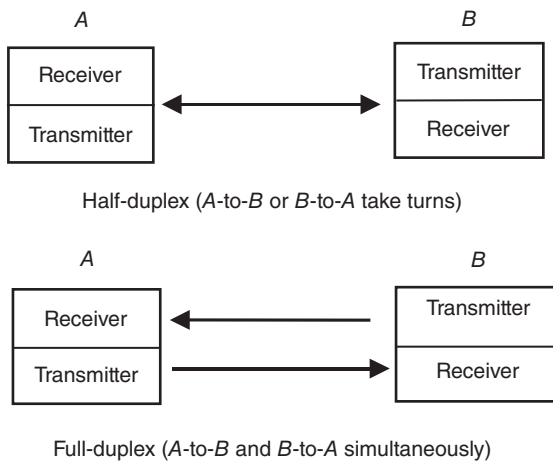


Figure 1.2 Types of radio communication systems.

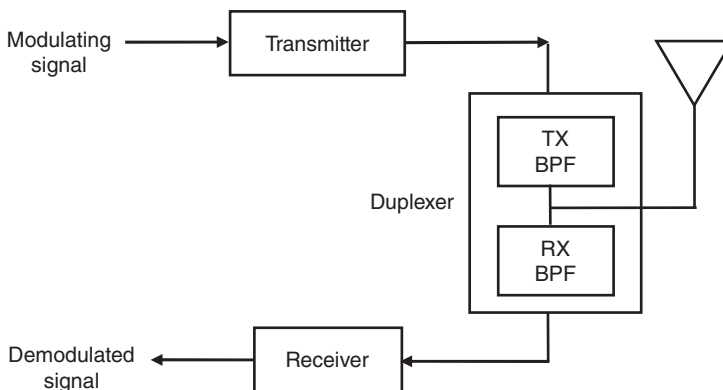


Figure 1.3 Block diagram of a radio transceiver front-end using a duplexer.

A duplexer is a device that enables bi-directional communication in wireless communications systems, and it isolates the receiver from the transmitter while permitting them to share a common antenna. In Figure 1.3, the duplexer consists of two bandpass filters: one is the transmit bandpass filter (TX BPF) that passes the transmit signal to the antenna and blocks the received signal, while the other is the receive bandpass filter (RX BPF) that passes the received signal from the antenna to the receiver and blocks the transmit signal. In this way, a single antenna can be shared by both the transmitter and the receiver.

If the transmitter and receiver operate on the same frequency, an RF switch connects the transmitter to the antenna during the transmission and isolates the receiver. The switch also connects the antenna to the receiver and isolates the transmitter during the reception to enable sharing of the antenna by the transmitter and the receiver. Figure 1.4 shows a block diagram of an RF transceiver that uses an RF switch.

To prevent transmit power leakage to the receiver, the RF switch should have sufficient isolation. The transmit (TX) leakage to the receiver's input reduces the signal-to-noise ratio, degrading the receiver sensitivity (i.e., the ability to detect weak signals). A circulator can be used to enable the transceiver to transmit and receive without constraint on the transmitter and the receiver timing and frequency. Figure 1.5 shows a radio transceiver that uses a circulator.

A circulator is a passive, nonreciprocal three-port device that enables a radiofrequency signal to pass from one port to another while isolating the signal from the other port. The performance specifications and testing of duplexers, RF switches, and circulators are discussed in further detail in Chapter 5. Figure 1.6 shows a block diagram of an RF transceiver that uses a transmit/receive (T/R) switch.

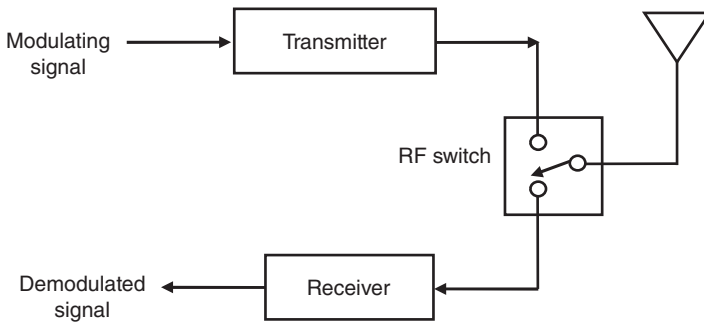


Figure 1.4 Block diagram of a radio transceiver with an RF switch.

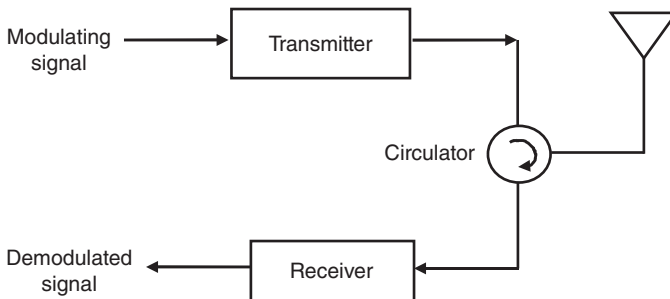


Figure 1.5 Block diagram of a radio transceiver using a circulator.

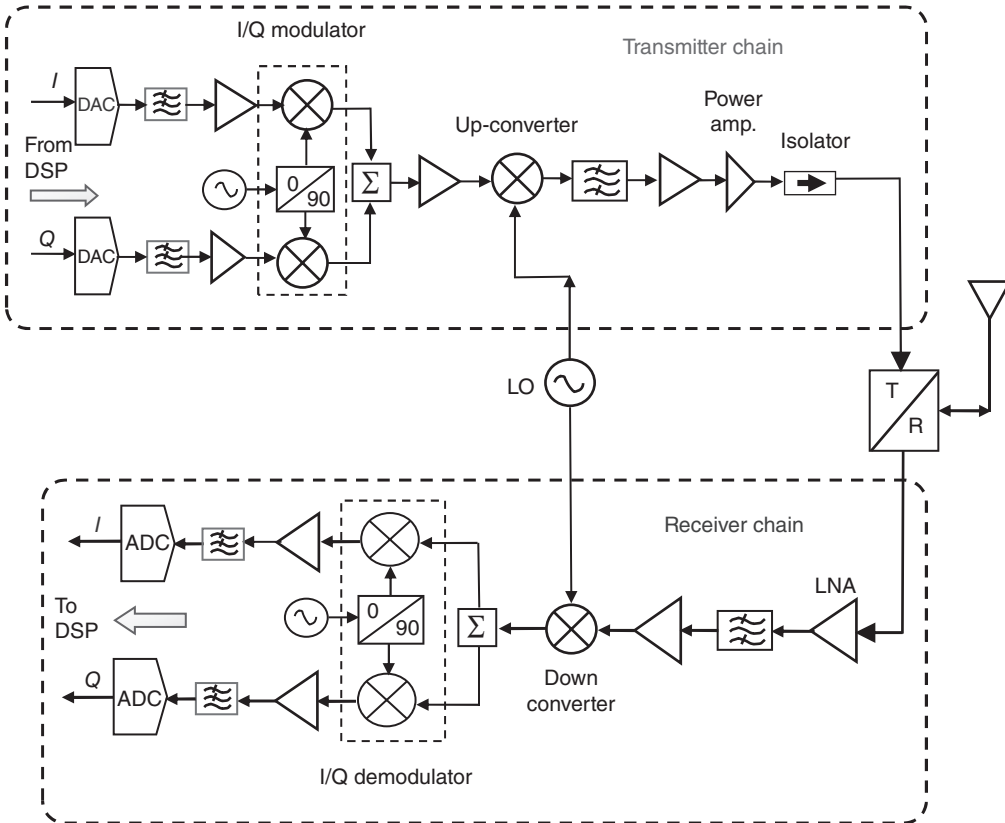


Figure 1.6 Block diagram of an RF transceiver.

Figure 1.6 shows the basic functional blocks of an RF transceiver, including a (T/R) switch, low-noise amplifier (LNA), filters, power amplifier, mixers, local oscillators (LO), analog-to-digital converter (ADC), digital-to-analog converter (DAC), modulator, and demodulator. Some of these building blocks can be used standalone or integrated into an integrated chip. Although similar RF building blocks in different types of transceivers perform the same basic function, the complexity of each implementation can considerably vary depending on the overall system requirement and operating environment for each specific application. The performance of these blocks is affected by many factors, such as the communication link range, information bandwidth, and power budget. The basic theory of operation and testing of the RF building blocks that are used in wireless communication systems are discussed in Chapter 5.

In the transmit chain shown in Figure 1.6, the in-phase/quadrature (I/Q) signals from the digital-signal-processing (DSP) block get converted by the DAC blocks and then filtered, amplified, and applied to the I/Q modulator. The signals from the I/Q modulator are combined by a power combiner and then applied to a gain block to drive the mixer that converts the signal to the required transmit frequency. The LO port of the mixer is connected to the LO block that generates the carrier signal. The output of the mixer is filtered by a bandpass filter that suppresses any undesired frequency components that are generated in the mixing process. The output of the filter is applied to a driver amplifier to compensate for the filter's insertion loss and to amplify the signal to the level that drives the power amplifier. The power amplifier amplifies the signal to the required

transmit power level. The isolator between the power amplifier and the T/R switch prevents any reflection from the switch to the power amplifier. The T/R switch connects the transmit signal to the antenna and isolates the receiver from the antenna during the transmission time. The antenna converts the transmit signal to electromagnetic waves propagating in the free space at the speed of light.

In the receiver chain shown in Figure 1.6, the antenna converts the received electromagnetic waves to an electrical signal. At the same time, the T/R switch connects the antenna to the LNA and isolates the transmit chain to protect the receiver. The LNA amplifies the received RF signal for subsequent processing; the output of the LNA is then applied to a BPF filter to suppress out-of-band signals. The down converter mixer converts the RF to a lower frequency signal to be demodulated by the I/Q demodulator and converted to I and Q signals by the ADC blocks. The I and Q signals are further processed by the DSP block to optimize the receiver performance. Each block of the transceiver's blocks and their performance parameters is discussed in Chapter 6.

1.4 Cellular Phone Systems

Cellular phones are the most widely used wireless systems because they enable users to connect to the standard telephone systems, support sending text messages, checking email, accessing the Internet, finding a location, and taking high-resolution photos. The original cellular technology advanced mobile phone system (AMPS) was commercially introduced in the 1980s as a 1G (first-generation) product and used the frequency division multiple access (FDMA) technique. Figure 1.7 shows a representation of an FDMA transmission.

The FDMA technique allows multiple users to communicate with the base station (i.e., a fixed radio system that handles the cellular traffic) without interfering with each other. In this technique, the multiplexing process is achieved by assigning each user a narrow frequency band (i.e., channel), and all the channels are combined and transmitted over a broadband channel. This multiplexing type is called frequency division multiplexing (FDM). In an FDM, narrowband channels are separated by guard bands to prevent interference between the channels. Figure 1.8 shows a simplified block diagram of an FDM transmitter. A representation of FDM transmission is shown in Figure 1.9.

In Figure 1.8, the multiple baseband signals $m_1(t)$, $m_2(t)$, and so on modulate different subcarriers $f_1, f_2, \dots, f_n$. The outputs of the subcarrier modulators are fed to a combiner that merges all the modulated signals to produce a composite baseband signal. This composite baseband signal is then fed to an RF up-conversion block (i.e., the frequency conversion to higher frequency) in the transmitter chain, where the output of the upconverter is filtered, amplified, and connected to an antenna for transmission over the air.

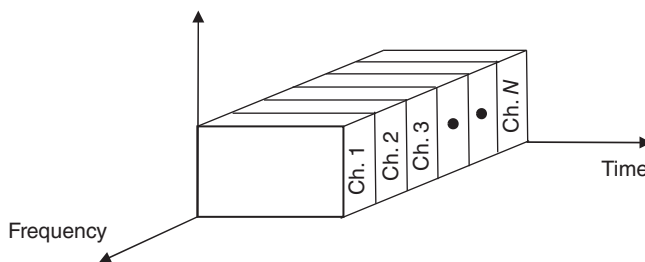


Figure 1.7 Illustration of an FDMA channels.

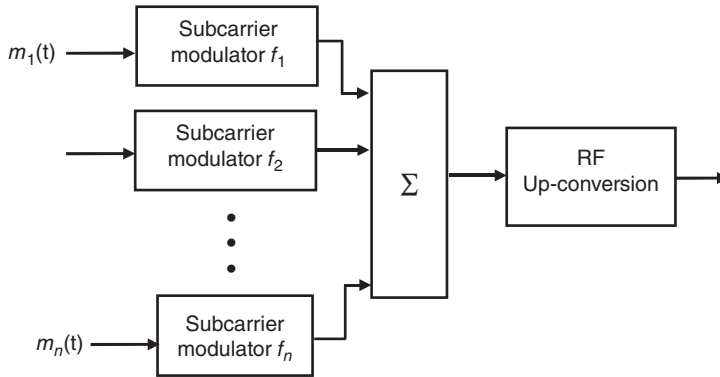


Figure 1.8 Simplified block diagram of an FDM system transmitter.

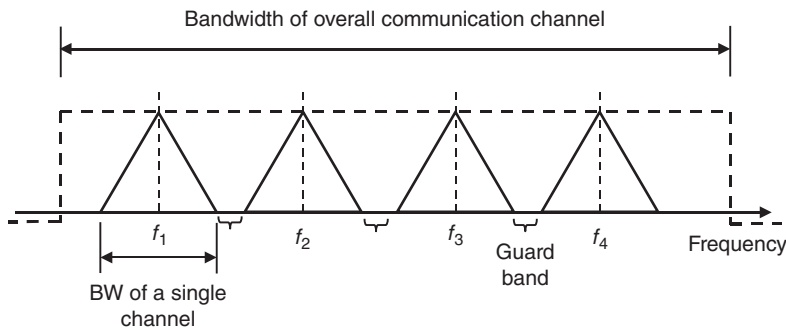


Figure 1.9 FDM transmission.

Since the AMPS technology could not meet the demand for more services, a 2G phone technology was developed. The 2G marked the transition of mobile networks from analog to digital.

The 2G technology supported basic data services such as short message services. It used time division multiple access (TDMA) multiplexing. In TDMA, multiplexing is achieved by assigning each user a time slot to transmit and receive. Figure 1.10 shows a representation of TDMA transmission.

Later, the continuous demand for more services led to the development of the 3G cellular systems. The 3G technology introduced improved mobile broadband services and enabled new applications such as multimedia message services, video calls, and mobile TV.

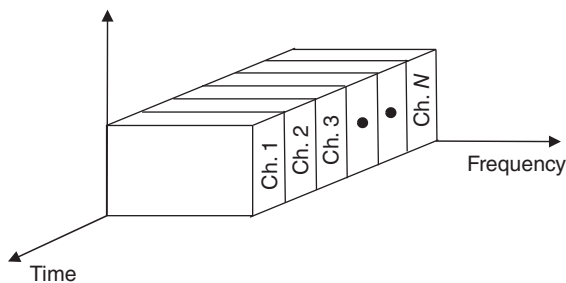


Figure 1.10 Illustration of TDMA transmission.

The 3G cellular systems used the code division multiple access (CDMA) technology. In CDMA, the narrow band message signal is multiplied by a large bandwidth signal called the *spreading signal*. Spreading signals are a pseudorandom sequence whose chip rate is larger than the data rate of the message. CDMA systems use the same carrier frequency to modulate all the users' signals and to allow the users to transmit simultaneously. In a CDMA system, each user has a unique pseudo-random code word, which is approximately orthogonal to all other code words to ensure minimum mutual interference among users. Figure 1.11 shows a representation of a CDMA transmission.

The CDMA receiver performs a time correlation function so that signals other than the desired signal appear uncorrelated. To decode the desired signal, the receiver uses the same code word that is used in the transmission.

Further, improved mobile broadband services, Voice Over Internet Protocol (VoIP), ultra-high-definition video streaming, and online gaming were introduced in the 4G systems. The 4G technology is also known as long-term evolution (LTE). It used orthogonal frequency division multiple access (OFDMA) and MIMO techniques. Figure 1.12 shows a representation of the frequency spectra of an OFDM signal.

In Figure 1.12, the subcarriers overlap and whenever there is a peak for one subcarrier, there is none for the other subcarriers.

A decade after introducing 4G systems, the fifth-generation new radio (5G NR) wireless systems were introduced. The 5G NR technology is a new standard provided by the 3rd Generation

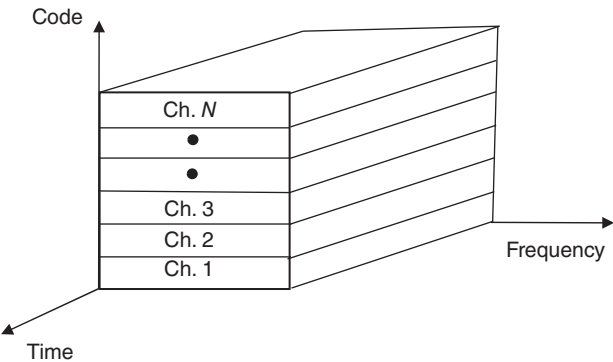


Figure 1.11 CDMA transmission.

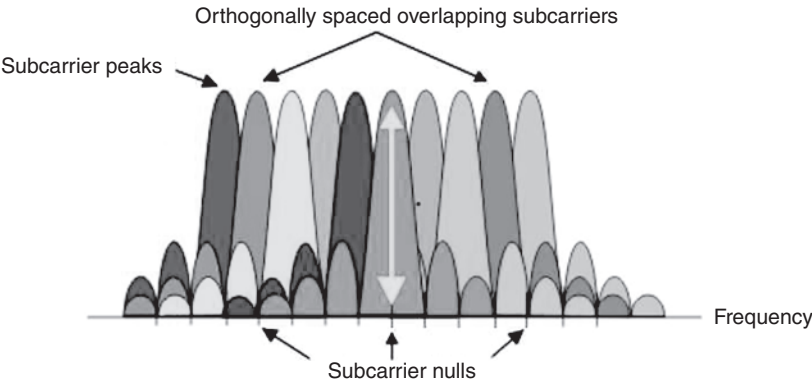


Figure 1.12 Representation of an OFDM transmission.

Partnership Project (3GPP) organization. The main goals of this technology include enhanced mobile broadband (eMBB), the downlink data rate of 10 Gbps, massive machine-type communication (mMTC) associated with Internet-of-Things (IoT), and ultra-reliable low-latency communication (uRLLC).¹ In addition, mmWave 5G systems support large bandwidth up to 400 MHz.

There are many 5G NR bands, and they vary from 600 MHz to 52.5 GHz. In the United States, the operating frequencies are designated FR1 and FR2. FR1 band ranges from 410 MHz to 7.125 GHz, which is used to carry most of the traditional cellular mobile communications traffic, whereas FR2 (24.25 to 52.6 GHz) band is focused on short-range, high data rate capabilities.

Additional space has been allocated in the mmWave spectrum from 24 up to 95 GHz. In the United States, three spectrum segments which are 28, 37–39, and 40 GHz have been dedicated to 5G NR. These segments offer sufficient bandwidth to support the Gbps data rate offered by the standard—specifically, 27.5–38.35 GHz, 37–38.6 GHz, and 38.6–40 GHz.

1.5 Terahertz (THz) for 6G Wireless Technology

Although the 5G mobile communication [9–11] networks are now widely deployed worldwide, the capabilities of the 5G technology are challenged by many new applications that are required. In this context, researchers have worked towards the next-generation 6G mobile communication network [12–14]. The THz frequency [15–17], also known as submillimeter-wave, ranges from 100 GHz to 10 THz ($1 \text{ THz} = 10^{12} \text{ Hz}$). It is becoming one of the cornerstones of the future 6G wireless systems, as this frequency has very large available bandwidths. Figure 1.13 shows the location of the THz region in the electromagnetic spectrum.

The THz technology enables high-definition video resolution radars that can provide TV-like pictures to complement radars at low frequencies that give a more extended range. The technology

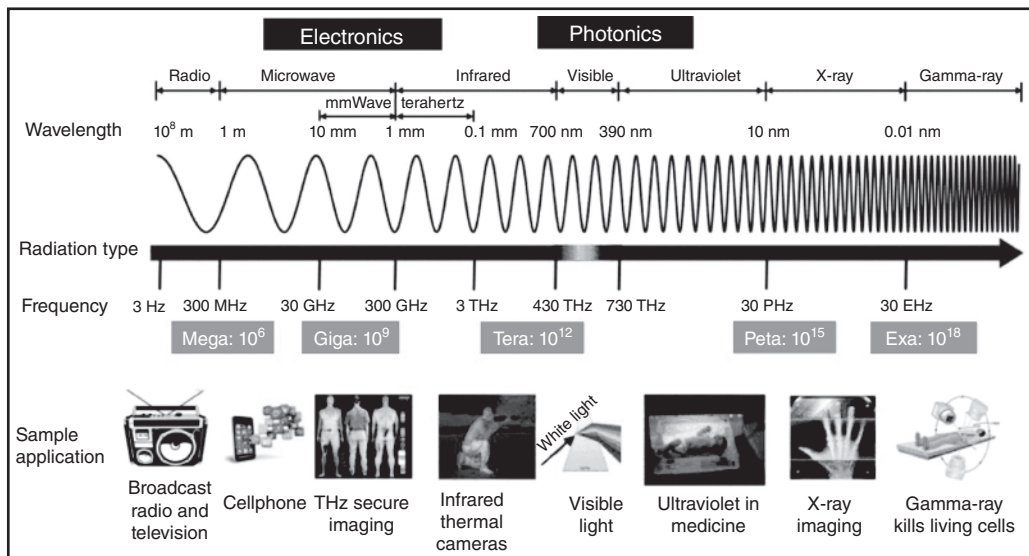


Figure 1.13 Illustration of THz region in the electromagnetic spectrum [17].

¹ Latency is the time delay between initiating an action and the time the action occurs.

also makes it possible to achieve high-resolution imaging through fog, dust, and smoke. In addition, the THz technology has promising applications in security, public safety, health environment, and education.

The disadvantages of THz communications are related to the strong absorption caused by water vapor in the atmosphere and the low output power from the currently available THz sources. These disadvantages limit the achievable link distance. In addition, the high propagation losses at THz frequencies will require the simultaneous use of high-gain directional antennas at the transmitter and the receiver of a THz communication link. However, the propagation path loss of a THz link can be compensated for by using ultra-massive MIMO (UM-MIMO) systems. The THz frequencies enable the implementation of UM-MIMO systems because of the small wavelengths at these frequencies. Furthermore, having a small wavelength empowers the development of small-size antenna elements, which is essential for implementing UM-MIMO systems.

In summary, future applications of THz communications will largely depend on the availability of more efficient sources, coherent detectors, and modulators at this frequency range, as well as on the availability of relevant test equipment to validate the performance of THz systems.

1.6 Multiple-Input Multiple-Output (MIMO)

MIMO [18] is a wireless technology that uses multiple antennas at the transmitter and receiver to use multipath signals to improve the link reliability and increase the channel capacity. Common arrangements of MIMO include 2×2 MIMO (i.e., two transmit antennas and two receive antennas), 4×4 MIMO, and 8×8 MIMO. At mmWave frequencies, massive MIMO systems use 100s antenna elements.

In MIMO systems, serial data are divided into separate data streams that are transmitted simultaneously over the same channel. Figure 1.14 illustrates a basic MIMO system with multiple transmit antennas at the input of the propagation channel and multiple receive antennas at the channel's output (i.e., MIMO).

Since the antenna size is inversely proportional to the frequency, mmWave frequencies enable having small antennas to implement large antenna arrays. A large antenna array provides a high gain and narrow beam, thereby enabling interference mitigation and extending the communication range of the link. Small-size antenna elements contribute to having an integrated antenna system and removing the interconnect cables. Further details on the concept of MIMO technology are provided in Chapter 8.

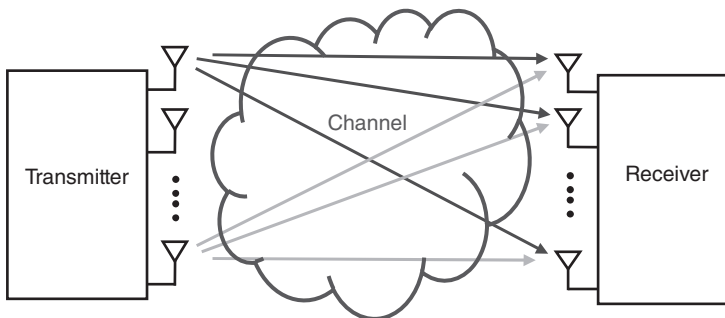


Figure 1.14 Illustration of a basic MIMO system.

1.7 Basic Concept of Modulation

1.7.1 Baseband Signals

Although this book focuses on the RF subsystem blocks of transmitters and receivers in wireless communication systems rather than on baseband subsystem blocks, it is worthwhile to describe baseband signals briefly for a more comprehensive view of a wireless communication system.

In wireless communication systems, to transmit a baseband signal (i.e., low-frequency signal) over the air via an antenna, it should be combined with a high-frequency signal called the carrier signal. The antenna structure has very small dimensions compared to the wavelength, λ , of the carrier signal. The wavelength of a carrier signal is given by

$$\lambda = \frac{c}{f} \text{ m/s} \quad (1.1)$$

where,

$$c = 3 \times 10^8 \text{ m/s}$$

f = frequency of the signal in Hz

The direct transmission of baseband signals would require very large antennas. For that reason, baseband signals need to modulate a high-frequency signal (i.e., to be mixed with RF signal) to be transmitted.

1.8 Modulation

In radio transmitters, having the baseband signal modify the carrier signal is called modulation, and the device that performs the modulation is called a modulator. Figure 1.15 shows a modulator block in a wireless transmitter system.

The carrier signal $s(t)$ of a wireless transmitter is expressed as

$$s(t) = A \cos(2\pi f_c t + \theta) \quad (1.2)$$

where

A = amplitude of the carrier

f_c = frequency of the carrier

θ = phase of the carrier

If the amplitude of the carrier changes proportionally to the amplitude of the baseband signal, this modulation is called **AM**. Conversely, if the frequency of the carrier changes proportionally

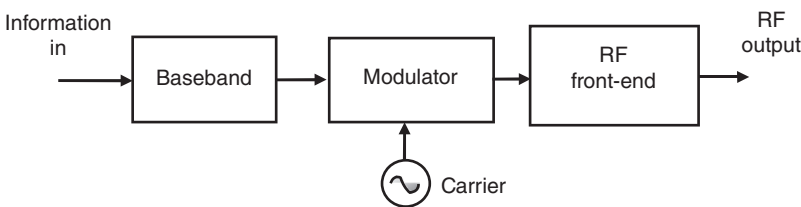


Figure 1.15 Modulator block in a wireless transmitter.

to the baseband, this modulation is called **FM**. Finally, if the phase of the carrier changes proportionally to the baseband’s amplitude, such modulation is called **PM**. AM, FM, and PM modulation schemes are discussed in further detail in Chapter 2, and the digital modulation schemes are discussed in Chapter 3.

In all modulation schemes, the modulation process produces frequency components different from the carrier frequency. The receiver of a communication link demodulates the received RF signal to extract the baseband signal that was used in the transmitter.

1.8.1 Time and Frequency Domains of Signals

Electrical signals can be represented in both time and frequency domains. In a time domain, the amplitude of the signal is expressed as a function of time, whereas in a frequency domain, the amplitude of the signal is expressed as a function of frequency. Time-domain signals are displayed using oscilloscopes, and frequency-domain signals are displayed using spectrum analyzers. Figure 1.16 shows two different sinusoidal signals’ time and frequency domains (A and B).

In Figure 1.16b, the frequency of signal A is smaller than that of signal B, and this is because the period (T) of signal A is longer than that of signal B (frequency = $1/T$), as shown in Figure 1.16a. Figure 1.17 shows the frequency and time domains of a signal $v(t)$, which results from mixing two signals. These two signals are $v_1(t)$ with amplitude “A” and $v_2(t)$ with amplitude “B.”

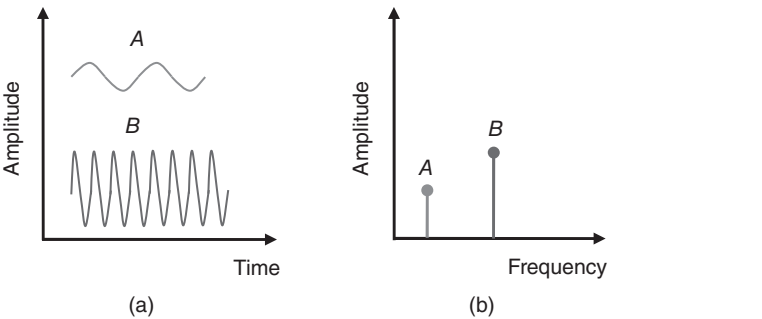


Figure 1.16 Time and frequency domains of two sinusoid signals A and B. (a) Time-domain representation. (b) Frequency domain representation.

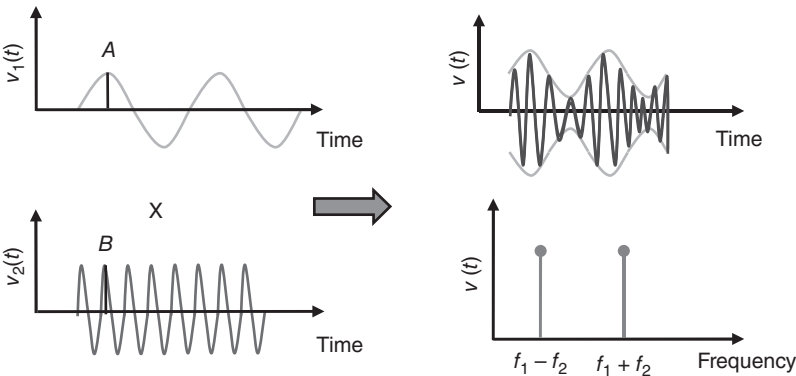


Figure 1.17 Time and frequency domains of two multiplied signals $v_1(t)$ and $v_2(t)$.

The signal $v(t)$ is expressed as

$$v(t) = v_1(t) \times v_2(t) \quad (1.3)$$

where

$$v_1(t) = A \cos(2\pi f_1 t)$$

$$v_2(t) = B \cos(2\pi f_2 t)$$

$$\therefore v(t) = \frac{AB}{2} \cos[2\pi(f_1 + f_2)t] + \frac{AB}{2} \cos[2\pi(f_1 - f_2)t] \quad (1.4)$$

where A , B , f_1 , and f_2 are the amplitudes and frequencies of $v_1(t)$ and $v_2(t)$ signals, respectively. From Eq. (1.4), the obtained signal from the multiplication process has two frequency components $(f_1 + f_2)$ and $(f_1 - f_2)$, referred to as upper and lower sidebands.

1.9 Radiofrequency Spectrum Allocation

Radio waves are controlled and regulated by various governmental and international organizations such as the International Telecommunication Union (ITU) in Geneva, Switzerland; Federal Communication Commission (FCC) in the United States; Innovation Science and Economic Development Canada (ISED) in Canada, Australia Communication and Media Authority (ACMA), and other organizations in other countries. Regulation of the spectrum is implemented to ensure that the communication systems do not interfere with each other. Table 1.1 lists standard frequency ranges in the radiofrequency spectrum. Table 1.2 specifies some spectrum allocations. The 3GPP frequency bands [19] for mmWave 5G-NR cellular phone systems that are time-division duplexing (TDD) systems are listed in Table 1.3.

Table 1.1 Standard frequency ranges.

Frequency	Designation	Abbreviation
30–300 Hz	Extremely low frequency	ELF
300–3000 Hz	Voice frequency	VF
3–30 KHz	Very low frequency	VLF
30–300 KHz	Low frequency	LF
300 KHz–3 MHz	Medium frequency	MF
3–30 MHz	High frequency	HF
30–300 MHz	Very high frequency	VHF
300 MHz–3 GHz	Ultra-high frequency	UHF
3–30 GHz	Super high frequency	SHF
30–300 GHz	Extra high frequency	EHF

Table 1.2 Some spectrum allocations.

Frequency (MHz)	Allocation
26.9–27.4	Citizens band
29–54	Land mobile
50–54	Amateur
54–88	TV low VHF
88–108	FM BCB
108–136	Aircraft
132–174	Land mobile
174–216	TV high VHF
406–512	Land mobile
470–806	TV UHF
806–947	Land mobile
806–947	Cellular AMPS
1200–1600	Amateur Land mobile GPS
1700–2000	Cellular PCS
2400–2500	ISM Bluetooth Wi-Fi

Table 1.3 Frequency range 2 (FR2) for 5G-NR mmWave systems.

Band	Frequency (GHz)	Uplink/Downlink (GHz)
n257	28	26.50–29.50
n258	26	24.25–27.50
n259	41	39.50–43.50
n260	39	37.00–40.00
n261	28	27.50–28.35
n262	47	47.20–48.20

Review Questions

- 1.1 Draw a block diagram of a wireless communication model and explain the function of each block.
- 1.2 Explain the difference between full-duplex and half-duplex radio systems.

- 1.3 Why baseband signals cannot be transmitted directly without modulation.
- 1.4 Briefly explain the difference between AM and FM and why modulation is needed.
- 1.5 Illustrate the time domain and frequency domain of a sinusoidal signal.
- 1.6 Illustrate the process of multiplexing in wireless communications.
- 1.7 Draw a block diagram of an FDM (frequency division multiplexing) system and illustrate the spectrum of an FDM signal.
- 1.8 Briefly discuss the advantages of 4G wireless technology compared to 3G wireless technology.
- 1.9 List the advantages of 5G wireless technology.
- 1.10 Explain the application of FR1 and FR2 bands of 5G NR wireless technology.
- 1.11 Explain the advantages and challenges of using THz frequency in 6G wireless technology.
- 1.12 Illustrate and explain the basic concept of MIMO, and what are the advantages of MIMO systems?
- 1.13 Explain why RF circulators and RF switches are used in radio front-ends of wireless systems.

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