CHAPTER 1

Introduction

1.1 BEGINNING OF WIRELESS

> WIRELESS TELEGRAPHY—At a time when relations are strained between Spain and this country, nothing could be more welcome than a practical method of carrying on electrical communication between distant points on land, and between ships at sea, without any prearranged connection between the two points. During the last year Guglielmo Marconi, an Italian student, developed a system of wireless telegraphy able to transmit intelligible Morse signals to a distance of over ten miles. It has been left, however, for an American inventor to design an apparatus suitable to the requirements of wireless telegraphy in this country. After months of experimenting, Mr. W. J. Clarke, of the United States Electrical Supply Company, has designed a complete wireless telegraphy apparatus that will probably come rapidly into use.
>
> —Scientific American April, 1898

This announcement appeared near the beginning of radio technology. Webster's dictionary [1] lists over 150 definitions that begin with the word *radio*, the first being:

> 1a. … the transmission and reception of electric impulses or signals by means of electromagnetic waves without a connecting wire (includes wireless, television and radar).

This remains today the real definition of *wireless* and, equivalently, *radio*. Today the uses of radio communication include not only the broadcast of sound through amplitude modulation (AM) and frequency modulation (FM) radio and video through television, but also a broad collection of radio applications, cordless telephones, cell phones, TV, and VCR remotes, automobile remote door locks, garage door openers, and so on.

High Frequency Techniques: An Introduction to RF and Microwave Design and Computer Simulation, First Edition. Joseph F. White.

There is some question about who actually invented radio as a communicative method. Mahlon Loomis, a dentist, experimented with wireless telegraphy using wires supported by kites and a galvanometer to sense the changes in current flow in a second wire when the ground connection of the first was interrupted. He received a patent in 1873 for this system [2].

James Clerk Maxwell [3], more about Maxwell's equations later, predicted the propagation of electromagnetic waves through a vacuum in about 1862. Nathan Stubblefield, a Kentucky farmer and sometimes telephone repairman, demonstrated wireless telephony as early as 1892, but to only one man, and in 1902 to a group [2].

Alexander Popov is said to have "utilized his equipment to obtain information for a study of atmospheric electricity … On 7 May 1895, in a lecture before the Russian Physicist Society of St. Petersburg, he stated he had transmitted and received signals at an intervening distance of 600 yards" [4]. In 1888 Heinrich Hertz conducted an experimental demonstration in a classroom at Karlsruhe Polytechnic in Berlin of the generation and detection of the propagating electromagnetic waves predicted by Maxwell [2].

Sir Oliver Lodge, a professor at Liverpool University was experimenting with wireless telegraphy in 1888, and he patented a system in 1897. Marconi purchased his patent in 1911 [2].

In the public mind Guglielmo Marconi enjoys the most credit for "inventing" radio. He was awarded patents for it; therefore, the Patent Office believed that he had made radio-related inventions. However, the U.S. Navy report [4] states

> Marconi can scarcely be called an inventor. His contribution was more in the fields of applied research and engineering development. He possessed a very practical business acumen, and he was not hampered by the same driving urge to do fundamental research, which had caused Lodge and Popoff to procrastinate in the development of a commercial radio system.

This is perhaps the most accurate description of Marconi's role in developing radio technology, a new communication medium. Nikola Tesla had earlier patents, although the focus of his work appears to have been directed to the transmission of power rather than to communication via radio waves. Tesla, well known for his *Tesla coil* that generated high voltages, actually detected signals consisting of noise bursts, resulting from the large atmospheric electrical discharges he originated, that had traveled completely around the earth. In 1943 the U.S. Supreme Court ruled that Marconi's patents were invalid due to Tesla's prior descriptions, but by that time both Marconi and Tesla were deceased [2].

From its beginnings around 1900, radio moved out to fill many communicative voids. In 1962 George Southworth, a well-known researcher in the field of microwaves, wrote a book about his 40 years of experience in the field [5, p. 1]. He begins:

> One of the more spectacular technical developments of our age has been radio. Beginning about the turn of the century with ship-to-shore telegraphy, radio has been extended through the years to intercontinental telegraphy, to broadcasting, to radio astronomy and to satellite communications.

Today, after an additional 40 years, Southworth could make a much longer list of radio applications. It would include garage door openers, global positioning satellites, cellular telephones, wireless computer networks, and radar applications such as speed measurement, ship and aircraft guidance, military surveillance, weapon directing, air traffic control, and automobile anticollision systems. The frequency spectrum for practical wireless devices has expanded as well. Amplitude modulated radio begins at 535 kHz and television remote controls extend into the infrared.

The advance of wireless applications is not complete and probably never will be. Certainly the last decade has seen an explosive growth in applications. And the quantities of systems has been extraordinary, too. Witness the adoption of the cellular telephone, which today rivals the wired telephone in numbers of applications.

Sending signals over telegraph wires formed the basis for the early wireless technology to follow. Using the Current International Morse code characters for the early Morse code message transmitted over the first telegraph wires, the first message inaugurating service between Baltimore and Washington, D.C., in 1843, would have looked like

.-- .... .- -   .... .- - ....   --. --- -.. .-- .-. --- ..- --. .... -   ..--..
W h a t   h a t h   G o d w r o u g h t   ?

Most of the full code cipher is shown in Figure 1.1-1. Morse code remains useful, although fewer individuals can interpret it on the fly. A distress signal using the code in Figure 1.1-1 can be sent using a transmitting radio or even a flashlight. Marconi's early wireless transmissions used pulse code modulation,

A .-	*K* -.-	*U* ..-	*5*	,	*(COMMA)*	--..--
B -...	*L* .-..	*V* ...-	*6* -....	.	*(PERIOD)*	.-.-.-
C -.-.	*M* --	*W* .--	*7* --...	?		..--..
D -..	*N* -.	*X* -..-	*8* ---..	;		-.-.-.
E .	*O* ---	*Y* -.--	*9* ----.	:		---...
F ..-.	*P* .--.	*Z* --..	*0*-----	’	*(APOSTROPHE)*	.----.
G --.	*Q* --.-	*1* .----		-	*(HYPHEN)*	-....-
H	*R* .-.	*2* ..---		/	*(slash)*	-..-.
I ..	*S* ...	*3* ...--		*(or)*	*PARENTHESIS*	-.--.-
J .---	*T* -	*4* ....-		______	*UNDERLINE*	..--.-

Figure 1.1-1 International Morse Code remains a standard for distress signals, S.O.S. is (… --- …) *(English Characters, [1]). Derived from the work of Samuel Morse (1791–1872).*

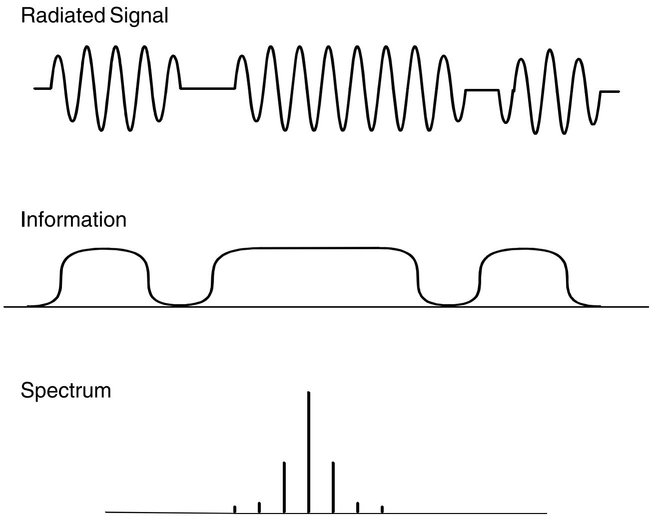

Figure 1.1-2 Modulation format for Morse code, illustrated for letter *R*. Today, pulse shaping, as suggested above, would be employed to reduce transmission spectrum, but Marconi's spark gap transmitter doubtless spanned an enormously wide bandwidth.

dots and dashes achieved by keying the transmitter on and off. Some nautical buoys are identifiable by the Morse letter that their lights flash.

Today, Marconi would need a transmitting license, and were he to continue with his prior transmission technique, his license almost certainly would be suspended due to the broad spectrum of his transmissions (Fig. 1.1-2). His RF source was a spark gap oscillator (Fig. 1.1-3), likely occupying a very broad transmission bandwidth. Powered by a several horsepower generator, the operating transmitter was audible without a radio receiver for several miles.

Marconi had his pivotal triumph in December, 1901, when the Morse character "s" was received at St. John's, Newfoundland (Figs. 1.1-4 and 1.1-5). It was transmitted from Poldhu, Cornwall England, 1800 miles across the Atlantic Ocean [5, p. 13; 6, p. 4]. From the South Wellfleet station, Marconi, himself, transmitted the first trans-Atlantic message on January 17, 1903, a communication from the president of the United States to the king of England.

1.2 CURRENT RADIO SPECTRUM

Today's radio spectrum is very crowded. Obtaining a commercial license to radiate carries the obligation to use bandwidth efficiently, using as little bandwidth as practical to convey the information to be transmitted (Tables 1.2-1 and 1.2-2).

Just the frequency allocations for the United States alone cannot be placed in a table of reasonable size. They occupy numerous pages of the *Rules and*

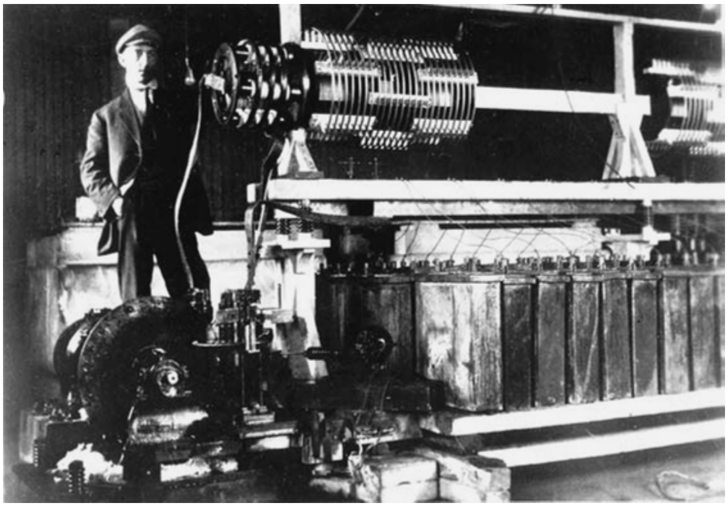

Figure 1.1-3 Joel Earl Hudson standing by Marconi's spark gap transmitter in 1907. (*Photo courtesy of Cape Cod National Seashore*.)

Regulations of the Federal Communications Commission, and have hundreds of footnotes. Since frequent changes are made in the rules and regulations, the latest issue always should be consulted [7, p. 1.8; 8].

As can be seen from Table 1.2-3, radio amateurs today enjoy many frequency allocations. This is due to the history of their pioneering efforts, particularly

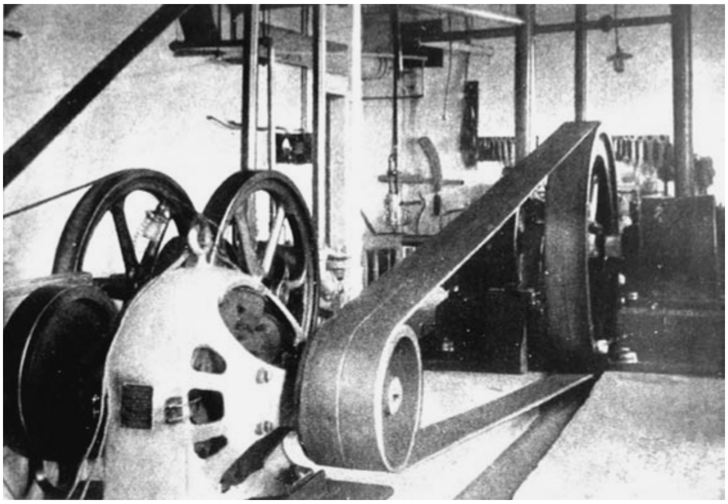

Figure 1.1-4 Prime power for Marconi's South Wellfleet transmitter. (*Photo courtesy of Cape Cod National Seashore*.)

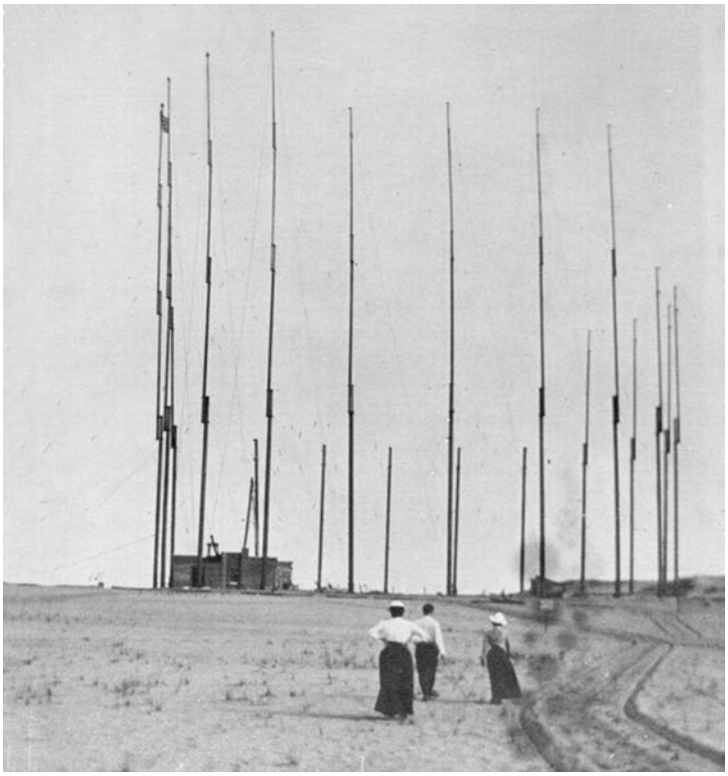

Figure 1.1-5 Marconi's first wireless station in South Wellfleet, Cape Cod, Massachusetts. Local residents predicted that antennas would blow down in first good storm. They did, and he rebuilt them. (*Photo courtesy of Cape Cod National Seashore*.)

at the higher frequencies. We owe much of the rapid development of short-wave radio to the experimental enterprise of amateur radio operators. George Southworth [5, p. 83] pointed out that, in about 1930:

> It is interesting that while the telephone people [researchers at the Bell Telephone Laboratories] were conducting intensive research on the lower frequencies … much was happening in the outside world at higher frequencies.… It is said that the advantages of short waves were first discovered by an amateur who had built for himself a short-wave receiver and upon listening had found that he could hear the harmonics of distant broadcasting stations … at distances far beyond those at which the fundamentals could be heard. Amateurs later built for themselves shortwave transmitters and soon thereafter carried on two-way communication.

Today, the electromagnetic spectrum is like a superhighway. There are only so many lanes and only so much traffic that it can sustain if everyone is to enjoy rapid and efficient transport.

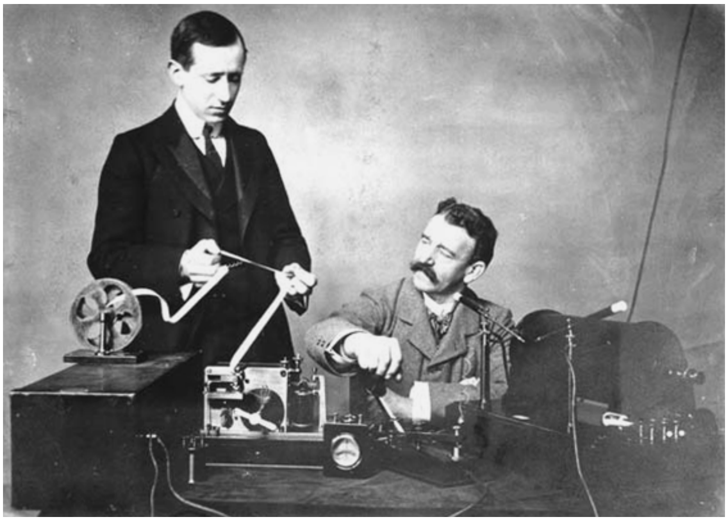

Figure 1.1-6 Guglielmo Marconi (left) received the Nobel Prize for his wireless communication work. He is shown in a 1901 photo with assistant George Kemp shortly after a successful wireless transmission test. (*Photo courtesy of Marconi, Ltd.*, UK.)

The simultaneous functioning of the intricate grid of radiation allocations, only a part of which are shown in Table 1.2-3, depend upon each user occupying his or her precise frequency, modulation format, bandwidth, and effective radiated power and, furthermore, not intruding on other frequency bands by generating spurious signals with his or her equipment. This is the task and challenge of today's high frequency engineering.

TABLE 1.2-1 General Frequency Band Designations

f	λ	Band	Description
30–300 Hz	10^4–10^3 km	ELF	Extremely low frequency
300–3000 Hz	10^3–10^2 km	VF	Voice frequency
3–30 kHz	100–10 km	VLF	Very low frequency
30–300 kHz	10–1 km	LF	Low frequency
0.3–3 MHz	1–0.1 km	MF	Medium frequency
3–30 MHz	100–10 m	HF	High frequency
30–300 MHz	10–1 m	VHF	Very high frequency
300–3000 MHz	100–10 cm	UHF	Ultra-high frequency
3–30 GHz	10–1 cm	SHF	Superhigh frequency
30–300 GHz	10–1 mm	EHF	Extremely high frequency (millimeter waves)

Source: From Reference [7, Section 1].

TABLE 1.2-2 Microwave Letter Bands

f (GHz)	Letter Band Designation
1–2	L band
2–4	S band
4–8	C band
8–12.4	X band
12.4–18	Ku band
18–26.5	K band
26.5–40	Ka band

Source: From Reference [9, p. 123].

1.3 CONVENTIONS USED IN THIS TEXT

This section lists the notational conventions used throughout this text.

Sections

Sections use a decimal number. To the left of the decimal is the chapter number and to the right is the section number. Thus, 7.10 refers to the tenth section in Chapter 7.

Equations

Equations have a number sequence that restarts in each section. Therefore, a reference to (7.15-4) is directed to the fourth equation in Section 7.15.

Figures

Figure and table numbering also restarts in each section. Therefore, a reference to Figure 7.24-2 relates to the second figure in Section 7.24.

Exercises

The exercises at the end of each chapter are numbered according to the section to which they most closely relate. For example, the exercise numbered E3.5-1 is the first exercise relating to the material in Section 3.5. Material contained in prior sections also may be needed to complete the exercise.

Symbols

The principal symbols used in this text and the quantities that they represent are listed in Appendix A. For example, c refers to the velocity of electromagnetic propagation in free space, while v refers to the velocity of propagation in

TABLE 1.2-3 Selected U.S. Radio Frequency Allocations

Frequencies in kHz	Allocated Purposes
490–510	Distress (telegraph)
510–535	Government
535–1605	AM radio
1605–1750	Land/mobile public safety
1800–2000	Amateur radio

Frequencies in MHz	Allocated Purposes
26.96–27.23, 462.525–467.475	Citizen band radios
30.56–32, 33–34, 35–38, 39–40, 40.02–40.98, 41.015–46.6, 47–49.6, 72–73, 74.6–74.8, 75.2–76, 150.05–156.2475, 157.1875–161.575, 162.0125–173.4	Private mobil radio (taxis, trucks, buses, railroads)
220–222, 421–430, 451–454, 456–459, 460–512	
746–824, 851–869, 896–901, 935–940	
74.8–75.2, 108–137, 328.6–335.4, 960–1215, 1427–1525, 220–2290, 2310–2320, 2345–2390	Aviation (communication and radar)
162.0125–173.2	Vehicle recovery (LoJack)
50–54, 144–148, 216–220, 222–225, 420–450, 902–928, 1240–1300, 2300–2305, 2390–2450	Amateur radio
72–73, 75.2–76, 218–219	Radio control (personal)
54–72, 76–88, 174–216, 470–608	Television broadcasting VHF and UHF
88–99, 100–108	FM radio broadcasting
824–849	Cellular telephones
1850–1990	Personal communications
1910–1930, 2390–2400	Personal comm. (unlicensed)
1215–1240, 1350–1400, 1559–1610	Global Positioning Systems (GPS)

Frequencies in GHz	Allocated Purposes
0.216–0.220, 0.235–0.267, 0.4061–0.45, 0.902–0.928, 0.960–1.215, 1.215–2.229, 2.320–2.345, 2.360–2.390, 2.7–3.1, 3.1–3.7, 5.0–5.47, 5.6–5.925, 8.5–10, 10.0–10.45, 10.5–10.55, 13.25–13.75, 14–14.2, 15.4–16.6, 17.2–17.7, 24.05–24.45, 33.4–36, 45–46.9, 59–64, 66–71, 76–77, 92–100	Radar, all types
2.390–2.400	LANs (unlicensed)
2.40–2.4835	Microwave ovens
45.5–46.9, 76–77, 95–100, 134–142	Vehicle, anticollision, navigation
10.5–10.55, 24.05–24.25	Police speed radar
0.902–0.928, 2.4–2.5, 5.85–5.925	Radio frequency identification (RFID)
3.7–4.2, 11.7–12.2, 14.2–14.5, 17.7–18.8, 27.5–29.1, 29.25–30, 40.5–41.5, 49.2–50.2	Geostationary satellites with fixed earth receivers

TABLE 1.2-3 *(Continued)*

Frequencies in GHz	Allocated Purposes
1.610–1626.5, 2.4835–2.5, 5.091–5.25, 6.7–7.075, 15.43–15.63	Nongeostationary satellites, mobile receivers (big LEO, global phones)
0.04066–0.0407, 902–928, 2450–2500, 5.725–5.875, 24–24.25, 59–59.9, 60–64, 71.5–72, 103.5–104, 116.5–117, 122–123, 126.5–127, 152.5–153, 244–246	Unlicensed industrial, scientific, and medical communication devices
3.3–3.5, 5.65–5.925, 10–10.5, 24–24.25, 47–47.2	Amateur radio
6.425–6.525, 12.7–13.25, 19.26–19.7, 31–31.3	Cable television relay
27.5–29.5	Local multipoint TV distribution
12.2–12.7, 24.75–25.05, 25.05–25.25	Direct broadcast TV (from satellites)
0.928–0.929, 0.932–0.935, 0.941–0.960, 1.850–1.990, 2.11–2.20, 2.450–2.690, 3.7–4.2, 5.925–6.875, 10.55–10.68, 10.7–13.25, 14.2–14.4, 17.7–19.7, 21.2–23.6, 27.55–29.5, 31–31.3, 38.6–40	Fixed microwave (public and private)

a medium for which the relative dielectric and permeability constants may be greater than unity.

Prefixes

Except where noted otherwise, this text uses the International System of Units (SI). Standard prefixes are listed in Table 1.3-1.

Fonts

The font types used throughout this text to connote variable types are listed in Table 1.3-2. Combinations of these representational styles are used to convey the dual nature of some variables. For example, in Maxwell's equation

$$\nabla \cdot \vec{\mathrm{D}} = \rho$$

$\vec{\mathrm{D}}$ is written in regular type because the equation applies to all time waveforms, not just sinusoidal variations, and $\vec{\mathrm{D}}$ is also a vector quantity. On the other hand, the Helmholtz equation is written

$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$

TABLE 1.3-1 Standard Prefixes

Prefix	Abbreviation	Factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deka	da	10
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto		10^{-18}

using italic type for the variable $\vec{E}$ because *this equation only applies for sinusoidal time variations*, and therefore the components of the vector $\vec{E}$ are *phasor quantities*.

Throughout this text, except where otherwise noted, the magnitudes of sinusoidal waveforms (V, I, E, D, H, B) are peak values. To obtain root-mean-square (rms) values, divide these values by $\sqrt{2}$.

1.4 VECTORS AND COORDINATES

General vector representations are three dimensional. They can be described by any three-dimensional, *orthogonal coordinate system* in which each coordinate direction is at right angles to the other two. Unless otherwise specified, *rectangular*

TABLE 1.3-2 Fonts Used in This Text to Identify Variable Types

Variable Type	Font	Examples
DC or general time-varying function (not sinusoidal)	Regular type	V, I, H, E, B, D
Explicit general time variation	Regular type, lowercase	v(t), i(t)
Explicit sinusoidal time variation	Italic type, lowercase	$v(t)$, $i(t)$
Phasors, impedance, admittance, general functions, and variables, unit vectors	Italic type	V, I, H, E, B, D, Z, Y $f(x)$, $g(y)$, x, y, z, $\vec{x}$, $\vec{y}$, $\vec{z}$
Vectors	$\overrightarrow{\text{Arrow above}}$	$\vec{\mathrm{E}}$, $\vec{\mathrm{H}}$, $\vec{\mathrm{B}}$, $\vec{\mathrm{D}}$, $\vec{E}$, $\vec{H}$, $\vec{B}$, $\vec{D}$
Normalized parameters	Lowercase	$z = Z/Z_0$, $y = Y/Y_0$

(Cartesian) coordinates are implied. Certain circular and spherical symmetries of a case can make its analysis and solution more convenient if the geometry is described in *cylindrical coordinates* or *spherical coordinates*.

In this text all coordinate systems are *right-handed orthogonal coordinate systems*. That is,

> In a right-hand orthogonal coordinate system, rotating a vector in the direction of any coordinate into the direction of the next named coordinate causes a rotational sense that would advance a right-hand screw in the positive direction of the third respective coordinate.

We define that *unit vectors are vectors having unity amplitude and directions in the directions of the increasing value of the respective variables that they represent*.

In rectangular coordinates (Fig. 1.4-1) the order is (x, y, z) and an arbitrary point is written as $P(x, y, z)$. The unit vectors in these respective directions are $\vec{x}$, $\vec{y}$, and $\vec{z}$. Thus, a three-dimensional vector field $\vec{\mathrm{E}}$ can be written

$$\vec{\mathrm{E}} = \vec{\mathrm{E}}_x + \vec{\mathrm{E}}_y + \vec{\mathrm{E}}_z \tag{1.4-1a}$$

or

$$\vec{\mathrm{E}} = \mathrm{E}_x\vec{x} + \mathrm{E}_y\vec{y} + \mathrm{E}_z\vec{z} \tag{1.4-1b}$$

or

$$\vec{\mathrm{E}} = \vec{x}\mathrm{E}_x + \vec{y}\mathrm{E}_y + \vec{z}\mathrm{E}_z \tag{1.4-1c}$$

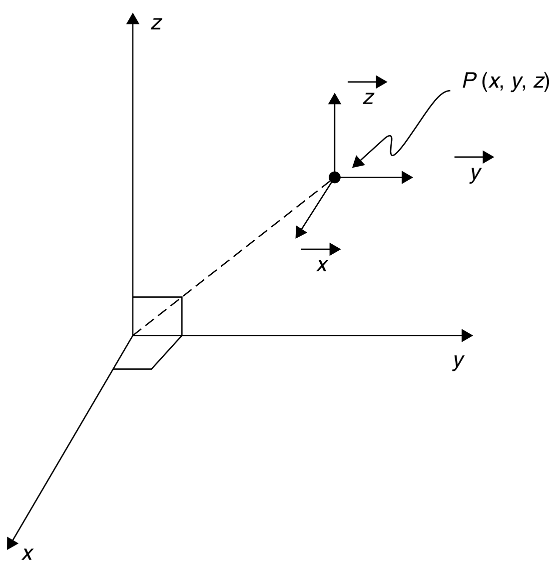

Figure 1.4-1 Rectangular (Cartesian) right-hand coordinate system.

Generally, the format of (1.4-1c) is used in this text. In the language of vector mathematics, rotating a unit vector $\vec{x}$ in the direction of another unit vector $\vec{y}$ is called *crossing* $\vec{x}$ into $\vec{y}$, and this is written as $\vec{x} \times \vec{y}$. This is a specific example of the *vector cross product*. The vector cross product can be applied to any two vectors having any magnitudes and relative orientations; but, in general, we must take into account the product of their magnitudes and the angle between them, as will be shown more specifically for the vector cross product in Chapter 7. For present purposes, since $\vec{x}$, $\vec{y}$, and $\vec{z}$ form a right-hand orthogonal set of unit vectors, we can express the right-handedness of their coordinate system by requiring that the following cross product relations apply:

$$\vec{x} \times \vec{y} = \vec{z} \tag{1.4-2a}$$

$$\vec{y} \times \vec{z} = \vec{x} \tag{1.4-2b}$$

$$\vec{z} \times \vec{x} = \vec{y} \tag{1.4-2c}$$

Notice that *the vector cross product yields a new vector that is orthogonal to the plane of the crossed vectors and in a direction that would be taken by the advance of a right-hand screw when the first vector is crossed into the second.*

Also notice that *for a right-hand coordinate system any coordinate unit vector can be crossed into the next named coordinate vector to yield the direction of positive increase of the remaining coordinate, beginning with any coordinate.* For example (x, y, z), (y, z, x), or (z, x, y) all satisfy the right-hand advancing rule, as specified by (1.4-2a) to (1.4-2c).

The cylindrical coordinate system is shown in Figure 1.4-2. The order of coordinate listing is (r, φ, z) and the unit vectors are $\vec{r}$, $\vec{\varphi}$, and $\vec{z}$, which satisfy

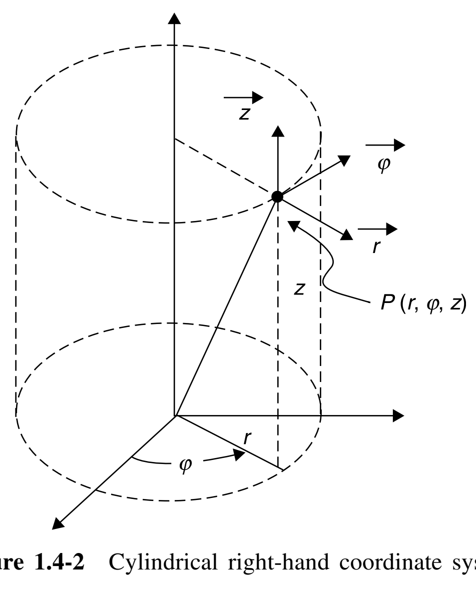

Figure 1.4-2 Cylindrical right-hand coordinate system.

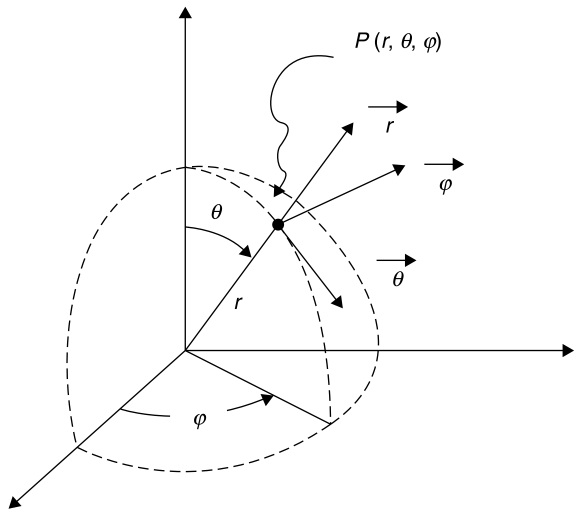

Figure 1.4-3 Spherical right-hand coordinate system.

the same sequential cross-product rules as do rectangular coordinates, namely $\vec{r} \times \vec{\varphi} = \vec{z}$, $\vec{\varphi} \times \vec{z} = \vec{r}$, and $\vec{z} \times \vec{r} = \vec{\varphi}$.

The spherical coordinate system is shown in Figure 1.4-3. The order of coordinate listing is (r, θ, φ) and the unit vectors are $\vec{r}$, $\vec{\theta}$, and $\vec{\varphi}$, which satisfy the sequential cross-product rules $\vec{r} \times \vec{\theta} = \vec{\varphi}$, $\vec{\theta} \times \vec{\varphi} = \vec{r}$, and $\vec{\varphi} \times \vec{r} = \vec{\theta}$. *Note that this r is not the same as the r used in cylindrical coordinates.*

1.5 GENERAL CONSTANTS AND USEFUL CONVERSIONS

There are several values of physical constants, conversion factors, and identities useful to the practice of microwave engineering. For ready reference, a selection of them is printed on the inside covers of this text.

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