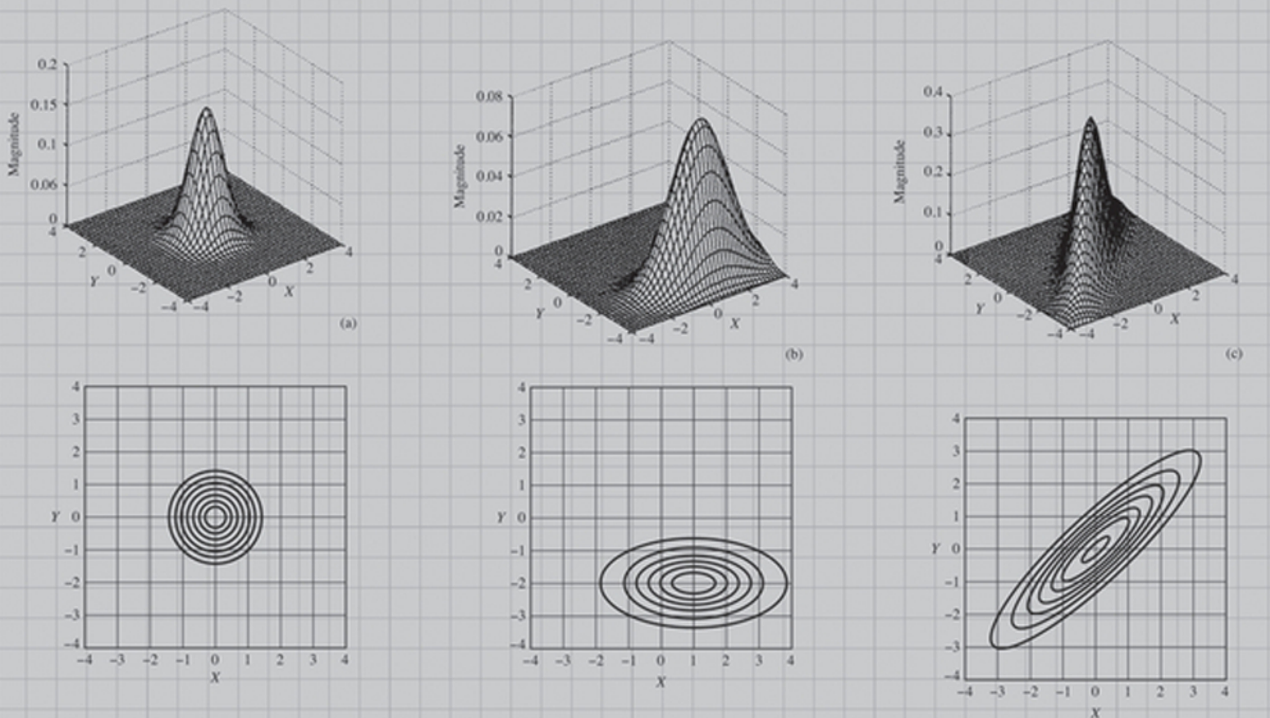
Seventh Edition

Principles of COMMUNICATIONS

Systems, Modulation, and Noise

RODGER E. ZIEMER • WILLIAM H. TRANTER



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PRINCIPLES OF COMMUNICATIONS

Systems, Modulation, and Noise

SEVENTH EDITION

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PREFACE

The first edition of this book was published in 1976, less than a decade after Neil Armstrong became the first man to walk on the moon in 1969. The programs that lead to the first moon landing gave birth to many advances in science and technology. A number of these advances, especially those in microelectronics and digital signal processing (DSP), became enabling technologies for advances in communications. For example, prior to 1969, essentially all commercial communication systems, including radio, telephones, and television, were analog. Enabling technologies gave rise to the internet and the World Wide Web, digital radio and television, satellite communications, Global Positioning Systems, cellular communications for voice and data, and a host of other applications that impact our daily lives. A number of books have been written that provide an in-depth study of these applications. In this book we have chosen not to cover application areas in detail but, rather, to focus on basic theory and fundamental techniques. A firm understanding of basic theory prepares the student to pursue study of higher-level theoretical concepts and applications.

True to this philosophy, we continue to resist the temptation to include a variety of new applications and technologies in this edition and believe that application examples and specific technologies, which often have short lifetimes, are best treated in subsequent courses after students have mastered the basic theory and analysis techniques. Reactions to previous editions have shown that emphasizing fundamentals, as opposed to specific technologies, serve the user well while keeping the length of the book reasonable. This strategy appears to have worked well for advanced undergraduates, for new graduate students who may have forgotten some of the fundamentals, and for the working engineer who may use the book as a reference or who may be taking a course after-hours. New developments that appear to be fundamental, such as multiple-input multiple-output (MIMO) systems and capacity-approaching codes, are covered in appropriate detail.

The two most obvious changes to the seventh edition of this book are the addition of drill problems to the Problems section at the end of each chapter and the division of chapter three into two chapters. The drill problems provide the student problem-solving practice with relatively simple problems. While the solutions to these problems are straightforward, the complete set of drill problems covers the important concepts of each chapter. Chapter 3, as it appeared in previous editions, is now divided into two chapters mainly due to length. Chapter 3 now focuses on linear analog modulation and simple discrete-time modulation techniques that are direct applications of the sampling theorem. Chapter 4 now focuses on nonlinear modulation techniques. A number of new or revised end-of-chapter problems are included in all chapters.

In addition to these obvious changes, a number of other changes have been made in edition seven. An example on signal space was deleted from Chapter 2 since it is really not necessary at this point in the book. (Chapter 11 deals more fully with the concepts of signal space.) Chapter 3, as described in the previous paragraph, now deals with linear analog modulation techniques. A section on measuring the modulation index of AM signals and measuring transmitter linearity has been added. The section on analog television has been deleted from Chapter 3 since it is no longer relevant. Finally, the section on adaptive delta modulation has been deleted. Chapter 4 now deals with non-linear analog modulation techniques. Except for the problems, no significant additions or deletions have been made to Chapter 5. The same is true of Chapters 6 and 7, which treat probability and random processes, respectively. A section on signal-to-noise ratio measurement has been added to Chapter 8, which treats noise effects in modulation systems. More detail on basic channel models for fading channels has been added in Chapter 9 along with simulation results for bit error rate (BER) performance of a minimum mean-square error (MMSE) equalizer with optimum weights and an additional example of the MMSE equalizer with adaptive weights. Several changes have been made to Chapter 10. Satellite communications was reluctantly deleted because it would have required adding several additional pages to do it justice. A section was added on MIMO systems using the Alamouti approach, which concludes with a BER curve comparing performances of 2-transmit 1-receive Alamouti signaling in a Rayleigh fading channel with a 2-transmit 2-receive diversity system. A short discussion was also added to Chapter 10 illustrating the features of 4G cellular communications as compared with 2G and 3G systems. With the exception of the Problems, no changes have been made to Chapter 11. A ''Quick Overview'' section has been added to Chapter 12 discussing capacity-approaching codes, run-length codes, and digital television.

A feature of the later editions of *Principles of Communications* was the inclusion of several computer examples within each chapter. (MATLAB was chosen for these examples because of its widespread use in both academic and industrial settings, as well as for MATLAB's rich graphics library.) These computer examples, which range from programs for computing performance curves to simulation programs for certain types of communication systems and algorithms, allow the student to observe the behavior of more complex systems without the need for extensive computations. These examples also expose the student to modern computational tools for analysis and simulation in the context of communication systems. Even though we have limited the amount of this material in order to ensure that the character of the book is not changed, the number of computer examples has been increased for the seventh edition. In addition to the in-chapter computer examples, a number of ''computer exercises'' are included at the end of each chapter. The number of these has also been increased in the seventh edition. These exercises follow the end-of-chapter problems and are designed to make use of the computer in order to illustrate basic principles and to provide the student with additional insight. A number of new problems have been included at the end of each chapter in addition to a number of problems that were revised from the previous edition.

The publisher maintains a web site from which the source code for all in-chapter computer examples can be downloaded. Also included on the web site are Appendix G (answers to the drill problems) and the bibliography. The URL is

www.wiley.com/college/ziemer

We recommend that, although MATLAB code is included in the text, students download MATLAB code of interest from the publisher website. The code in the text is subject to printing and other types of errors and is included to give the student insight into the computational techniques used for the illustrative examples. In addition, the MATLAB code on the publisher website is periodically updated as need justifies. This web site also contains complete solutions for the end-of-chapter problems and computer exercises. (The solutions manual is password protected and is intended only for course instructors.)

We wish to thank the many persons who have contributed to the development of this textbook and who have suggested improvements for this and previous editions of this book. We also express our thanks to the many colleagues who have offered suggestions to us by correspondence or verbally as well as the industries and agencies that have supported our research. We especially thank our colleagues and students at the University of Colorado at Colorado Springs, the Missouri University of Science and Technology, and Virginia Tech for their comments and suggestions. It is to our students that we dedicate this book. We have worked with many people over the past forty years and many of them have helped shape our teaching and research philosophy. We thank them all.

Finally, our families deserve much more than a simple thanks for the patience and support that they have given us throughout forty years of seemingly endless writing projects.

Rodger E. Ziemer
William H. Tranter

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CHAPTER 1

INTRODUCTION

We are said to live in an era called the intangible economy, driven not by the physical flow of material goods but rather by the flow of information. If we are thinking about making a major purchase, for example, chances are we will gather information about the product by an Internet search. Such information gathering is made feasible by virtually instantaneous access to a myriad of facts about the product, thereby making our selection of a particular brand more informed. When one considers the technological developments that make such instantaneous information access possible, two main ingredients surface—a reliable, fast means of communication and a means of storing the information for ready access, sometimes referred to as the *convergence* of communications and computing.

This book is concerned with the theory of systems for the conveyance of information. A *system* is a combination of circuits and/or devices that is assembled to accomplish a desired task, such as the transmission of intelligence from one point to another. Many means for the transmission of information have been used down through the ages ranging from the use of sunlight reflected from mirrors by the Romans to our modern era of electrical communications that began with the invention of the telegraph in the 1800s. It almost goes without saying that we are concerned about the theory of systems for *electrical* communications in this book.

A characteristic of electrical communication systems is the presence of uncertainty. This uncertainty is due in part to the inevitable presence in any system of unwanted signal perturbations, broadly referred to as *noise*, and in part to the unpredictable nature of information itself. Systems analysis in the presence of such uncertainty requires the use of probabilistic techniques.

Noise has been an ever-present problem since the early days of electrical communication, but it was not until the 1940s that probabilistic systems analysis procedures were used to analyze and optimize communication systems operating in its presence [Wiener 1949; Rice 1944, 1945].[1] It is also somewhat surprising that the unpredictable nature of information was not widely recognized until the publication of Claude Shannon's mathematical theory of communications [Shannon 1948] in the late 1940s. This work was the beginning of the science of information theory, a topic that will be considered in some detail later.

Major historical facts related to the development of electrical communications are given in Table 1.1. It provides an appreciation for the accelerating development of communications-related inventions and events down through the years.

[1]References in brackets [ ] refer to Historical References in the Bibliography.

Table 1.1 Major Events and Inventions in the Development of Electrical Communications

Year	Event
1791	Alessandro Volta invents the galvanic cell, or battery
1826	Georg Simon Ohm establishes a law on the voltage-current relationship in resistors
1838	Samuel F. B. Morse demonstrates the telegraph
1864	James C. Maxwell predicts electromagnetic radiation
1876	Alexander Graham Bell patents the telephone
1887	Heinrich Hertz verifies Maxwell's theory
1897	Guglielmo Marconi patents a complete wireless telegraph system
1904	John Fleming patents the thermionic diode
1905	Reginald Fessenden transmits speech signals via radio
1906	Lee De Forest invents the triode amplifier
1915	The Bell System completes a U.S. transcontinental telephone line
1918	B. H. Armstrong perfects the superheterodyne radio receiver
1920	J. R. Carson applies sampling to communications
1925–27	First television broadcasts in England and the United States
1931	Teletypewriter service is initialized
1933	Edwin Armstrong invents frequency modulation
1936	Regular television broadcasting begun by the BBC
1937	Alec Reeves conceives pulse-code modulation (PCM)
WWII	Radar and microwave systems are developed; Statistical methods are applied to signal extraction problems
1944	Computers put into public service (government owned)
1948	The transistor is invented by W. Brattain, J. Bardeen, & W. Shockley
1948	Claude Shannon's ''A Mathematical Theory of Communications'' is published
1950	Time-division multiplexing is applied to telephony
1956	First successful transoceanic telephone cable
1959	Jack Kilby patents the ''Solid Circuit''—precurser to the integrated circuit
1960	First working laser demonstrated by T. H. Maiman of Hughes Research Labs (patent awarded to G. Gould after 20-year dispute with Bell Labs)
1962	First communications satellite, Telstar I, launched
1966	First successful FAX (facsimile) machine
1967	U.S. Supreme Court Carterfone decision opens door for modem development
1968	Live television coverage of the moon exploration
1969	First Internet started—ARPANET
1970	Low-loss optic fiber developed
1971	Microprocessor invented
1975	Ethernet patent filed
1976	Apple I home computer invented
1977	Live telephone traffic carried by fiber-optic cable system
1977	Interplanetary grand tour launched; Jupiter, Saturn, Uranus, and Neptune
1979	First cellular telephone network started in Japan
1981	IBM personal computer developed and sold to public
1981	Hayes Smartmodem marketed (automatic dial-up allowing computer control)
1982	Compact disk (CD) audio based on 16-bit PCM developed
1983	First 16-bit programmable digital signal processors sold
1984	Divestiture of AT&T's local operations into seven Regional Bell Operating Companies

Table 1.1 (*Continued*)

Year	Event
1985	Desktop publishing programs first sold; Ethernet developed
1988	First commercially available flash memory (later applied in cellular phones, etc.)
1988	ADSL (asymmetric digital subscriber lines) developed
1990s	Very small aperture satellites (VSATs) become popular
1991	Application of echo cancellation results in low-cost 14,400 bits/s modems
1993	Invention of turbo coding allows approach to Shannon limit
mid-1990s	Second-generation (2G) cellular systems fielded
1995	Global Positioning System reaches full operational capability
1996	All-digital phone systems result in modems with 56 kbps download speeds
late-1990s	Widespread personal and commercial applications of the Internet
	High-definition TV becomes mainstream
	Apple iPoD first sold (October); 100 million sold by April 2007
2001	Fielding of 3G cellular telephone systems begins; WiFi and WiMAX allow wireless access to the Internet and electronic devices wherever mobility is desired
2000s	Wireless sensor networks, originally conceived for military applications, find civilian applications such as environment monitoring, healthcare applications, home automation, and traffic control as well
2010s	Introduction of fourth-generation cellular radio. Technological convergence of communications-related devices—e.g., cell phones, television, personal digital assistants, etc.

It is an interesting fact that the first electrical communication system, the telegraph, was digital—that is, it conveyed information from point to point by means of a digital code consisting of words composed of dots and dashes.[2] The subsequent invention of the telephone 38 years after the telegraph, wherein voice waves are conveyed by an analog current, swung the pendulum in favor of this more convenient means of word communication for about 75 years.[3]

One may rightly ask, in view of this history, why the almost complete domination by digital formatting in today's world? There are several reasons, among which are: (1) Media integrity—a digital format suffers much less deterioration in reproduction than does an analog record; (2) Media integration—whether a sound, picture, or naturally digital data such as a word file, all are treated the same when in digital format; (3) Flexible interaction—the digital domain is much more convenient for supporting anything from one-on-one to many-to-many interactions; (4) Editing—whether text, sound, images, or video, all are conveniently and easily edited when in digital format.

With this brief introduction and history, we now look in more detail at the various components that make up a typical communication system.

[2]In the actual physical telegraph system, a dot was conveyed by a short double-click by closing and opening of the circuit with the telegrapher's key (a switch), while a dash was conveyed by a longer double click by an extended closing of the circuit by means of the telegrapher's key.

[3]See B. Oliver, J. Pierce, and C. Shannon, ''The Philosophy of PCM,'' *Proc. IRE*, Vol. 16, pp. 1324–1331, November 1948.

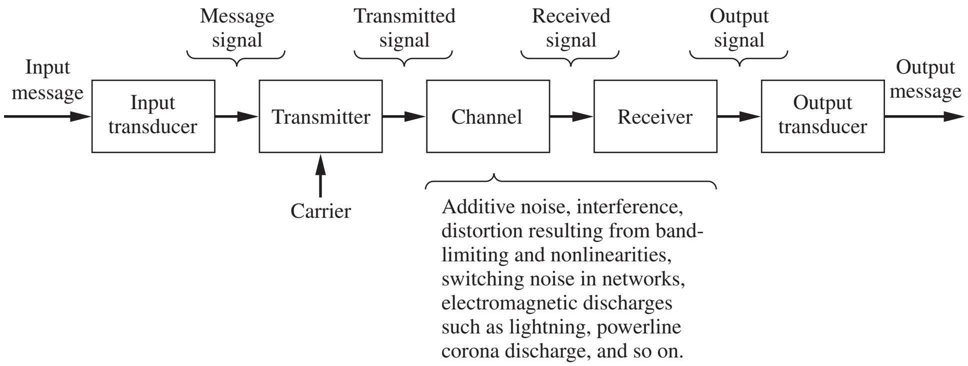

Figure 1.1
The Block Diagram of a Communication System.

1.1 THE BLOCK DIAGRAM OF A COMMUNICATION SYSTEM

Figure 1.1 shows a commonly used model for a single-link communication system.[4] Although it suggests a system for communication between two remotely located points, this block diagram is also applicable to remote sensing systems, such as radar or sonar, in which the system input and output may be located at the same site. Regardless of the particular application and configuration, all information transmission systems invariably involve three major subsystems—a transmitter, the channel, and a receiver. In this book we will usually be thinking in terms of systems for transfer of information between remotely located points. It is emphasized, however, that the techniques of systems analysis developed are not limited to such systems.

We will now discuss in more detail each functional element shown in Figure 1.1.

Input Transducer The wide variety of possible sources of information results in many different forms for messages. Regardless of their exact form, however, messages may be categorized as *analog* or *digital*. The former may be modeled as functions of a continuous-time variable (for example, pressure, temperature, speech, music), whereas the latter consist of discrete symbols (for example, written text or a sampled/quantized analog signal such as speech). Almost invariably, the message produced by a source must be converted by a transducer to a form suitable for the particular type of communication system employed. For example, in electrical communications, speech waves are converted by a microphone to voltage variations. Such a converted message is referred to as the *message signal*. In this book, therefore, a *signal* can be interpreted as the variation of a quantity, often a voltage or current, with time.

[4]More complex communications systems are the rule rather than the exception: a broadcast system, such as television or commercial rado, is a one-to-many type of situation composed of several sinks receiving the same information from a single source; a multiple-access communication system is where many users share the same channel and is typified by satellite communications systems; a many-to-many type of communications scenario is the most complex and is illustrated by examples such as the telephone system and the Internet, both of which allow communication between any pair out of a multitude of users. For the most part, we consider only the simplest situation in this book of a single sender to a single receiver, although means for sharing a communication resource will be dealt with under the topics of multiplexing and multiple access.

Transmitter The purpose of the transmitter is to couple the message to the channel. Although it is not uncommon to find the input transducer directly coupled to the transmission medium, as for example in some intercom systems, it is often necessary to *modulate* a carrier wave with the signal from the input transducer. *Modulation* is the systematic variation of some attribute of the carrier, such as amplitude, phase, or frequency, in accordance with a function of the message signal. There are several reasons for using a carrier and modulating it. Important ones are (1) for ease of radiation, (2) to reduce noise and interference, (3) for channel assignment, (4) for multiplexing or transmission of several messages over a single channel, and (5) to overcome equipment limitations. Several of these reasons are self-explanatory; others, such as the second, will become more meaningful later.

In addition to modulation, other primary functions performed by the transmitter are filtering, amplification, and coupling the modulated signal to the channel (for example, through an antenna or other appropriate device).

Channel The channel can have many different forms; the most familiar, perhaps, is the channel that exists between the transmitting antenna of a commercial radio station and the receiving antenna of a radio. In this channel, the transmitted signal propagates through the atmosphere, or free space, to the receiving antenna. However, it is not uncommon to find the transmitter hard-wired to the receiver, as in most local telephone systems. This channel is vastly different from the radio example. However, all channels have one thing in common: the signal undergoes degradation from transmitter to receiver. Although this degradation may occur at any point of the communication system block diagram, it is customarily associated with the channel alone. This degradation often results from noise and other undesired signals or interference but also may include other distortion effects as well, such as fading signal levels, multiple transmission paths, and filtering. More about these unwanted perturbations will be presented shortly.

Receiver The receiver's function is to extract the desired message from the received signal at the channel output and to convert it to a form suitable for the output transducer. Although amplification may be one of the first operations performed by the receiver, especially in radio communications, where the received signal may be extremely weak, the main function of the receiver is to *demodulate* the received signal. Often it is desired that the receiver output be a scaled, possibly delayed, version of the message signal at the modulator input, although in some cases a more general function of the input message is desired. However, as a result of the presence of noise and distortion, this operation is less than ideal. Ways of approaching the ideal case of perfect recovery will be discussed as we proceed.

Output Transducer The output transducer completes the communication system. This device converts the electric signal at its input into the form desired by the system user. Perhaps the most common output transducer is a loudspeaker or ear phone.

1.2 CHANNEL CHARACTERISTICS

1.2.1 Noise Sources

Noise in a communication system can be classified into two broad categories, depending on its source. Noise generated by components within a communication system, such as resistors and solid-state active devices is referred to as *internal noise*. The second category, *external noise*, results from sources outside a communication system, including atmospheric, man-made, and extraterrestrial sources.

Atmospheric noise results primarily from spurious radio waves generated by the natural electrical discharges within the atmosphere associated with thunderstorms. It is commonly referred to as *static* or *spherics*. Below about 100 MHz, the field strength of such radio waves is inversely proportional to frequency. Atmospheric noise is characterized in the time domain by large-amplitude, short-duration bursts and is one of the prime examples of noise referred to as *impulsive*. Because of its inverse dependence on frequency, atmospheric noise affects commercial AM broadcast radio, which occupies the frequency range from 540 kHz to 1.6 MHz, more than it affects television and FM radio, which operate in frequency bands above 50 MHz.

Man-made noise sources include high-voltage powerline corona discharge, commutator-generated noise in electrical motors, automobile and aircraft ignition noise, and switching-gear noise. Ignition noise and switching noise, like atmospheric noise, are impulsive in character. Impulse noise is the predominant type of noise in switched wireline channels, such as telephone channels. For applications such as voice transmission, impulse noise is only an irritation factor; however, it can be a serious source of error in applications involving transmission of digital data.

Yet another important source of man-made noise is radio-frequency transmitters other than the one of interest. Noise due to interfering transmitters is commonly referred to as *radio-frequency interference* (RFI). RFI is particularly troublesome in situations in which a receiving antenna is subject to a high-density transmitter environment, as in mobile communications in a large city.

Extraterrestrial noise sources include our sun and other hot heavenly bodies, such as stars. Owing to its high temperature (6000°C) and relatively close proximity to the earth, the sun is an intense, but fortunately localized source of radio energy that extends over a broad frequency spectrum. Similarly, the stars are sources of wideband radio energy. Although much more distant and hence less intense than the sun, nevertheless they are collectively an important source of noise because of their vast numbers. Radio stars such as quasars and pulsars are also intense sources of radio energy. Considered a signal source by radio astronomers, such stars are viewed as another noise source by communications engineers. The frequency range of solar and cosmic noise extends from a few megahertz to a few gigahertz.

Another source of interference in communication systems is multiple transmission paths. These can result from reflection off buildings, the earth, airplanes, and ships or from refraction by stratifications in the transmission medium. If the scattering mechanism results in numerous reflected components, the received multipath signal is noiselike and is termed *diffuse*. If the multipath signal component is composed of only one or two strong reflected rays, it is termed *specular*. Finally, signal degradation in a communication system can occur because of random changes in attenuation within the transmission medium. Such signal perturbations are referred to as *fading*, although it should be noted that specular multipath also results in fading due to the constructive and destructive interference of the received multiple signals.

Internal noise results from the random motion of charge carriers in electronic components. It can be of three general types: the first is referred to as *thermal noise*, which is caused by the random motion of free electrons in a conductor or semiconductor excited by thermal agitation; the second is called *shot noise* and is caused by the random arrival of discrete charge carriers in such devices as thermionic tubes or semiconductor junction devices; the third, known as *flicker noise*, is produced in semiconductors by a mechanism not well understood and is more severe the lower the frequency. The first type of noise source, *thermal noise*, is modeled analytically in Appendix A, and examples of system characterization using this model are given there.

1.2.2 Types of Transmission Channels

There are many types of transmission channels. We will discuss the characteristics, advantages, and disadvantages of three common types: electromagnetic-wave propagation channels, guided electromagnetic-wave channels, and optical channels. The characteristics of all three may be explained on the basis of electromagnetic-wave propagation phenomena. However, the characteristics and applications of each are different enough to warrant our considering them separately.

Electromagnetic-Wave Propagation Channels

The possibility of the propagation of electromagnetic waves was predicted in 1864 by James Clerk Maxwell (1831–1879), a Scottish mathematician who based his theory on the experimental work of Michael Faraday. Heinrich Hertz (1857–1894), a German physicist, carried out experiments between 1886 and 1888 using a rapidly oscillating spark to produce electromagnetic waves, thereby experimentally proving Maxwell's predictions. Therefore, by the latter part of the nineteenth century, the physical basis for many modern inventions utilizing electromagnetic-wave propagation—such as radio, television, and radar—was already established.

The basic physical principle involved is the coupling of electromagnetic energy into a propagation medium, which can be free space or the atmosphere, by means of a radiation element referred to as an *antenna*. Many different propagation modes are possible, depending on the physical configuration of the antenna and the characteristics of the propagation medium. The simplest case—which never occurs in practice—is propagation from a point source in a medium that is infinite in extent. The propagating wave fronts (surfaces of constant phase) in this case would be concentric spheres. Such a model might be used for the propagation of electromagnetic energy from a distant spacecraft to earth. Another idealized model, which approximates the propagation of radio waves from a commercial broadcast antenna, is that of a conducting line perpendicular to an infinite conducting plane. These and other idealized cases have been analyzed in books on electromagnetic theory. Our purpose is not to summarize all the idealized models, but to point out basic aspects of propagation phenomena in practical channels.

Except for the case of propagation between two spacecraft in outer space, the intermediate medium between transmitter and receiver is never well approximated by free space. Depending on the distance involved and the frequency of the radiated waveform, a terrestrial communication link may depend on line-of-sight, ground-wave, or ionospheric skip-wave propagation (see Figure 1.2). Table 1.2 lists frequency bands from 3 kHz to 10^7 GHz, along with letter designations for microwave bands used in radar among other applications. Note that the frequency bands are given in decades; the VHF band has 10 times as much frequency space as the HF band. Table 1.3 shows some bands of particular interest.

General application allocations are arrived at by international agreement. The present system of frequency allocations is administered by the International Telecommunications Union (ITU), which is responsible for the periodic convening of Administrative Radio Conferences

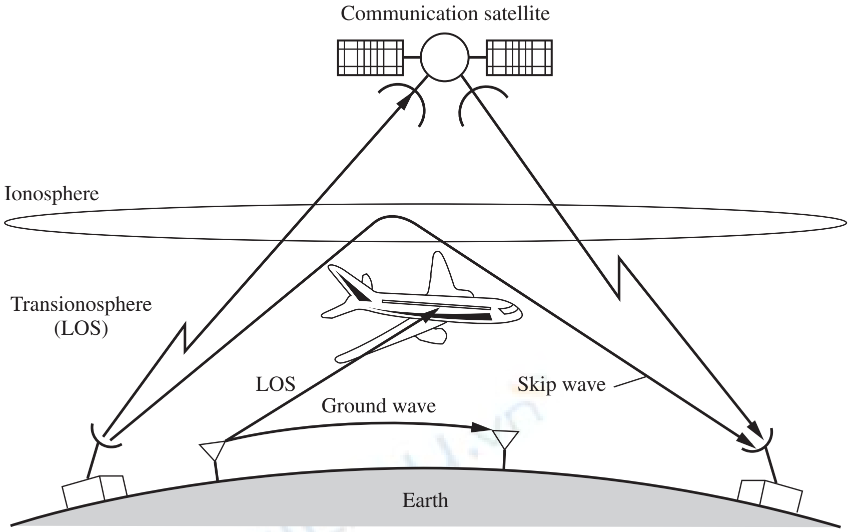

Figure 1.2
The various propagation modes for electromagnetic waves (LOS stands for line of sight).

Table 1.2 Frequency Bands with Designations

Frequency band	Name	Microwave band (GHz)	Letter designation
3–30 kHz	Very low frequency (VLF)		
30–300 kHz	Low frequency (LF)		
300–3000 kHz	Medium frequency (MF)		
3–30 MHz	High frequency (HF)		
30–300 MHz	Very high frequency (VHF)		
0.3–3 GHz	Ultrahigh frequency (UHF)	1.0–2.0	L
		2.0–3.0	S
3–30 GHz	Superhigh frequency (SHF)	3.0–4.0	S
		4.0–6.0	C
		6.0–8.0	C
		8.0–10.0	X
		10.0–12.4	X
		12.4–18.0	Ku
		18.0–20.0	K
		20.0–26.5	K
30–300 GHz	Extremely high frequency (EHF)	26.5–40.0	Ka
43–430 THz	Infrared (0.7–7 μm)		
430–750 THz	Visible light (0.4–0.7 μm)		
750–3000 THz	Ultraviolet (0.1–0.4 μm)		

Note: kHz = kilohertz = $\times 10^3$; MHz = megahertz = $\times 10^6$; GHz = gigahertz = $\times 10^9$; THz = terahertz = $\times 10^{12}$; μm = micrometers = $\times 10^{-6}$ meters.