RF and Microwave Wireless Systems. Kai Chang

ISBNs: 0-471-35199-7 (Hardback); 0-471-22432-4 (Electronic)

CHAPTER ONE

Introduction

1.1 BRIEF HISTORY OF RF AND MICROWAVE WIRELESS SYSTEMS

The wireless era was started by two European scientists, James Clerk Maxwell and Heinrich Rudolf Hertz. In 1864, Maxwell presented Maxwell's equations by unifying the works of Lorentz, Faraday, Ampere, and Gauss. He predicted the propagation of electromagnetic waves in free space at the speed of light. He postulated that light was an electromagnetic phenomenon of a particular wavelength and predicted that radiation would occur at other wavelengths as well. His theory was not well accepted until 20 years later, after Hertz validated the electromagnetic wave (wireless) propagation. Hertz demonstrated radio frequency (RF) generation, propagation, and reception in the laboratory. His radio system experiment consisted of an end-loaded dipole transmitter and a resonant square-loop antenna receiver operating at a wavelength of 4 m. For this work, Hertz is known as the father of radio, and frequency is described in units of hertz (Hz).

Hertz's work remained a laboratory curiosity for almost two decades, until a young Italian, Guglielmo Marconi, envisioned a method for transmitting and receiving information. Marconi commercialized the use of electromagnetic wave propagation for wireless communications and allowed the transfer of information from one continent to another without a physical connection. The telegraph became the means of fast communications. Distress signals from the *S.S. Titanic* made a great impression on the public regarding the usefulness of wireless communications. Marconi's wireless communications using the telegraph meant that a ship was no longer isolated in the open seas and could have continuous contact to report its positions. Marconi's efforts earned him the Nobel Prize in 1909.

In the early 1900s, most wireless transmission occurred at very long wavelengths. Transmitters consisted of Alexanderson alternators, Poulsen arcs, and spark gaps. Receivers used coherers, Fleming valves, and DeForest audions. With the advent of DeForest's triode vacuum tube in 1907, continuous waves (CW) replaced spark gaps, and more reliable frequency and power output were obtained for radio broadcasting at frequencies below 1.5 MHz. In the 1920s, the one-way broadcast was made to police cars in Detroit. Then the use of radio waves for wireless broadcasting, communications between mobile and land stations, public safety systems, maritime mobile services, and land transportation systems was drastically increased. During World War II, radio communications became indispensable for military use in battlefields and troop maneuvering.

World War II also created an urgent need for radar (standing for radio detection and ranging). The acronym radar has since become a common term describing the use of reflections from objects to detect and determine the distance to and relative speed of a target. A radar's resolution (i.e., the minimum object size that can be detected) is proportional to wavelength. Therefore, shorter wavelengths or higher frequencies (i.e., microwave frequencies and above) are required to detect smaller objects such as fighter aircraft.

Wireless communications using telegraphs, broadcasting, telephones, and point-to-point radio links were available before World War II. The widespread use of these communication methods was accelerated during and after the war. For long-distance wireless communications, relay systems or tropospheric scattering were used. In 1959, J. R. Pierce and R. Kompfner envisioned transoceanic communications by satellites. This opened an era of global communications using satellites. The satellite uses a broadband high-frequency system that can simultaneously support thousands of telephone users, tens or hundreds of TV channels, and many data links. The operating frequencies are in the gigahertz range. After 1980, cordless phones and

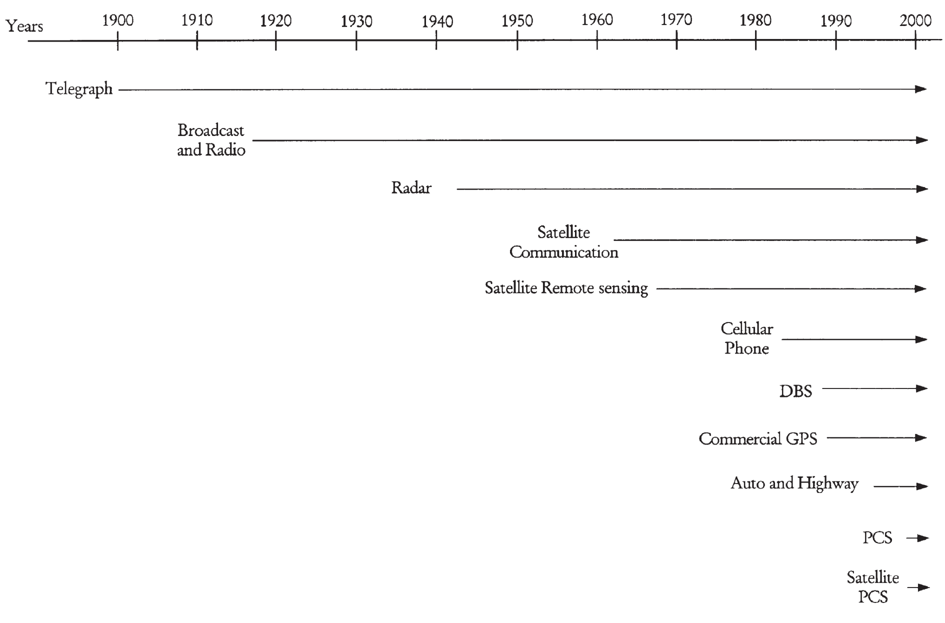

FIGURE 1.1 Summary of the history of wireless systems.

cellular phones became popular and have enjoyed very rapid growth in the past two decades. Today, personal communication systems (PCSs) operating at higher frequencies with wider bandwidths are emerging with a combination of various services such as voice mail, email, video, messaging, data, and computer on-line services. The direct link between satellites and personal communication systems can provide voice, video, or data communications anywhere in the world, even in the most remote regions of the globe.

In addition to communication and radar applications, wireless technologies have many other applications. In the 1990s, the use of wireless RF and microwave technologies for motor vehicle and highway applications has increased, especially in Europe and Japan. The direct broadcast satellite (DBS) systems have offered an alternative to cable television, and the end of the Cold War has made many military technologies available to civilian applications. The global positioning systems (GPSs), RF identification (RFID) systems, and remote sensing and surveillance systems have also found many commercial applications.

Figure 1.1 summarizes the history of these wireless systems.

1.2 FREQUENCY SPECTRUMS

Radio frequencies, microwaves, and millimeter waves occupy the region of the electromagnetic spectrum below 300 GHz. The microwave frequency spectrum is from 300 MHz to 30 GHz with a corresponding wavelength from 100 cm to 1 cm. Below the microwave spectrum is the RF spectrum and above is the millimeter-wave spectrum. Above the millimeter-wave spectrum are submillimeter-wave, infrared, and optical spectrums. Millimeter waves (30–300 GHz), which derive their name from the dimensions of the wavelengths (from 10 to 1 mm), can be classified as microwaves since millimeter-wave technology is quite similar to that of microwaves. Figure 1.2 shows the electromagnetic spectrum. For convenience, microwave and millimeter-wave spectrums are further divided into many frequency bands. Figure 1.2 shows some microwave bands, and Table 1.1 shows some millimeter-wave bands. The RF spectrum is not well defined. One can consider the frequency spectrum below 300 MHz as the RF spectrum. But frequently, literatures use the RF term up to 2 GHz or even higher.

The Federal Communications Commission (FCC) allocates frequency ranges and specifications for different applications in the United States, including televisions, radios, satellite communications, cellular phones, police radar, burglar alarms, and navigation beacons. The performance of each application is strongly affected by the atmospheric absorption. The absorption curves are shown in Fig. 1.3. For example, a secure local area network would be ideal at 60 GHz due to the high attenuation caused by the O_2 resonance.

As more applications spring up, overcrowding and interference at lower frequency bands pushes applications toward higher operating frequencies. Higher frequency operation has several advantages, including:

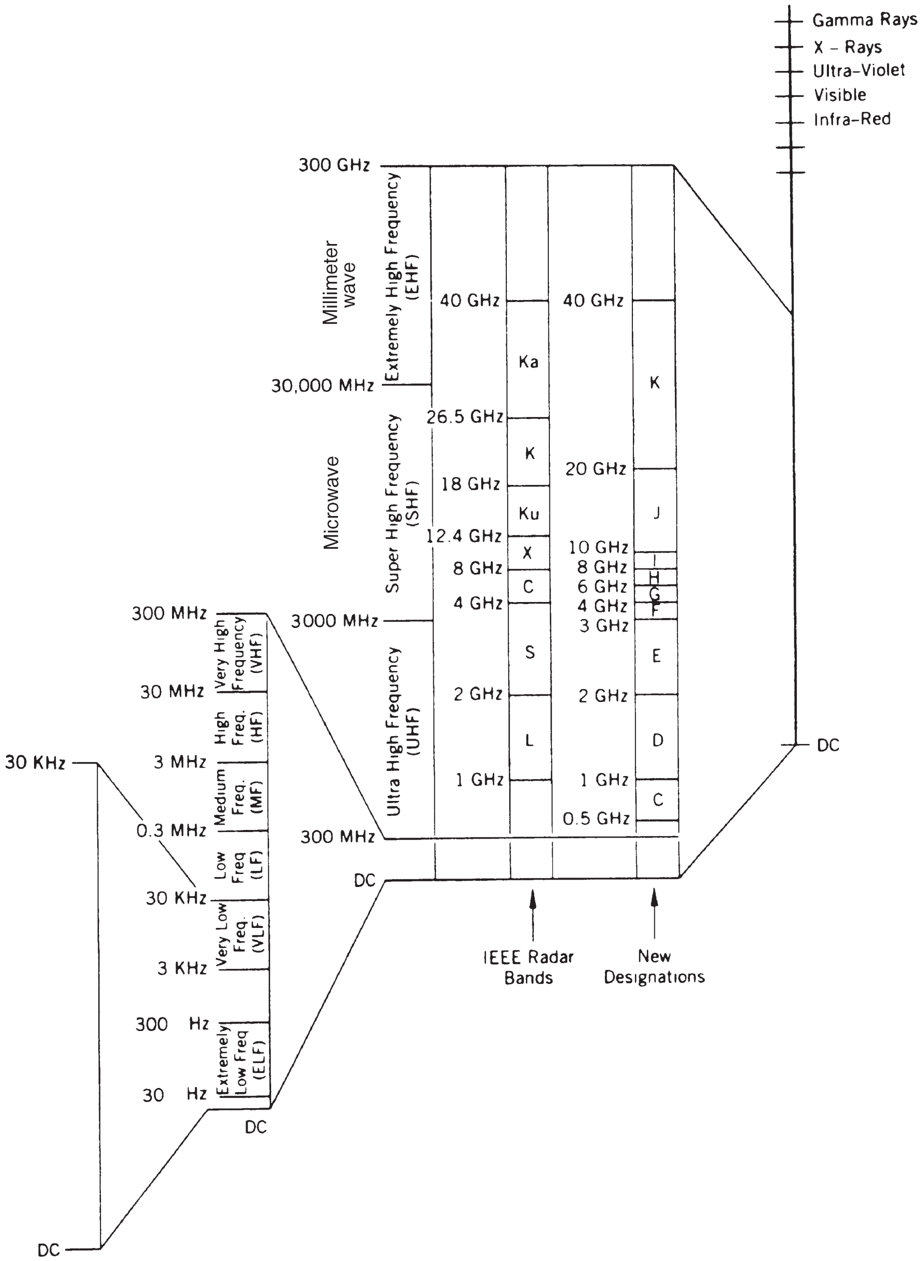

FIGURE 1.2 Electromagnetic spectrum.

1. Larger instantaneous bandwidth for greater transfer of information
2. Higher resolution for radar, bigger doppler shift for CW radar, and more detailed imaging and sensing
3. Reduced dimensions for antennas and other components
4. Less interference from nearby applications
5. Fast speed for digital system signal processing and data transmission
6. Less crowded spectrum
7. Difficulty in jamming (military applications)

TABLE 1.1 Millimeter-Wave Band Designation

Designation	Frequency Range (GHz)
Q-band	33–50
U-band	40–60
V-band	50–75
E-band	60–90
W-band	75–110
D-band	110–170
G-band	140–220
Y-band	220–325

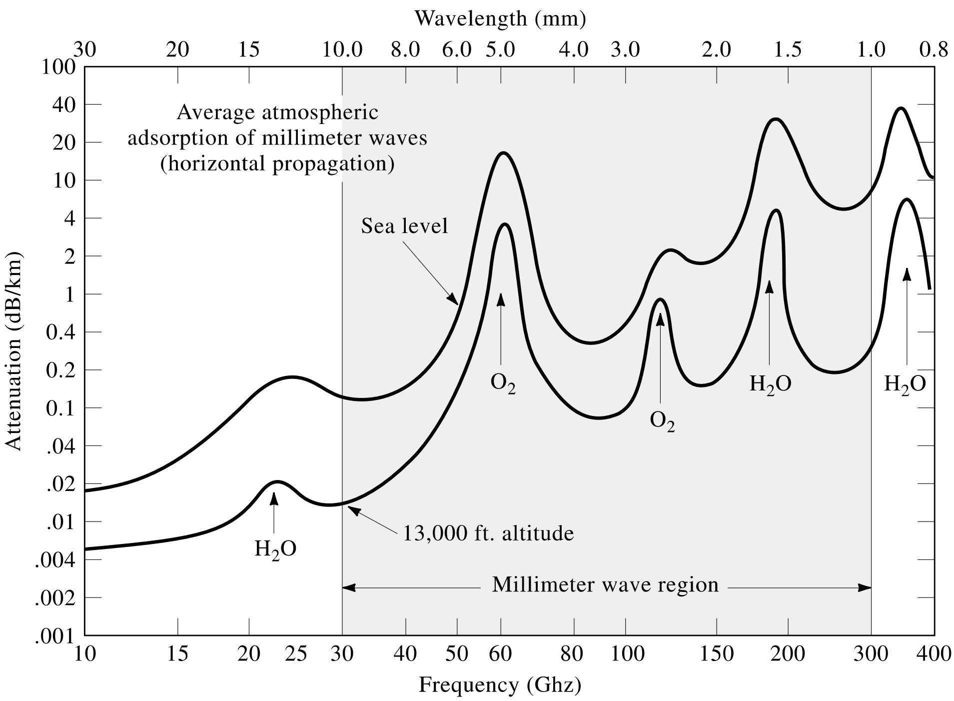

FIGURE 1.3 Absorption by the atmosphere in clear weather.

The use of higher frequency also has some disadvantages:

1. More expensive components
2. Higher atmospheric losses
3. Reliance on GaAs instead of Si technology
4. Higher component losses and lower output power from active devices
5. Less accurate design tools and less mature technologies

The electron mobility in GaAs is higher than that in silicon. Therefore, GaAs devices can operate at higher frequencies and speeds. Current silicon-based devices are commonly used up to 2 GHz. Above 4 GHz, GaAs devices are preferred for better performance. However, GaAs processing is more expensive, and the yield is lower than that of silicon.

1.3 WIRELESS APPLICATIONS

Two of the most historically important RF/microwave applications are communication systems and radar; but there are many others. Currently, the market is driven by the phenomenal growth of PCSs, although there is also an increased demand for satellite-based video, telephone, and data communication systems.

Radio waves and microwaves play an important role in modern life. Television signals are transmitted around the globe by satellites using microwaves. Airliners are guided from takeoff to landing by microwave radar and navigation systems. Telephone and data signals are transmitted using microwave relays. The military uses microwaves for surveillance, navigation, guidance and control, communications, and identification in their tanks, ships, and planes. Cellular telephones are everywhere.

The RF and microwave wireless technologies have many commercial and military applications. The major application areas include communications, radar, navigation, remote sensing, RF identification, broadcasting, automobiles and highways, sensors, surveillance, medical, and astronomy and space exploration. The details of these applications are listed below:

1. *Wireless Communications*. Space, long-distance, cordless phones, cellular telephones, mobile, PCSs, local-area networks (LANs), aircraft, marine, citizen's band (CB) radio, vehicle, satellite, global, etc.
2. *Radar*. Airborne, marine, vehicle, collision avoidance, weather, imaging, air defense, traffic control, police, intrusion detection, weapon guidance, surveillance, etc.
3. *Navigation*. Microwave landing system (MLS), GPS, beacon, terrain avoidance, imaging radar, collision avoidance, auto-pilot, aircraft, marine, vehicle, etc.

4. *Remote Sensing*. Earth monitoring, meteorology, pollution monitoring, forest, soil moisture, vegetation, agriculture, fisheries, mining, water, desert, ocean, land surface, clouds, precipitation, wind, flood, snow, iceberg, urban growth, aviation and marine traffic, surveillance, etc.
5. *RF Identification*. Security, antitheft, access control, product tracking, inventory control, keyless entry, animal tracking, toll collection, automatic checkout, asset management, etc.
6. *Broadcasting*. Amplitude- and frequency-modulated (AM, FM) radio, TV, DBS, universal radio system, etc.
7. *Automobiles and Highways*. Collision warning and avoidance, GPS, blind-spot radar, adaptive cruise control, autonavigation, road-to-vehicle communications, automobile communications, near-obstacle detection, radar speed sensors, vehicle RF identification, intelligent vehicle and highway system (IVHS), automated highway, automatic toll collection, traffic control, ground penetration radar, structure inspection, road guidance, range and speed detection, vehicle detection, etc.
8. *Sensors*. Moisture sensors, temperature sensors, robotics, buried-object detection, traffic monitoring, antitheft, intruder detection, industrial sensors, etc.
9. *Surveillance and Electronic Warfare*. Spy satellites, signal or radiation monitoring, troop movement, jamming, antijamming, police radar detectors, intruder detection, etc.
10. *Medical*. Magnetic resonance imaging, microwave imaging, patient monitoring, etc.
11. *Radio Astronomy and Space Exploration*. Radio telescopes, deep-space probes, space monitoring, etc.
12. *Wireless Power Transmission*. Space to space, space to ground, ground to space, ground to ground power transmission.

1.4 A SIMPLE SYSTEM EXAMPLE

A wireless system is composed of active and passive devices interconnected to perform a useful function. A simple example of a wireless radio system is shown in Fig. 1.4.

The transmitter operates as follows. The input baseband signal, which could be voice, video, or data, is assumed to be bandlimited to a frequency f_m. This signal is filtered to remove any components that may be beyond the channel's passband. The message signal is then mixed with a local oscillator (LO) signal to produce a modulated carrier in a process called up-conversion since it produces signals at frequencies $f_{\mathrm{LO}} + f_m$ or $f_{\mathrm{LO}} - f_m$ which are normally much higher than f_m. The modulated carrier can then be amplified and transmitted by the antenna.

When the signal arrives at the receiver, it is normally amplified by a low-noise amplifier (LNA). The LNA may be omitted from some systems when the received signal has enough power to be mixed directly, as may occur in short-distance

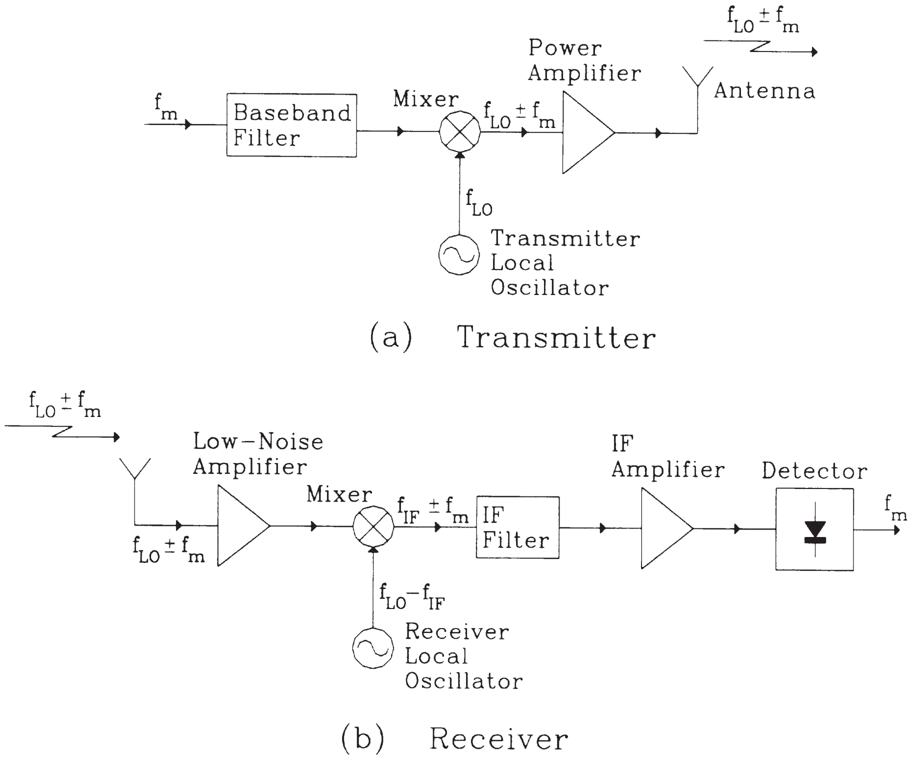

FIGURE 1.4 Block diagram of a simplified wireless radio system.

communication links. The mixer then produces a signal at a frequency $f_{\mathrm{IF}} + f_m$ or $f_{\mathrm{IF}} - f_m$ in a process called down-conversion since f_{IF} is chosen to be much lower than f_{LO}. The signal is filtered to remove any undesired harmonic and spurious products resulting from the mixing process and is amplified by an intermediate-frequency (IF) amplifier. The output of the amplifier goes to a detector stage where the baseband signal f_m, which contains the original message, is recovered.

To perform all of these functions, the microwave system relies on separate components that contribute specific functions to the overall system performance. Broadly speaking, microwave components can be classified as transmission lines, couplers, filters, resonators, signal control components, amplifiers, oscillators, mixers, detectors, and antennas.

1.5 ORGANIZATION OF THIS BOOK

This book is organized into 11 chapters. Chapter 2 reviews some fundamental principles of transmission lines and electromagnetic waves. Chapter 3 gives a brief overview of how antennas and antenna arrays work. Chapter 4 provides a discussion of system parameters for various components that form building blocks for a system. Chapters 5 and 6 are devoted to receiver and transmitter systems. Chapter 7 introduces the radar equation and the basic principles for pulse and CW radar systems. Chapter 8 describes various wireless communication systems, including radios, microwave links, satellite communications, and cellular phones. It also discusses the Friis transmission equation, space loss, and link budget calculation. A brief introduction to modulation techniques and multiple-access methods is given in Chapters 9 and 10. Finally, Chapter 11 describes other wireless applications, including navigation systems, automobile and highway applications, direct broadcast systems, remote sensing systems, RF identification systems, and surveillance systems.