1

Introduction

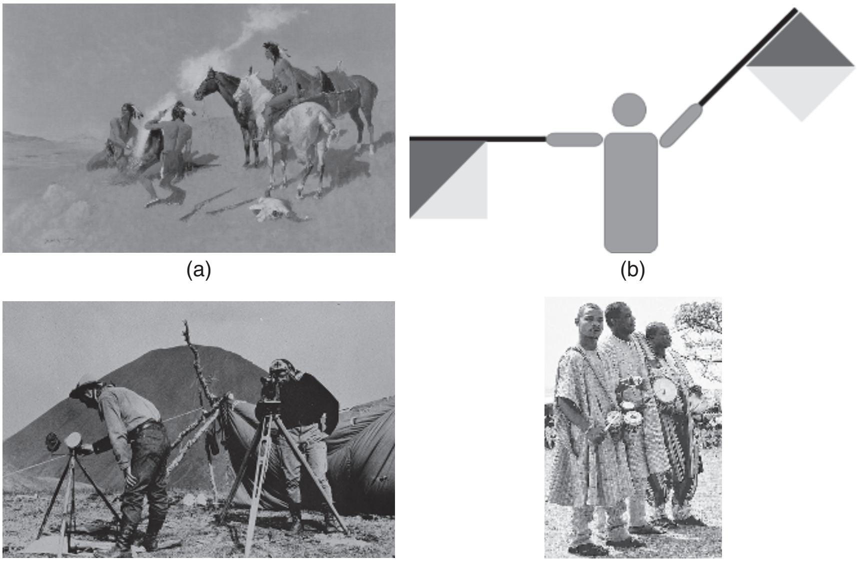
At the end of the nineteenth century, “wireless” meant “wireless telegraphy” which eventually became known as radio. Ham radio kept the term “wireless” alive, but obscure, until cell phones resurrected it toward the end of the twentieth century. Most wireless technologies use radio frequencies (RF), but infrared (IR), magnetic, optical, and acoustic systems also enable wireless communication. Wireless systems include a wide range of fixed, mobile, and portable applications. Designing a wireless system involves all the same challenges as a wired system plus the antennas and propagation channel. This chapter begins with a brief history of wireless communications then explains some basic concepts needed for proceeding through the rest of this book. The second half of this book (Chapters 6–12) is devoted to practical applications.

1.1 Historical Development of Wireless Communications

Long distance communications seem easy now, but that was not the case throughout history. In 490 BC, legend says that Philippides ran from Marathon to Athens and announced that the Greeks defeated the Persians in the Battle of Marathon (according to Google Maps about a 44.4 km drive), then dropped dead [1]. That long run became the standard for today’s marathon. Current wireless networks deliver that same message in a blink of the eye. People wanted a faster way to communicate over long distances than using a messenger. Several ingenious, low data rate innovations emerged. Figure 1.1 shows four early wireless communication systems that replaced face-to-face delivery of the message: smoke signals, heliographs (mirrors), semaphore (flags), and drums. Weather and limited line of sight hindered most wireless communications. In addition, messages had to be simple and were prone to misinterpretation at the receiver.

The first quantum leap in fast long distance communication occurred in the 1800s with the introduction of electrical circuits that send signals over wires. In

Wireless Communications Systems: An Introduction, First Edition. Randy L. Haupt.



(a) (b) (c) (d)

Figure 1.1 Early forms of wireless communications. (a) Smoke signals, (b) semaphore, (c) heliograph, (d) drums.. *Source:* (a) https://commons.wikimedia.org/wiki/File:Frederic_Remington_smoke_signal.jpg. Public domain; (b) Author originated; (c) www.photolib.noaa.gov/historic/c&gs/theb1633.htm. Courtesy of NOAA; (d) https://www.flickr.com/photos/58034970@N00/178631090. Licensed under CC BY 2.0 [3].

the 1830s, Cooke and Wheatstone demonstrated a telegraph system with five magnetic needles that an electric current forced to point at letters and numbers that form a message. Britain adopted this invention for railroad signaling [2]. At the same time, Samuel Morse independently developed the electric telegraph. He collaborated with Gale and Vail to build a telegraph that transmitted an electric signal by pushing an operator key that connects a battery to a wire and sends the electric signal down a wire to a receiver [2]. This simple system required a switch and battery at both ends of a wire. The length of wire and the loss of the signal strength over that wire limited communication distance. Wired communications forced users to established nodes, but significantly increased the data rate as well as made communications independent of weather and line of sight.

Electronic wireless communications began when Maxwell found that all electromagnetic waves travel at the speed of light. He also discovered the relationship between electricity and magnetism [4]. Maxwell's mathematical ideas of electromagnetic wave propagation needed experimental verification, so Heinrich Hertz built and tested the 100 MHz dipole antenna shown in Figure 1.2. In order to increase the radiation intensity in a desired direction, he built the higher gain reflector antenna shown in Figure 1.3. Hertz provided

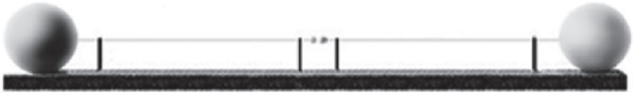


Figure 1.2 The first radiating dipole designed by Hertz. *Source:* https://en.wikipedia.org/wiki/Heinrich_Hertz#/media/File:Hertz_first_oscillator.png.

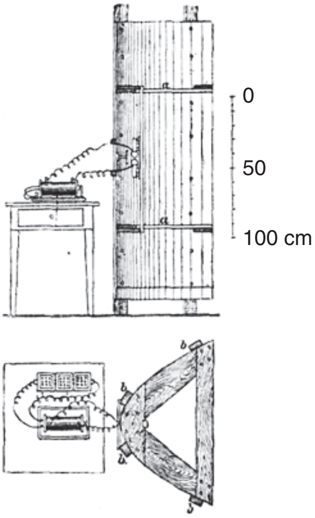


Figure 1.3 Hertz designed higher gain reflector antennas. *Source:* https://commons.wikimedia.org/wiki/File:Hertz_spark_gap_transmitter_and_parabolic_antenna.png.

the means for getting the transmitted signal from a wire to the air then back to another wire connected to a receiver. Professor Oliver Lodge demonstrated the reception of wireless Morse code in 1894 using a newly invented "coherer" or receiver [5]. In 1895, Guglielmo Marconi used a more practical setup to demonstrate transmitted signals up to one-half mile [6]. Marconi then tried two new ideas: (i) placing the antenna high off the ground and (ii) grounding the transmitter and receiver. These modifications demonstrated that signals could travel up to 3.2 km and over hills. Marconi received a British patent for radio in 1898 [7] and a US patent a few years later [8]. Around the same time, Tesla tinkered with radiowave propagation and invented radio remote control [9]. He transmitted an RF wave from the apparatus shown in Figure 1.4 that opened and closed switches in order to steer the model boat. Tesla received a US patent for radio in 1898 [10]. A patent battle between Tesla and Marconi continued until after their deaths. In 1943 (six years after Marconi's death and six months after Tesla's death), the US Supreme Court ruled that Tesla was the inventor of radio and not Marconi.

In 1900, Reginald Fessenden demonstrated amplitude-modulation (AM) radio that allowed more than one station to broadcast at the same time and in the same area (as opposed to spark-gap radio, where one transmitter covers the

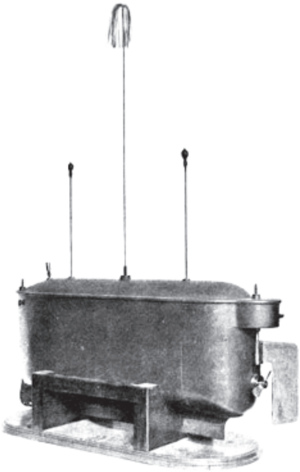


Figure 1.4 Tesla's apparatus for the remote control of a boat. *Source:* https://en.wikipedia.org/wiki/Nikola_Tesla#/media/File:Tesla_boat1.jpg.

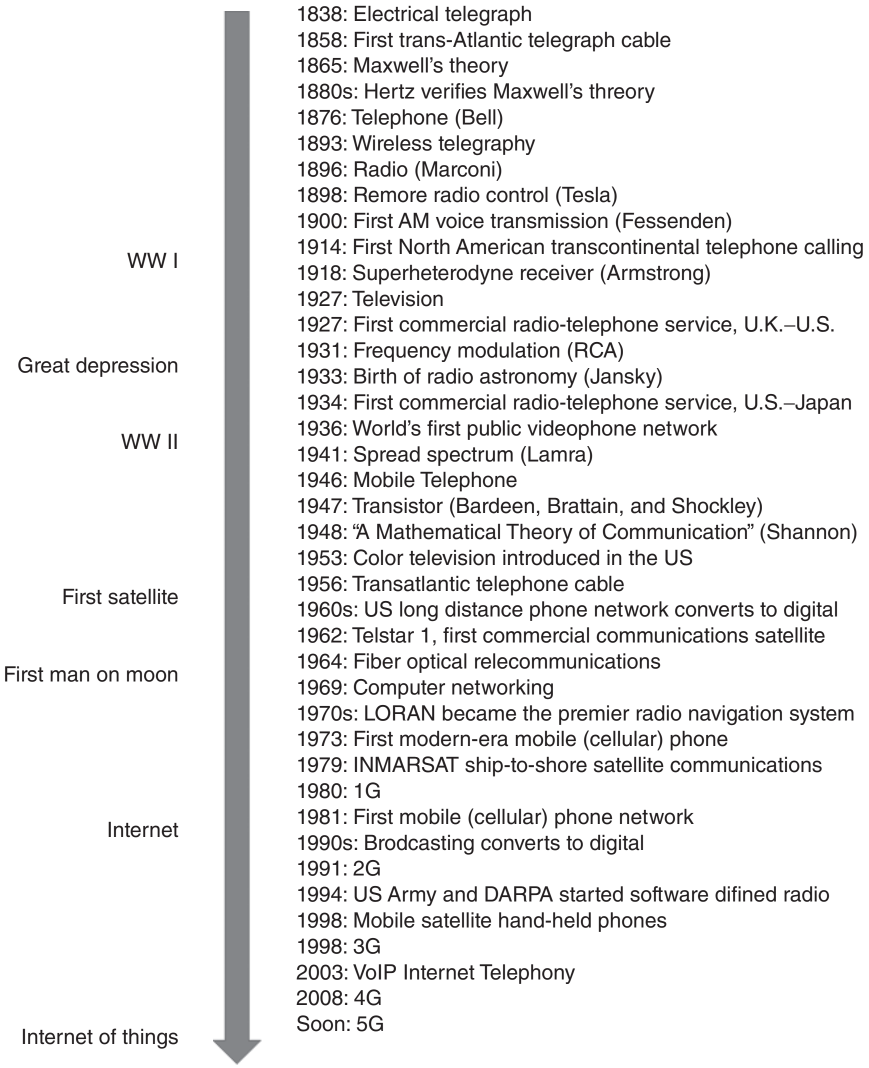
entire bandwidth of the spectrum) [11]. A few years later, Edwin Armstrong patented three important inventions that made today's radio possible: regeneration, superheterodyning, and wide-band frequency modulation (FM) [12]. Regeneration or the use of positive feedback increased the received radio signal amplitude to the point where headphones were no longer needed. The superheterodyne receiver replaced several tuning controls with only one. It made radios more sensitive and selective as well. Wideband FM improved the sound quality and fidelity over AM. Armstrong set the stage for the 1940s when a flurry of inventions made advanced wireless communications possible, including the mobile phone, spread spectrum, and television. In addition, Harry Nyquist's work (Nyquist rate) became the impetus for Claude Shannon to establish the theoretical foundations for modern information theory [13]. Some of the more notable advances in wireless communications appear in Figure 1.5.

1.2 Information

A message contains information that a sender wants the recipient to know. The sender and receiver may be human or not. Some messages are a simple "yes" or "no," while others are quite complicated, such as a movie. Message value depends on the information content. In mathematical terms, the information content of message n is expressed in bits by [14]

$$I_n = \log_2(1/p_n) \text{ bits} \tag{1.1}$$

where p_n is the probability of transmitting message n. Thus, a less likely message has a higher information content than a more likely message. The game of



1838: Electrical telegraph
1858: First trans-Atlantic telegraph cable
1865: Maxwell's theory
1880s: Hertz verifies Maxwell's threory
1876: Telephone (Bell)
1893: Wireless telegraphy
1896: Radio (Marconi)
1898: Remore radio control (Tesla)
1900: First AM voice transmission (Fessenden)
1914: First North American transcontinental telephone calling
1918: Superheterodyne receiver (Armstrong)
1927: Television
1927: First commercial radio-telephone service, U.K.–U.S.
1931: Frequency modulation (RCA)
1933: Birth of radio astronomy (Jansky)
1934: First commercial radio-telephone service, U.S.–Japan
1936: World's first public videophone network
1941: Spread spectrum (Lamra)
1946: Mobile Telephone
1947: Transistor (Bardeen, Brattain, and Shockley)
1948: "A Mathematical Theory of Communication" (Shannon)
1953: Color television introduced in the US
1956: Transatlantic telephone cable
1960s: US long distance phone network converts to digital
1962: Telstar 1, first commercial communications satellite
1964: Fiber optical relecommunications
1969: Computer networking
1970s: LORAN became the premier radio navigation system
1973: First modern-era mobile (cellular) phone
1979: INMARSAT ship-to-shore satellite communications
1980: 1G
1981: First mobile (cellular) phone network
1990s: Brodcasting converts to digital
1991: 2G
1994: US Army and DARPA started software difined radio
1998: Mobile satellite hand-held phones
1998: 3G
2003: VoIP Internet Telephony
2008: 4G
Soon: 5G

Figure 1.5 Timeline for the development of modern wireless systems.

Scrabble uses this concept to assign points to a letter. In Scrabble, players take turns placing tiles with letters and points onto a 15 × 15 grid of squares in order to form words as in a crossword puzzle [15]. Players receive points on the tiles used to form a word. The letter "Q" has a value of 10, whereas the letter "E" only has a value of 1, because "Q" occurs less frequently in the English language than "E." You know less about a word if it has the letter "E" than if it has the letter "Q." Table 1.1 contains the number of letter tiles and associated points in Scrabble.

Table 1.1 Distribution of letters and points in the game of Scrabble [16].

		Number of tiles							
		1	**2**	**3**	**4**	**6**	**8**	**9**	**12**
Points	0		[blank]						
	1				L S U	N R T	O	A I	E
	2			G	D				
	3		B C M P						
	4		F H V W Y						
	5	K							
	8	J X							
	10	Q Z							

The average information called entropy (H) equals the information of message n times its probability of occurrence summed over all N_{mess} messages.

$$H = \sum_{n=1}^{N_{\text{mess}}} p_n I_n = \sum_{n=1}^{N_{\text{mess}}} p_n \log_2(1/p_n) \ \text{bits} \tag{1.2}$$

Example

Calculate the information in the first five letters of the English alphabet given the graph in Figure 1.6.

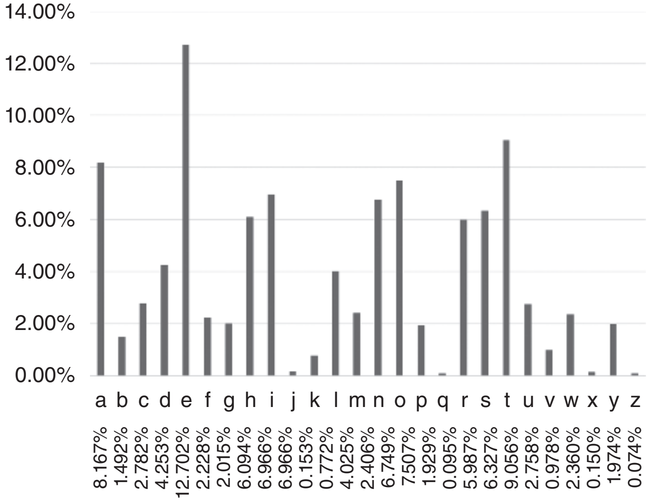


Figure 1.6 Frequency of letters in English text [17].

Solution

Use (1.1) and the values of p_n in Figure 1.6 to generate the following Table 1.2:

Table 1.2 Probability and information associated with the first five letters of the English alphabets.

Letter	A	B	C	D	E
p_n	0.08167	0.01492	0.02782	0.04253	0.12702
I_n	3.6140	6.0666	5.1677	4.5554	2.9769

1.3 Wired Communications

A transmission line or waveguide minimizes the signal loss by forcing the signal into a conduit from the transmitter to the receiver. Even wireless systems have cabling between the transmitter and the antenna or from the antenna to the receiver.

A single wire only carries a DC current (Figure 1.7a). Time varying signals need two paths as shown in Figure 1.7b. At one point along the twin wire transmission line, the current on one wire travels in the opposite direction of the current on the other wire. The fields between the wires add in phase while the fields outside the wires do not. Thus, the signal stays between the wires as it propagates from one end to the other. The copper wires have a protective plastic that keeps the wire separation constant. Twisting the two wires, as shown in Figure 1.7c, reduces coupling from other nearby wires. Cheap two-wire transmission lines work fine at frequencies below 1 GHz. The twin wire transmission line characteristic impedance is given by [18]

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}}\frac{1}{\pi}\cosh^{-1}\left(\frac{s}{d_{ia}}\right)\ \Omega \tag{1.3}$$

where

s = separation between wires
d_{ia}= wire diameter
μ= permeability
$\varepsilon = \varepsilon_r\varepsilon_0$= permittivity
ε_r= relative permittivity.

In free space, $\mu = \mu_0 = 4\pi \times 10^{-7}$ N/A^2 and $\varepsilon = \varepsilon_0 = 8.854\,187\,817 \times 10^{-12}$ F/m. When all components or lines in an RF circuit have the same impedance, the maximum power reaches the load. For instance, an antenna that has the same impedance as the transmission line receives the maximum possible power.

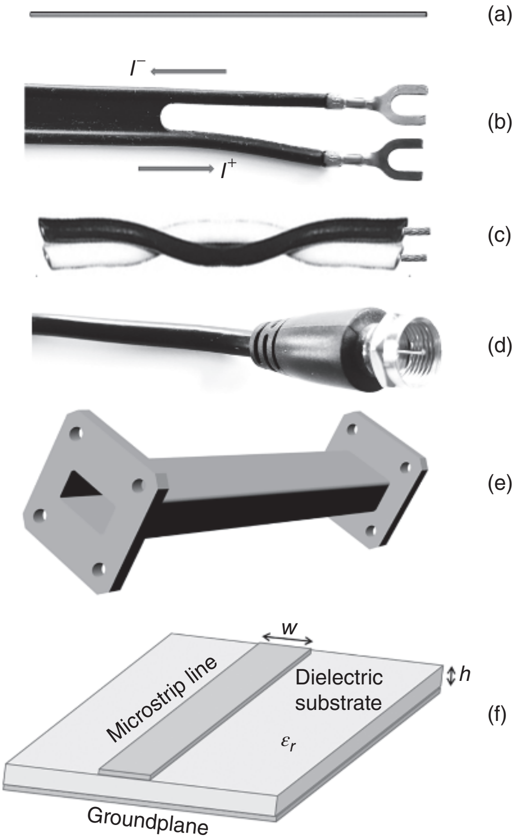


Figure 1.7 Different types of transmission lines and waveguides carry signals from one point to another. (a) Single wire DC, (b) twin wire, (c) twisted wire, (d) coaxial cable, (e) rectangular wave, and (f) microstrip.

Example

Find the wire separation in a twin wire transmission line with an impedance of 75 Ω using wires that are 1 mm in diameter and surrounded by plastic with $\varepsilon_r = 2.2$.

Solution

Substitute the known quantities into (1.3) and solve $75 = \frac{377}{\pi\sqrt{2.2}}\cosh^{-1}\left(\frac{s}{1}\right) \Rightarrow s = 1.462$ mm

Coaxial cable or coax (Figure 1.7d) appears in many communication systems above 50 MHz, including satellite and cellular communication systems. Its advantages include low cost, high bandwidth, and protection from interference. The coax has an inner wire of diameter d_{in} surrounded by an outer cylindrical conductor of diameter D_{out}. A dielectric surrounding the inner wire maintains a constant separation between the two conductors. If the dielectric

Table 1.3 RG-58 coaxial cable attenuation as a function of frequency (dB/m) [19].

Frequency (MHz)	**100**	**500**	**1000**	**2500**
Loss (dB)	0.125	0.313	0.478	0.87

is air or gas, then dielectric spacers placed at regular intervals maintain a constant separation between the conductors. The current on the inner conductor travels in the opposite direction as the current on the inside of the outer conductor, resulting in the signal propagating in a transverse electromagnetic (TEM) mode where both the electric and magnetic fields are perpendicular to the direction of propagation. The coaxial cable has characteristic impedance given by [19]

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}}\frac{1}{2\pi}\ln\frac{D_{\text{out}}}{d_{\text{in}}} \tag{1.4}$$

Table 1.3 shows the loss in dB/m of RG-58 coaxial cable. The loss increases with frequency. In contrast, free space loss for wireless systems is independent of frequency.

A waveguide (like the rectangular metal waveguide in Figure 1.7e) contains an electromagnetic wave as it propagates from one end to the other. These reflections form modes that are a function of frequency and the waveguide dimensions. Among other things, the impedance depends on the shape of the waveguide and the mode. Optical fibers rely on variations in the dielectric constant of the glass to contain the signal within the fiber.

A PCB (printed circuit board) consists of a thin dielectric sandwiched between two very thin layers of copper. Microstrip lines have a thin trace etched from the top layer (Figure 1.7f). The line width (w), substrate height (h), and substrate dielectric constant (ε_r) determine the line characteristic impedance [20]. Typically, the impedance is designed to be 50 Ω.

1.4 Spectrum

Signals in wireless communications occupy a designated region of the RF spectrum. The operating frequency depends on regulatory requirements, propagation characteristics, signal attenuation, and available bandwidth. These properties have a distinct impact on key requirements such as the radio link range and the peak throughput as well as on the system capacity. For example more bandwidth allows higher throughput. Throughput depends on the received signal strength. In turn, the received signal strength depends

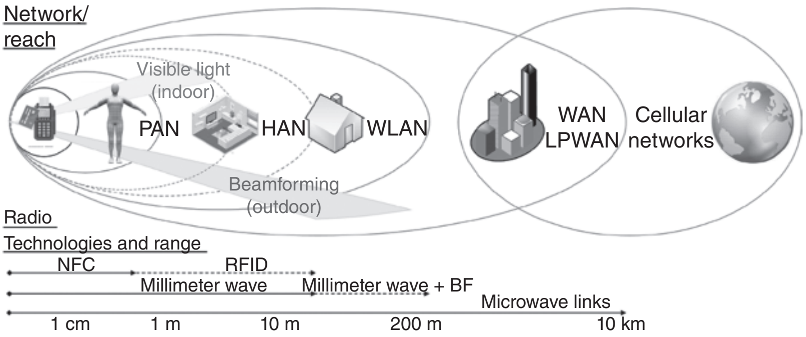


Figure 1.8 Overview of radio technologies. *Source:* Burg *et al*. [21]. Reproduced with permission of IEEE.

on the propagation characteristics (attenuation) and the maximum transmit power. On the one hand, higher frequencies have more available bandwidth, which allows for higher capacity. On the other hand, signal attenuation also increases proportional to the frequency which limits the range at a given transmit power. Higher frequencies are generally more attenuated by obstacles such as walls or windows. Figure 1.8 has an overview of different RF and technologies with their associated radio range.

A wireless system inserts its signal into the frequency spectrum in order to reduce interference with the myriad of other users. A party with many people talking to each other prevents a listener from hearing one particular conversation, because all speakers communicate at baseband. In other words, the frequency components in the signal extend from 0 Hz to some maximum voice frequency. Converting each conversation to an electrical signal does not help unless the different signals differ in time, frequency, coding, or polarization. The message rides on an electrical signal at a higher frequency called a carrier that propagates through the air (wireless) or through a transmission line or waveguide (wired). Frequency and polarization are properties of the carrier while time and coding are properties of the information signal. The transmitter modulates the baseband signal to a higher frequency and the receiver demodulates it.

The radio frequency spectrum extends from about 3 kHz to 300 GHz. Figure 1.9 shows the playground for various wireless applications. The small print precludes reading the designated frequency bands but provides an appreciation for the vast number of applications and the importance of having sufficient bandwidth to perform the desired function. Go to [22] to magnify the small print. Fierce and expensive battles occur between users that want to occupy the same frequency band. Governments auction the rights (licenses) to transmit signals over specific bands in order to efficiently allocate the resource as well as to raise money. Currently, commercial applications have

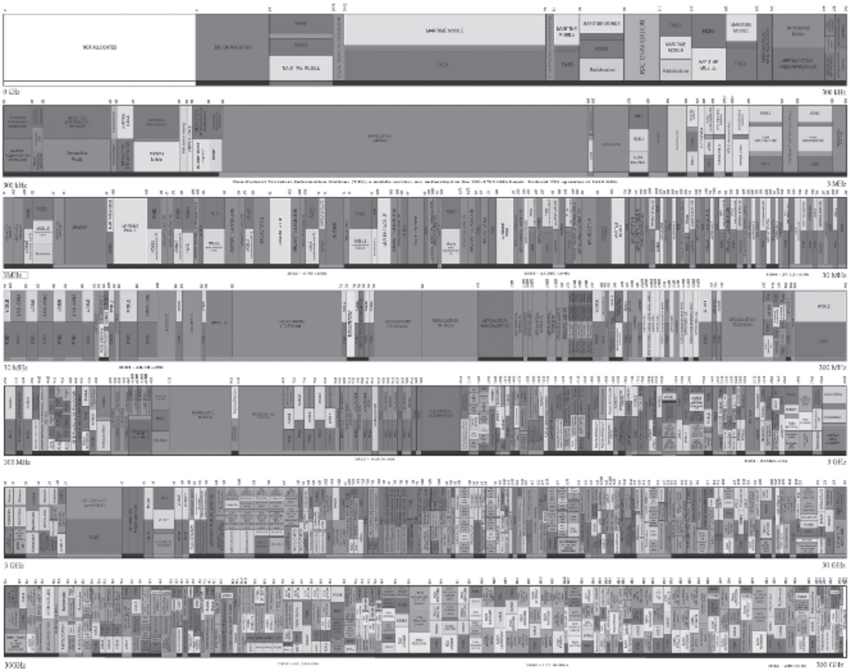


Figure 1.9 United States frequency allocations in the radio spectrum (courtesy of NTIA) [22]. *Source:* www.ntia.doc.gov.

needs that conflict with traditional government allocations, such as military and weather radar bands.

The International Telecommunications Union (ITU) advises national or regional regulatory bodies that assign and regulate licensed and unlicensed frequency bands. Licensed bands cover the majority of the spectrum and require a license for operating wireless systems. While licensing bands are expensive, the exclusive access avoids uncontrolled interference between users of the shared medium to provide reliable quality-of-service. Also, regulations often allow for larger power budgets in licensed bands than in unlicensed bands since interference is better controlled. In addition to the licensed spectrum, some frequency bands exist for use by anybody. These unlicensed parts of the spectrum are known as industrial, scientific, and medical (ISM) bands. Regulations define a set of rules that enables users to coexist. These rules typically restrict the maximum amount of transmit power in order to limit the range of each transmitter and enable spatial reuse of the spectrum.

The severe bandwidth limitations in the microwave spectrum motivate the use of higher (millimeter wave) frequencies at or beyond 28 GHz. Technology initially limited use of millimeter wave frequencies, but CMOS (complementary metal–oxide–semiconductor) processing opened consumer electronics to these frequencies [21]. Another recent push toward millimeter waves was the worldwide availability of almost 7 GHz of bandwidth at the ISM band around 60 GHz. Millimeter waves suffer more loss than microwaves, so they have limited use. Obstacles, including thin walls and windows, highly attenuate millimeter waves. The 60-GHz ISM band lies close to the oxygen absorption frequency that induces even more attenuation.

Radiation levels from wireless systems have government specified limits both in-band and out-of-band. Electromagnetic interference (EMI), also known as radio frequency interference (RFI), occurs when a device transmits signals that interfere with another device. Electromagnetic compatibility (EMC) means that a device does not emit radiation that causes EMI in other devices. EMI results from conducted and radiated emissions, as well as electrostatic discharge (ESD). EMC requires all equipment operating in a common electromagnetic environment to not interfere with each other. Three approaches to EMC include [23]:

1. Suppress emissions at the source.
2. Make the coupling path as inefficient as possible.
3. Make the receptor less susceptible to the EMI.

Simple solutions, such as grounding and shielding, solve many of these issues.

The Federal Communications Commission (FCC) regulates broadcast stations, amateur radio operators, and repeater stations in the United States. In addition, the FCC regulates EMC compliance under Title 47 of the Code of Federal Regulations [24]. Part 15 of these regulations concerns radio frequency devices, including intentional transmitters (e.g. mobile phones) and nonintentional radiators (e.g. PCs and TV receivers). Part 18 concerns equipment operating in the ISM bands. The FCC requirements only relate to radiated and conducted emissions. The FCC has no immunity limits like those associated with European EMC Certification.

1.5 Communication System

This book has two parts. The first part introduces the fundamentals of wireless communications. The block diagram of the wireless system in Figure 1.10 forms an outline for Chapters 2 through 5. Wireless communication starts with information. The information might be data or music. An analog-to-digital converter (ADC) transforms an analog signal into bits. Symbols contain groups of bits. For example the 8-bit ASCII code for the symbol “1” is 00110001. Additional bits added to the code detect and/or correct errors. This “channel coding” allows the receiver to correct errors induced by the channel. The modulator maps the channel encoder output to an analog signal suitable for

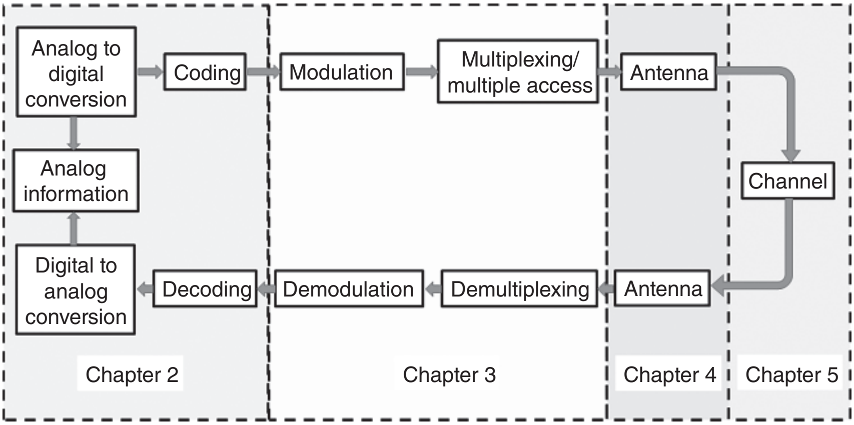


Figure 1.10 Block diagram of a digital wireless communications system.

transmission into the channel. An antenna transmits the signal into the channel at one end and another antenna receives the signal at the other end. A channel is the path taken by the transmitted signal to the receiver. Signals become distorted, noisy, and attenuated in the channel. The demodulator converts the received analog signal into a digital signal that feeds the channel decoder, etc. before arriving at the receiver. Successful signal detection occurs when the signal strength exceeds the receiver threshold and noise and interference did not induce errors that cannot be corrected.

The second half of this book uses the basic information from the first half to cover some practical topics in wireless communications. Chapter 6 introduces satellite communications, while Chapter 7 presents radio frequency identification (RFID). Smart antennas are critical to future advancements in communications, so Chapters 8–10 cover direction finding, adaptive nulling, and multiple input multiple output (MIMO). Security (Chapter 11) and Biological Effects of RF (Chapter 12) are topics of great concern and complete the book. The appendix has several short topics of interest. Many examples and problems in this book use MATLAB, so a few MATLAB hints appear in Appendix A.

Problems

1.1 Calculate the information in the letters A, B, C, D, and E of the English alphabet using the probabilities in Figure 1.6.

1.2 How many bits do the following pieces of information contain? (a) message probability = ½ and (b) message probability = 1.0.

1.3 Calculate the entropy of the English alphabet using Figure 1.6.

1.4 Generate a histogram plot for Scrabble that is similar to Figure 1.6, except the y-axis is (a) points and (b) number of letters.

1.5 Calculate the entropy of Scrabble.

1.6 A meter has a read out of [−5, −3, −1, 0, 1, 3, and 5 V] with corresponding probabilities of [0.05 0.1 0.1 0.15 0.05 0.25 0.3]. Find the (a) entropy and (b) entropy if the output is only represented by three levels [−4 V 0 V 4 V].

1.7 Find the entropy of a binary code with two symbols, one with probability p and the other with probability $1 - p$.

1.8 Calculate the entropy of the string "`asasdgasdgdsg`" based on the frequency of occurrence of the letters in the string.

1.9 A codebook has four messages with probabilities of [0.1 0.2 0.3 0.4]. Find the number of bits needs to communicate the message using entropy as the lower bound.

1.10 If four messages have probabilities of [1/8 3/8 3/8 1/8], find the average information per message.

1.11 If five messages have probabilities of [1/2 1/4 1/16 1/16], find the average information per message.

1.12 A code uses a dash that is three times as long as a dot and occurs one in three symbols.
(a) Calculate the information in a dot and a dash.
(b) Calculate the average information of this code.
(c) If a dot lasts 10 ms and the interval between symbols is 10 ms, then calculate the average rate of information transmission.

1.13 Plot the input impedance of a twin wire transmission line vs. s/d_{in} using (1.3). Assume the wires are enclosed in plastic (find permittivity on web).

1.14 Calculate the input impedance for RG-58 cable. Obtain data for the calculation from a company on the web. How does your calculation compare with that given by the company?

1.15 Locate an online calculator for microstrip impedance. Find the impedance of a microstrip line with $\varepsilon_r = 4$, $h = 0.8$, and $w = 1.65$ mm. Assume the microstrip trace is 0.035 mm thick.

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