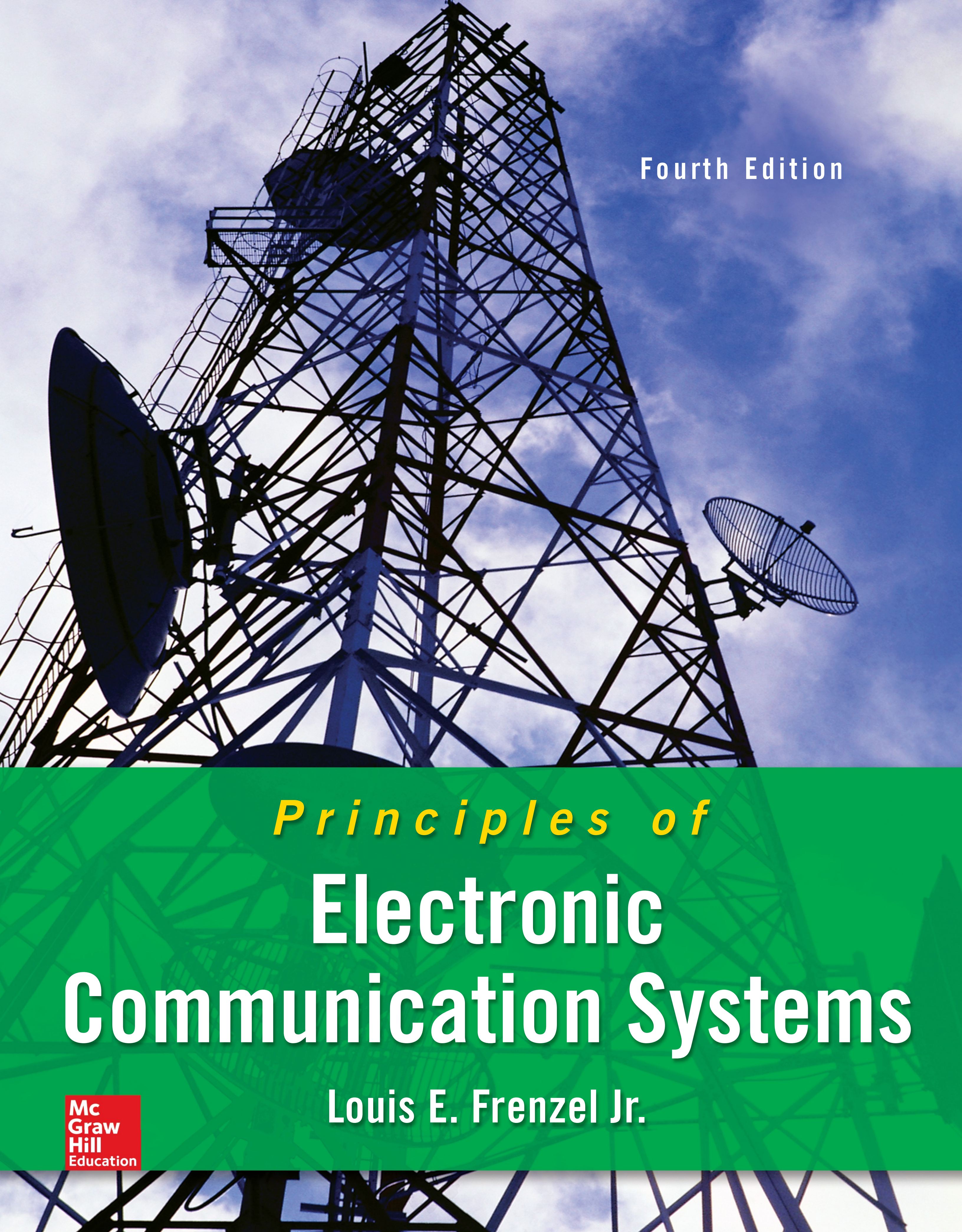

Fourth Edition

Principles of Electronic Communication Systems

Louis E. Frenzel Jr.

McGraw Hill Education

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PRINCIPLES OF ELECTRONIC COMMUNICATION SYSTEMS, FOURTH EDITION

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1 2 3 4 5 6 7 8 9 0 DOW/DOW 1 0 9 8 7 6 5

ISBN 978-0-07-337385-0
MHID 0-07-337385-0

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Design: *Studio Montage, St. Louis, MO*
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Cover Image: ©Royalty Free/Corbis
Compositor: *Aptara®, Inc.*
Typeface: *10/12 Times Roman*
Printer: *R.R. Donnelley*

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Library of Congress Cataloging-in-Publication Data

Frenzel, Louis E., Jr., 1938–
Principles of electronic communication systems / Louis E. Frenzel Jr. —Fourth edition.
pages cm
Includes index.
ISBN 978-0-07-337385-0 (alk. paper) — ISBN 0-07-337385-0 (alk. paper)
1. Telecommunication—Textbooks. 2. Wireless communication systems—Textbooks.
I. Title.

TK5101.F664 2014
384.5—dc23

2014031478

www.mhhe.com

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Preface

This new fourth edition of *Principles of Electronic Communication Systems* is fully revised and updated to make it one of the most current textbooks available on wireless, networking, and other communications technologies. Because the field of electronic communications changes so fast, it is a never-ending challenge to keep a textbook up to date. While principles do not change, their emphasis and relevance do as technology evolves. Furthermore, students need not only a firm grounding in the fundamentals but also an essential understanding of the real world components, circuits, equipment, and systems in everyday use. This latest edition attempts to balance the principles with an overview of the latest techniques.

A continuing goal of this latest revision is to increase the emphasis on the *system level understanding* of wireless, networking, and other communications technologies. Because of the heavy integration of communications circuits today, the engineer and the technician now work more with printed circuit boards, modules, plug-in cards, and equipment rather than component level circuits. As a result, older obsolete circuits have been removed from this text and replaced with more integrated circuits and block diagram level analysis. Modern communications engineers and technicians work with specifications and standards and spend their time testing, measuring, installing, and troubleshooting. This edition moves in that direction. Detailed circuit analysis is still included in selected areas where it proves useful in understanding the concepts and issues in current equipment.

In the past, a course in communications was considered an option in many electronic programs. Today, communications is the largest sector of the electronics field with the most employees and the largest equipment sales annually. In addition, wireless, networking, or other communications technologies are now contained in almost every electronic product. This makes a knowledge and understanding of communication a must rather than an option for every student. Without at least one course in communications, the student may graduate with an incomplete view of the products and systems so common today. This book can provide the background to meet the needs of such a general course.

As the Communications Editor for *Electronic Design Magazine* (Penton), I have observed the continuous changes in the components, circuits, equipment, systems, and applications of modern communications. As I research the field, interview engineers and executives, and attend the many conferences for the articles and columns I write, I have come to see the growing importance of communications in all of our lives. I have tried to bring that perspective to this latest edition where the most recent techniques and technologies are explained. That perspective coupled with the feedback and insight from some of you who teach this subject has resulted in a textbook that is better than ever.

New to this Edition

Here is a chapter-by-chapter summary of revisions and additions to this new edition.

Chapters 1–6	Updating of circuits. Removing obsolete circuits and adding current circuits.
Chapter 7	Updated section on data conversion, including a new section on oversampling and undersampling.

Chapter 8	Expanded coverage of the I/Q architecture for digital data transmission. New section on phase noise. Addition of broadband linear power amplifiers using feedforward and adaptive predistortion techniques. New coverage of Doherty amplifiers and envelope tracking amplifiers for improved power efficiency. Addition of new IC transmitters and transceivers. New coverage of LDMOS and GaN RF power transistors.
Chapter 9	Expanded coverage of receiver sensitivity and signal-to-noise ratio, its importance and calculation. Addition of AWGN and expanded coverage of intermodulation distortion. Increased coverage of the software-defined radio (SDR). New IC receiver circuits and transceivers.
Chapter 10	Updated coverage of multiplexing and access techniques.
Chapter 11	Expanded coverage of digital modulation and spectral efficiency. Increased coverage of digital modulation schemes. New coverage of DSL, ADSL, and VDSL. Addition of cable TV system coverage. Improved coverage of the OSI model. Addition of an explanation of how different digital modulation schemes affect the bit error rate (BER) in communications systems. Updated sections on spread spectrum and OFDM. A new section on convolutional and turbo coding and coding gain.
Chapter 12	Heavily revised to emphasize fundamentals and Ethernet. Dated material removed. Expanded and updated to include the latest Ethernet standards for fiber-optic and copper versions for 100 Gbps.
Chapter 13	Minor revisions and updates.
Chapter 14	Minor revisions and updates.
Chapter 15	Fully updated. Addition of coverage of IPv6 and the Optical Transport Network standard.
Chapter 16	Updated with new emphasis on millimeter waves. Updated circuitry.
Chapter 17	Revised and updated.
Chapter 18	Removal of dated material and updating.
Chapter 19	Expanded section on MSA optical transceiver modules, types and specifications. OM fiber added. Addition of coverage of 100-Gbps techniques, including Mach-Zehnder modulators and DP-QPSK modulation.
Chapter 20	Extensively revisions on cell phone technologies. New coverage on HSPA and Long Term Evolution (LTE) 4G systems. Analysis of a smartphone. Backhaul. A glimpse of 5G including small cells.
Chapter 21	Updates include addition of the latest 802.11ac and 802.11ad Wi-Fi standards. New coverage on machine-to-machine (M2M), the Internet of Things (IoT), and white space technology.
Chapter 22	Revisions and updates include a new section on vector signal analyzers and generators.

One major change is the elimination of the ineffective chapter summaries. Instead, new Online Activity sections have been added to give students the opportunity to further explore new communications techniques, to dig deeper into the theory, and to become more adept at using the Internet to find needed information. These activities show students the massive stores of communications information they can tap for free at any time.

In a large book such as this, it's difficult to give every one what he or she wants. Some want more depth, others greater breadth. I tried to strike a balance between the two. As always, I am always eager to hear from those of you who use the book and welcome your suggestions for the next edition.

Learning Features

Principles of Electronic Communication Systems, fourth edition, has an attractive and accessible page layout. To guide readers and provide an integrated learning approach, each chapter contains the following features:

- Chapter Objectives
- Key Terms
- Good to Know margin features
- Examples with solutions
- Online Activities
- Questions
- Problems
- Critical Thinking

Student Resources

Experiments and Activities Manual

The *Experiments and Activities Manual* has been minimally revised and updated. Building a practical, affordable but meaningful lab is one of the more difficult parts of creating a college course in communications. This new manual provides practice in the principles by using the latest components and methods. Affordable and readily available components and equipment have been used to make it easy for professors to put together a communications lab that validates and complements the text. A new section listing sources of communications laboratory equipment has been added.

The revised *Experiments and Activities Manual* includes some new projects that involve Web access and search to build the student's ability to use the vast resources of the Internet and World Wide Web. The practical engineers and technicians of today have become experts at finding relevant information and answers to their questions and solutions to their problems this way. While practicing this essential skill of any communications engineer or technician knowledge, the student will be able to expand his or her knowledge of any of the subjects in this book, either to dig deeper into the theory and practice or to get the latest update information on chips and other products.

Connect Engineering

The online resources for this edition include McGraw-Hill Connect®, a Web-based assignment and assessment platform that can help students to perform better in their coursework and to master important concepts. With Connect®, instructors can deliver assignments, quizzes, and tests easily online. Students can practice important skills at their own pace and on their own schedule. Ask your McGraw-Hill Representative for more detail and check it out at www.mcgrawhillconnect.com.

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McGraw-Hill LearnSmart® is an adaptive learning system designed to help students learn faster and study more efficiently, and retain more knowledge for greater success. Through a series of adaptive questions, LearnSmart® pinpoints concepts the student does not understand and maps out a personalized study plan for success. It also lets instructors see exactly what students have accomplished, and it features a built-in assessment tool for graded assignments. Ask your McGraw-Hill Representative for more information, and visit www.mhlearnsmart.com for a demonstration.

McGraw-Hill SmartBook™

Powered by the intelligent and adaptive LearnSmart engine, SmartBook is the first and only continuously adaptive reading experience available today. Distinguishing what students know from what they don't, and honing in on concepts they are most likely to forget, SmartBook personalizes content for each student. Reading is no longer a passive and linear experience but an engaging and dynamic one, where students are more likely to master and retain important concepts, coming to class better prepared. SmartBook includes powerful reports that identify specific topics and learning objectives students need to study. These valuable reports also provide instructors insight into how students are progressing through textbook content, and they are useful for identifying class trends, focusing precious class time, providing personalized feedback to students, and tailoring assessment.

How does SmartBook work? Each SmartBook contains four components: Preview, Read, Practice, and Recharge. Starting with an initial preview of each chapter and key learning objectives, students read the material and are guided to topics for which they need the most practice based on their responses to a continuously adapting diagnostic. Read and Practice continue until SmartBook directs students to recharge important material they are most likely to forget to ensure concept mastery and retention.

Electronic Textbooks

This textbook is available as an eBook at www.CourseSmart.com. At CourseSmart, your students can take advantage of significant savings off the cost of a print textbook, reduce their impact on the environment, and gain access to powerful Web tools for learning. CourseSmart eBooks can be viewed online or downloaded to a computer. The eBooks allow students to do full text searches, add highlighting and notes, and share notes with classmates. CourseSmart has the largest selection of eBooks available anywhere. Visit www.CourseSmart.com to learn more and to try a sample chapter.

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The Connect site for this textbook includes a number of instructor and student resources, including:

- A MultiSim Primer for those who want to get up and running with this popular simulation software. The section is written to provide communications examples and applications.
- MultiSim circuit files for communications electronics.
- Answers and solutions to the text problems and lab activities and instructor PowerPoint slides, under password protection.

To access the Instructor Resources through Connect, you must first contact your McGraw-Hill Learning Technology Representative to obtain a password. If you do not know your McGraw-Hill representative, please go to www.mhhe.com/rep, to find your representative.

Once you have your password, go to connect.mheducation.com, and log in. Click on the course for which you are using this textbook. If you have not added a course, click "Add Course," and select "Engineering Technology" from the drop-down menu. Select Principles of Electronic Communication Systems, 4e and click "Next."

Once you have added the course, Click on the "Library" link, and then click "Instructor Resources."

Acknowledgments

My special thanks to McGraw-Hill editor Raghu Srinivasan for his continued support and encouragement to make this new edition possible. Thanks also to Vincent Bradshaw and the other helpful McGraw-Hill support staff, including Kelly Lowery and Amy Hill. It has been a pleasure to work with all of you.

I also want to thank Nancy Friedrich of *Microwaves & RF* magazine and Bill Baumann from *Electronic Design* magazine, both of Penton Media Inc., for permission to use sections of my articles in updating chapters 20 and 21.

And my appreciation also goes out to those professors who reviewed the book and offered your feedback, criticism, and suggestions. Thanks for taking the time to provide that valuable input. I have implemented most of your recommendations. The following reviewers looked over the manuscript in various stages, and provided a wealth of good suggestions for the new edition:

Norman Ahlhelm
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David W. Astorino
Lorain County Community College
Noureddine Bekhouche
Jacksonville State University
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The University of the Arts
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Thomas Henderson
Tulsa Community College
Paul Hollinshead
Cochise Community College
Joe Morales
Dona Ana Community College
Jeremy Spraggs
Fulton-Montgomery Community College
Yun Liu
Baltimore City Community College

With the latest input from industry and the suggestions from those who use the book, this edition should come closer than ever to being an ideal textbook for teaching current day communications electronics.

Lou Frenzel
Austin, Texas
2014

Guided Tour

Learning Features

The fourth edition of *Principles of Electronic Communication Systems* retains many of the popular learning elements featured in previous editions, as well as a few new elements. These include:

Chapter Introduction

Each chapter begins with a brief introduction setting the stage for what the student is about to learn.

Chapter Objectives

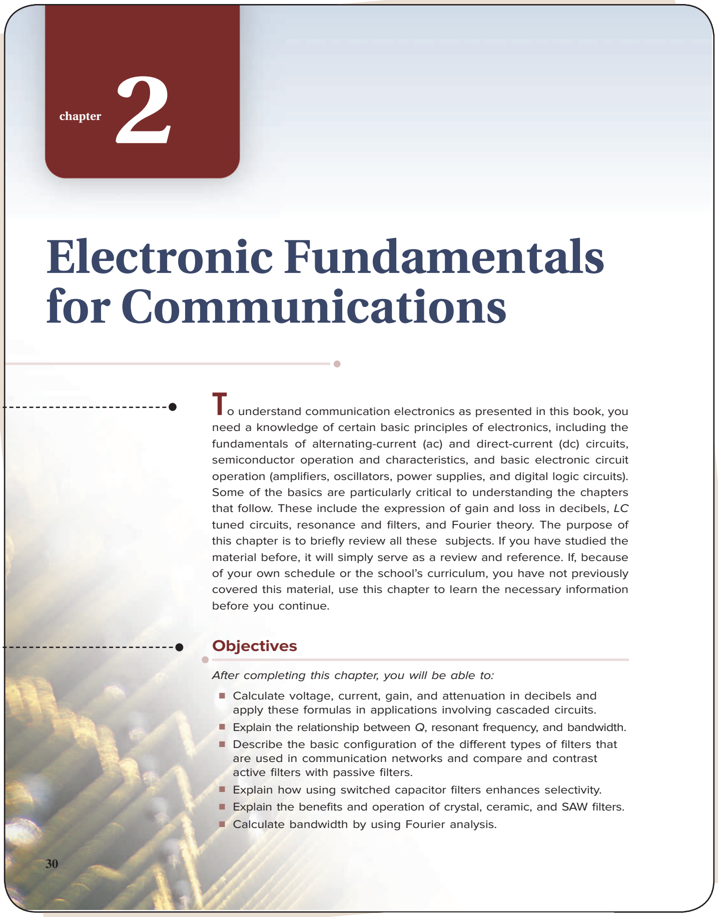
Chapter Objectives provide a concise statement of expected learning outcomes.

Good To Know

Good To Know statements, found in margins, provide interesting added insights to topics being presented.

Examples

Each chapter contains worked-out Examples that demonstrate important concepts or circuit operations, including circuit analysis, applications, troubleshooting, and basic design.



chapter 2

Electronic Fundamentals for Communications

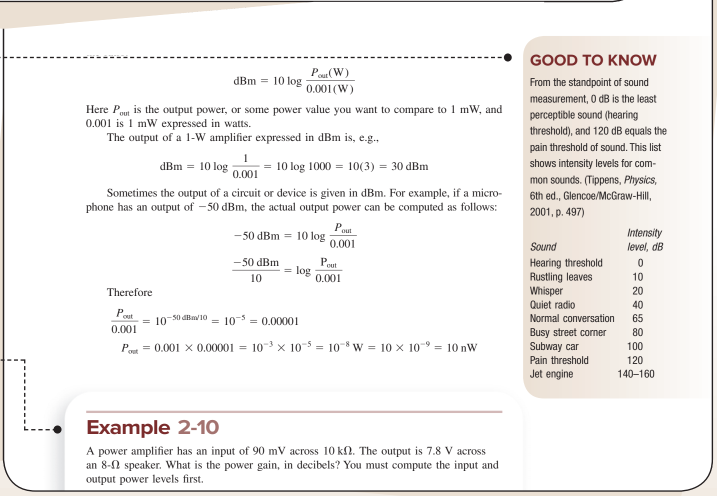
To understand communication electronics as presented in this book, you need a knowledge of certain basic principles of electronics, including the fundamentals of alternating-current (ac) and direct-current (dc) circuits, semiconductor operation and characteristics, and basic electronic circuit operation (amplifiers, oscillators, power supplies, and digital logic circuits). Some of the basics are particularly critical to understanding the chapters that follow. These include the expression of gain and loss in decibels, *LC* tuned circuits, resonance and filters, and Fourier theory. The purpose of this chapter is to briefly review all these subjects. If you have studied the material before, it will simply serve as a review and reference. If, because of your own schedule or the school's curriculum, you have not previously covered this material, use this chapter to learn the necessary information before you continue.

Objectives

After completing this chapter, you will be able to:

- Calculate voltage, current, gain, and attenuation in decibels and apply these formulas in applications involving cascaded circuits.
- Explain the relationship between *Q*, resonant frequency, and bandwidth.
- Describe the basic configuration of the different types of filters that are used in communication networks and compare and contrast active filters with passive filters.
- Explain how using switched capacitor filters enhances selectivity.
- Explain the benefits and operation of crystal, ceramic, and SAW filters.
- Calculate bandwidth by using Fourier analysis.

30



$$\text{dBm} = 10 \log \frac{P_{\text{out}}(\text{W})}{0.001(\text{W})}$$

Here P_{out} is the output power, or some power value you want to compare to 1 mW, and 0.001 is 1 mW expressed in watts.

The output of a 1-W amplifier expressed in dBm is, e.g.,

$$\text{dBm} = 10 \log \frac{1}{0.001} = 10 \log 1000 = 10(3) = 30 \text{ dBm}$$

Sometimes the output of a circuit or device is given in dBm. For example, if a microphone has an output of −50 dBm, the actual output power can be computed as follows:

$$-50 \text{ dBm} = 10 \log \frac{P_{\text{out}}}{0.001}$$

$$\frac{-50 \text{ dBm}}{10} = \log \frac{P_{\text{out}}}{0.001}$$

Therefore

$$\frac{P_{\text{out}}}{0.001} = 10^{-50 \text{ dBm}/10} = 10^{-5} = 0.00001$$

$$P_{\text{out}} = 0.001 \times 0.00001 = 10^{-3} \times 10^{-5} = 10^{-8} \text{ W} = 10 \times 10^{-9} = 10 \text{ nW}$$

GOOD TO KNOW

From the standpoint of sound measurement, 0 dB is the least perceptible sound (hearing threshold), and 120 dB equals the pain threshold of sound. This list shows intensity levels for common sounds. (Tippens, *Physics*, 6th ed., Glencoe/McGraw-Hill, 2001, p. 497)

Sound	*Intensity level, dB*
Hearing threshold	0
Rustling leaves	10
Whisper	20
Quiet radio	40
Normal conversation	65
Busy street corner	80
Subway car	100
Pain threshold	120
Jet engine	140–160

Example 2-10

A power amplifier has an input of 90 mV across 10 kΩ. The output is 7.8 V across an 8-Ω speaker. What is the power gain, in decibels? You must compute the input and output power levels first.

Online Activities

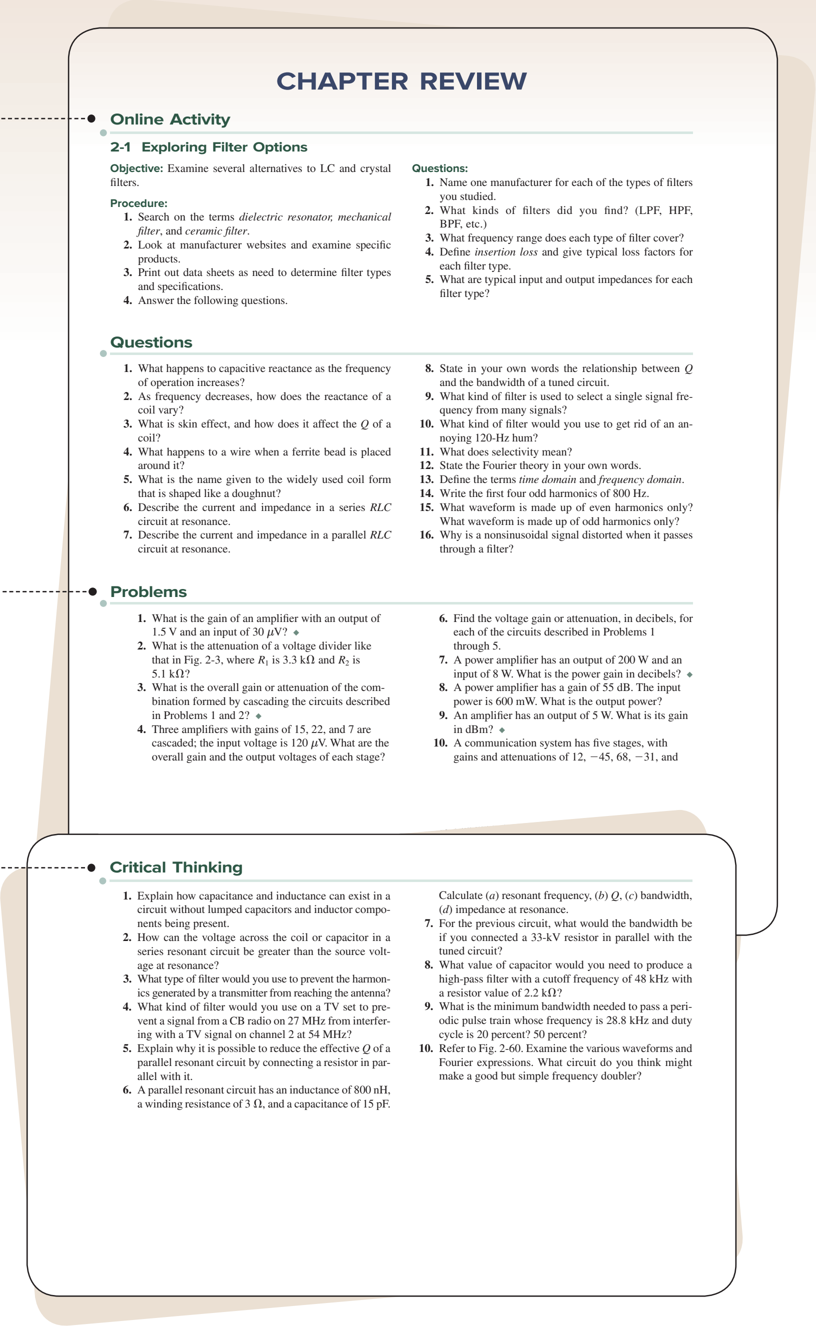
These sections give students the opportunity to further explore new communications techniques, to dig deeper into the theory, and to become more adept at using the Internet to find needed information.

Problems

Students can obtain critical feedback by performing the Practice Problems at the end of the chapter. Answers to selected problems are found at the end of the book.

Critical Thinking

A wide variety of questions and problems are found at the end of each chapter; over 30 percent are new or revised in this edition. Those include circuit analysis, trouble shooting, critical thinking, and job interview questions.



CHAPTER REVIEW

Online Activity

2-1 Exploring Filter Options

Objective: Examine several alternatives to LC and crystal filters.

Procedure:

1. Search on the terms *dielectric resonator, mechanical filter*, and *ceramic filter*.
2. Look at manufacturer websites and examine specific products.
3. Print out data sheets as need to determine filter types and specifications.
4. Answer the following questions.

Questions:

1. Name one manufacturer for each of the types of filters you studied.
2. What kinds of filters did you find? (LPF, HPF, BPF, etc.)
3. What frequency range does each type of filter cover?
4. Define *insertion loss* and give typical loss factors for each filter type.
5. What are typical input and output impedances for each filter type?

Questions

1. What happens to capacitive reactance as the frequency of operation increases?
2. As frequency decreases, how does the reactance of a coil vary?
3. What is skin effect, and how does it affect the *Q* of a coil?
4. What happens to a wire when a ferrite bead is placed around it?
5. What is the name given to the widely used coil form that is shaped like a doughnut?
6. Describe the current and impedance in a series *RLC* circuit at resonance.
7. Describe the current and impedance in a parallel *RLC* circuit at resonance.
8. State in your own words the relationship between *Q* and the bandwidth of a tuned circuit.
9. What kind of filter is used to select a single signal frequency from many signals?
10. What kind of filter would you use to get rid of an annoying 120-Hz hum?
11. What does selectivity mean?
12. State the Fourier theory in your own words.
13. Define the terms *time domain* and *frequency domain*.
14. Write the first four odd harmonics of 800 Hz.
15. What waveform is made up of even harmonics only? What waveform is made up of odd harmonics only?
16. Why is a nonsinusoidal signal distorted when it passes through a filter?

Problems

1. What is the gain of an amplifier with an output of 1.5 V and an input of 30 μV? ◆
2. What is the attenuation of a voltage divider like that in Fig. 2-3, where R_1 is 3.3 kΩ and R_2 is 5.1 kΩ?
3. What is the overall gain or attenuation of the combination formed by cascading the circuits described in Problems 1 and 2? ◆
4. Three amplifiers with gains of 15, 22, and 7 are cascaded; the input voltage is 120 μV. What are the overall gain and the output voltages of each stage?
5. Find the voltage gain or attenuation, in decibels, for each of the circuits described in Problems 1 through 5.
7. A power amplifier has an output of 200 W and an input of 8 W. What is the power gain in decibels? ◆
8. A power amplifier has a gain of 55 dB. The input power is 600 mW. What is the output power?
9. An amplifier has an output of 5 W. What is its gain in dBm? ◆
10. A communication system has five stages, with gains and attenuations of 12, −45, 68, −31, and

Critical Thinking

1. Explain how capacitance and inductance can exist in a circuit without lumped capacitors and inductor components being present.
2. How can the voltage across the coil or capacitor in a series resonant circuit be greater than the source voltage at resonance?
3. What type of filter would you use to prevent the harmonics generated by a transmitter from reaching the antenna?
4. What kind of filter would you use on a TV set to prevent a signal from a CB radio on 27 MHz from interfering with a TV signal on channel 2 at 54 MHz?
5. Explain why it is possible to reduce the effective *Q* of a parallel resonant circuit by connecting a resistor in parallel with it.
6. A parallel resonant circuit has an inductance of 800 nH, a winding resistance of 3 Ω, and a capacitance of 15 pF. Calculate (*a*) resonant frequency, (*b*) *Q*, (*c*) bandwidth, (*d*) impedance at resonance.
7. For the previous circuit, what would the bandwidth be if you connected a 33-kV resistor in parallel with the tuned circuit?
8. What value of capacitor would you need to produce a high-pass filter with a cutoff frequency of 48 kHz with a resistor value of 2.2 kΩ?
9. What is the minimum bandwidth needed to pass a periodic pulse train whose frequency is 28.8 kHz and duty cycle is 20 percent? 50 percent?
10. Refer to Fig. 2-60. Examine the various waveforms and Fourier expressions. What circuit do you think might make a good but simple frequency doubler?

chapter 1

Introduction to Electronic Communication

Objectives

After completing this chapter, you will be able to:

- Explain the functions of the three main parts of an electronic communication system.
- Describe the system used to classify different types of electronic communication and list examples of each type.
- Discuss the role of modulation and multiplexing in facilitating signal transmission.
- Define the electromagnetic spectrum and explain why the nature of electronic communication makes it necessary to regulate the electromagnetic spectrum.
- Explain the relationship between frequency range and bandwidth and give the frequency ranges for spectrum uses ranging from voice to ultra-high-frequency television.
- List the major branches of the field of electronic communication and describe the qualifications necessary for different jobs.
- State the benefit of licensing and certification and name at least three sources.

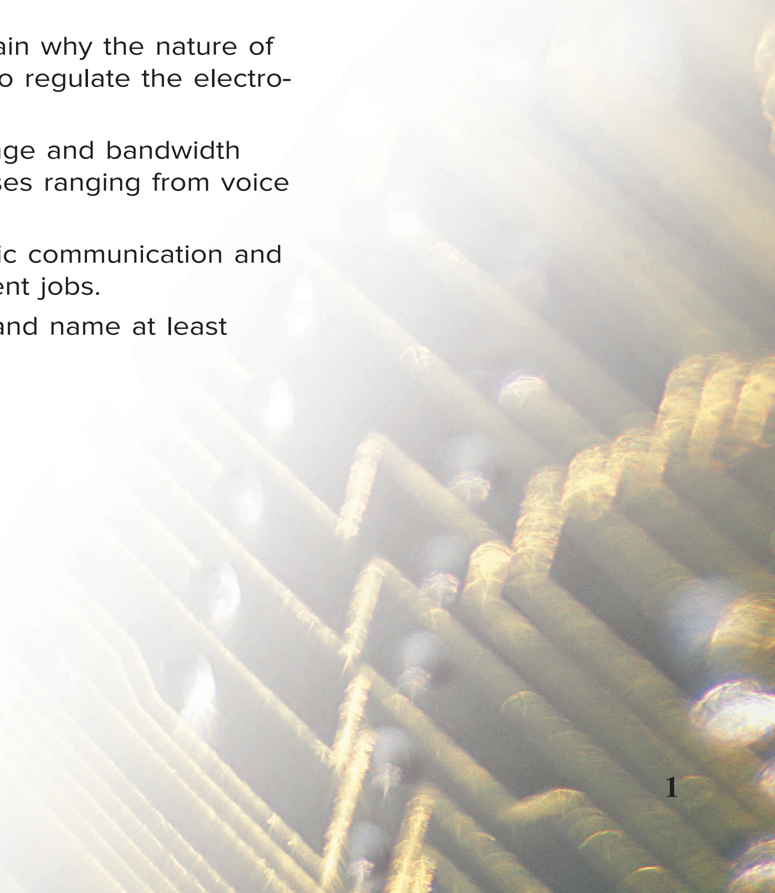


Figure 1-1 Milestones in the history of electronic communication.

When?	Where or Who?	What?
1837	Samuel Morse	Invention of the telegraph (patented in 1844).
1843	Alexander Bain	Invention of facsimile.
1866	United States and England	The first transatlantic telegraph cable laid.
1876	Alexander Bell	Invention of the telephone.
1877	Thomas Edison	Invention of the phonograph.
1879	George Eastman	Invention of photography.
1887	Heinrich Hertz (German)	Discovery of radio waves.
1887	Guglielmo Marconi (Italian)	Demonstration of "wireless" communications by radio waves.
1901	Marconi (Italian)	First transatlantic radio contact made.
1903	John Fleming	Invention of the two-electrode vacuum tube rectifier.
1906	Reginald Fessenden	Invention of amplitude modulation; first electronic voice communication demonstrated.
1906	Lee de Forest	Invention of the triode vacuum tube.
1914	Hiram P. Maxim	Founding of American Radio Relay League, the first amateur radio organization.
1920	KDKA Pittsburgh	First radio broadcast.
1923	Vladimir Zworykin	Invention and demonstration of television.
1933–1939	Edwin Armstrong	Invention of the superheterodyne receiver and frequency modulation.
1939	United States	First use of two-way radio (walkie-talkies).
1940–1945	Britain, United States	Invention and perfection of radar (World War II).
1948	John von Neumann and others	Creation of the first stored program electronic digital computer.
1948	Bell Laboratories	Invention of transistor.
1953	RCA/NBC	First color TV broadcast.
1958–1959	Jack Kilby (Texas Instruments) and Robert Noyce (Fairchild)	Invention of integrated circuits.
1958–1962	United States	First communication satellite tested.
1961	United States	Citizens band radio first used.
1973–1976	Metcalfe	Ethernet and first LANs.
1975	United States	First personal computers.
1977	United States	First use of fiber-optic cable.
1982	United States	TCP/IP protocol adopted.
1982–1990	United States	Internet development and first use.
1983	United States	Cellular telephone networks.
1993	United States	First browser Mosaic.
1995	United States	Global Positioning System deployed.
1996–2001	Worldwide	First smartphones by BlackBerry, Nokia, Palm.
1997	United States	First wireless LANs.
2000	Worldwide	Third-generation digital cell phones.
2009	Worldwide	First fourth-generation LTE cellular networks.
2009	Worldwide	First 100 Gb/s fiber optical networks.

1-1 The Significance of Human Communication

Communication is the process of exchanging information. People communicate to convey their thoughts, ideas, and feelings to others. The process of communication is inherent to all human life and includes verbal, nonverbal (body language), print, and electronic processes.

Communication

Two of the main barriers to human communication are language and distance. Language barriers arise between persons of different cultures or nationalities.

Communicating over long distances is another problem. Communication between early human beings was limited to face-to-face encounters. Long-distance communication was first accomplished by sending simple signals such as drumbeats, horn blasts, and smoke signals and later by waving signal flags (semaphores). When messages were relayed from one location to another, even greater distances could be covered.

The distance over which communication could be sent was extended by the written word. For many years, long-distance communication was limited to the sending of verbal or written messages by human runner, horseback, ship, and later trains.

GOOD TO KNOW

Marconi is generally credited with inventing radio, but he did not. Although he was a key developer and the first deployer of radio, the real credit goes to Heinrich Hertz, who first discovered radio waves, and Nicola Tesla, who first developed real radio applications.

Human communication took a dramatic leap forward in the late nineteenth century when electricity was discovered and its many applications were explored. The telegraph was invented in 1844 and the telephone in 1876. Radio was discovered in 1887 and demonstrated in 1895. Fig. 1-1 is a timetable listing important milestones in the history of electronic communication.

Well-known forms of electronic communication, such as the telephone, radio, TV, and the Internet, have increased our ability to share information. The way we do things and the success of our work and personal lives are directly related to how well we communicate. It has been said that the emphasis in our society has now shifted from that of manufacturing and mass production of goods to the accumulation, packaging, and exchange of information. Ours is an information society, and a key part of it is communication. Without electronic communication, we could not access and apply the available information in a timely way.

This book is about electronic communication, and how electrical and electronic principles, components, circuits, equipment, and systems facilitate and improve our ability to communicate. Rapid communication is critical in our very fast-paced world. It is also addictive. Once we adopt and get used to any form of electronic communication, we become hooked on its benefits. In fact, we cannot imagine conducting our lives or our businesses without it. Just imagine our world without the telephone, radio, e-mail, television, cell phones, tablets, or computer networking.

1-2 Communication Systems

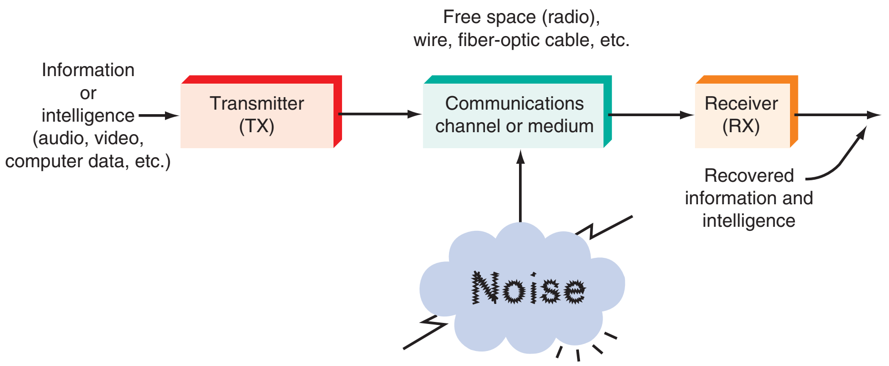
All electronic communication systems have a transmitter, a communication channel or medium, and a receiver. These basic components are shown in Fig. 1-2. The process of communication begins when a human being generates some kind of message, data, or other intelligence that must be received by others. A message may also be generated by a computer or electronic current. In *electronic communication systems,* the message is referred to as *information,* or an intelligence signal. This message, in the form of an electronic signal, is fed to the transmitter, which then transmits the message over the communication channel. The message is picked up by the receiver and relayed to another human. Along the way, noise is added in the communication channel and in the receiver. *Noise* is the general term applied to any phenomenon that degrades or interferes with the transmitted information.

Electronic communication systems

Information

Noise

Figure 1-2 A general model of all communication systems.



Transmitter

Audio

The first step in sending a message is to convert it into electronic form suitable for transmission. For voice messages, a microphone is used to translate the sound into an electronic *audio* signal. For TV, a camera converts the light information in the scene to a video signal. In computer systems, the message is typed on a keyboard and converted to binary codes that can be stored in memory or transmitted serially. Transducers convert physical characteristics (temperature, pressure, light intensity, and so on) into electrical signals.

Transmitter

The *transmitter* itself is a collection of electronic components and circuits designed to convert the electrical signal to a signal suitable for transmission over a given communication medium. Transmitters are made up of oscillators, amplifiers, tuned circuits and filters, modulators, frequency mixers, frequency synthesizers, and other circuits. The original intelligence signal usually modulates a higher-frequency carrier sine wave generated by the transmitter, and the combination is raised in amplitude by power amplifiers, resulting in a signal that is compatible with the selected transmission medium.

Communication Channel

Communication channel

The *communication channel* is the medium by which the electronic signal is sent from one place to another. Many different types of media are used in communication systems, including wire conductors, fiber-optic cable, and free space.

Electrical Conductors. In its simplest form, the medium may simply be a pair of wires that carry a voice signal from a microphone to a headset. It may be a coaxial cable such as that used to carry cable TV signals. Or it may be a twisted-pair cable used in a local-area network (LAN).

Optical Media. The communication medium may also be a fiber-optic cable or “light pipe” that carries the message on a light wave. These are widely used today to carry long-distance calls and all Internet communications. The information is converted to digital form that can be used to turn a laser diode off and on at high speeds. Alternatively, audio or video analog signals can be used to vary the amplitude of the light.

Wireless radio

Free Space. When free space is the medium, the resulting system is known as radio. Also known *as wireless, radio* is the broad general term applied to any form of wireless communication from one point to another. Radio makes use of the electromagnetic spectrum. Intelligence signals are converted to electric and magnetic fields that propagate nearly instantaneously through space over long distances. Communication by visible or infrared light also occurs in free space.

Other Types of Media. Although the most widely used media are conducting cables and free space (radio), other types of media are used in special communication systems. For example, in sonar, water is used as the medium. Passive sonar "listens" for underwater sounds with sensitive hydrophones. Active sonar uses an echo-reflecting technique similar to that used in radar for determining how far away objects under water are and in what direction they are moving.

The earth itself can be used as a communication medium, because it conducts electricity and can also carry low-frequency sound waves.

Alternating-current (ac) power lines, the electrical conductors that carry the power to operate virtually all our electrical and electronic devices, can also be used as communication channels. The signals to be transmitted are simply superimposed on or added to the power line voltage. This is known as *carrier current transmission* or *power line communications (PLC).* It is used for some types of remote control of electrical equipment and in some LANs.

Carrier current transmission

Receivers

Receiver

A *receiver* is a collection of electronic components and circuits that accepts the transmitted message from the channel and converts it back to a form understandable by humans. Receivers contain amplifiers, oscillators, mixers, tuned circuits and filters, and a demodulator or detector that recovers the original intelligence signal from the modulated carrier. The output is the original signal, which is then read out or displayed. It may be a voice signal sent to a speaker, a video signal that is fed to an LCD screen for display, or binary data that is received by a computer and then printed out or displayed on a video monitor.

Transceivers

Most electronic communication is two-way, and so both parties must have both a transmitter and a receiver. As a result, most communication equipment incorporates circuits that both send and receive. These units are commonly referred to as *transceivers.* All the transmitter and receiver circuits are packaged within a single housing and usually share some common circuits such as the power supply. Telephones, handheld radios, cellular telephones, and computer modems are examples of transceivers.

Transceiver

Attenuation

Attenuation

Signal *attenuation,* or degradation, is inevitable no matter what the medium of transmission. Attenuation is proportional to the square of the distance between the transmitter and receiver. Media are also frequency-selective, in that a given medium will act as a low-pass filter to a transmitted signal, distorting digital pulses in addition to greatly reducing signal amplitude over long distances. Thus considerable signal amplification, in both the transmitter and the receiver, is required for successful transmission. Any medium also slows signal propagation to a speed slower than the speed of light.

GOOD TO KNOW

Solar flares can send out storms of ionized radiation that can last for a day or more. The extra ionization in the atmosphere can interfere with communication by adding noise. It can also interfere because the ionized particles can damage or even disable communication satellites. The most serious X-class flares can cause planetwide radio blackouts.

Noise

Noise is mentioned here because it is the bane of all electronic communications. Its effect is experienced in the receiver part of any communications system. For that reason, we cover noise at that more appropriate time in Chapter 9. While some noise can be filtered out, the general way to minimize noise is to use components that contribute less noise and to lower their temperatures. The measure of noise is usually expressed in terms of the signal-to-noise (S/N) ratio (SNR), which is the signal power divided by the noise power and can be stated numerically or in terms of decibels (dB). Obviously, a very high SNR is preferred for best performance.

1-3 Types of Electronic Communication

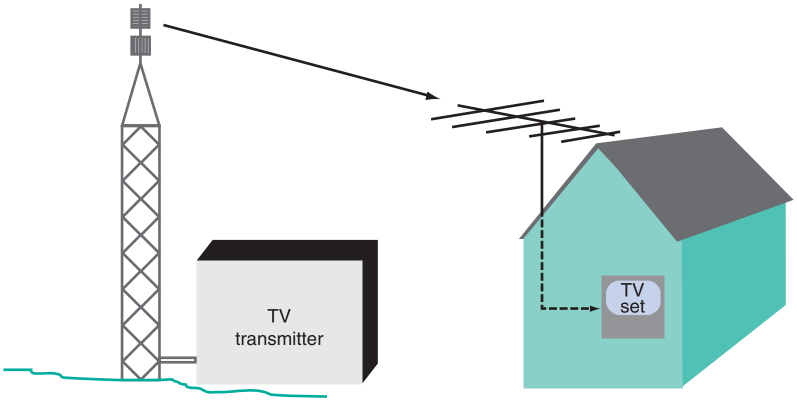
Electronic communications are classified according to whether they are (1) one-way (simplex) or two-way (full duplex or half duplex) transmissions and (2) analog or digital signals.

Simplex

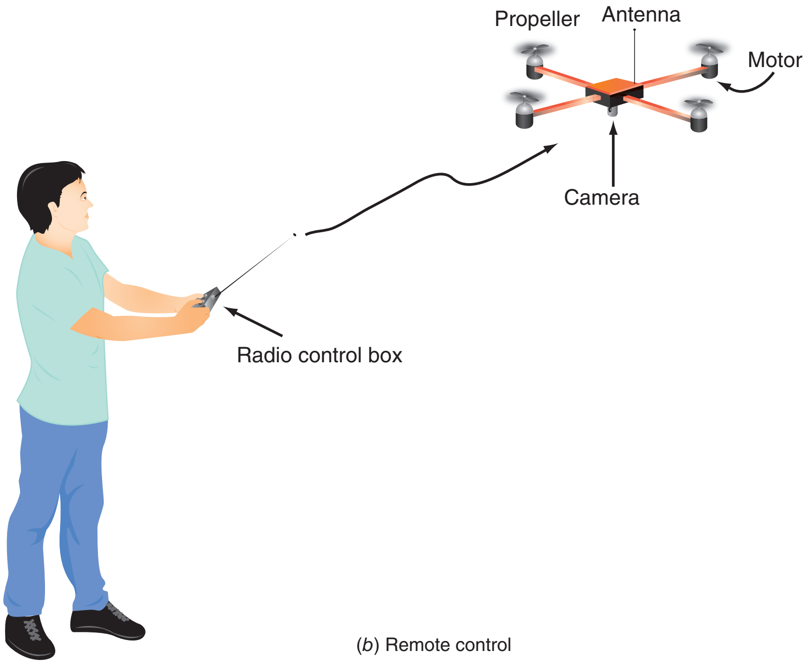
Simplex communication

The simplest way in which electronic communication is conducted is one-way communications, normally referred to as *simplex communication.* Examples are shown in Fig. 1-3. The most common forms of simplex communication are radio and TV broadcasting. Another example of one-way communication is transmission to a remotely controlled vehicle like a toy car or an unmanned aerial vehicle (UAV or drone).

Figure 1-3 Simplex communication.

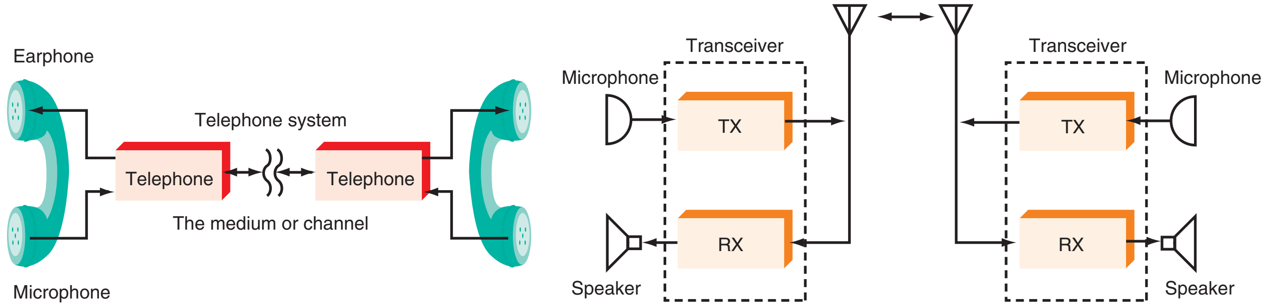


(*a*) TV broadcasting



(*b*) Remote control

Figure 1-4 Duplex communication. (*a*) Full duplex (simultaneous two-way). (*b*) Half duplex (one way at a time).



(*a*) Full duplex (simultaneous, two-way)

(*b*) Half duplex (one way at a time)

Full Duplex

Duplex communication

Full duplex communication

The bulk of electronic communication is two-way, or *duplex communication.* Typical duplex applications are shown in Fig. 1-4. For example, people communicating with one another over the telephone can talk and listen simultaneously, as Fig. 1-4(*a*) illustrates. This is called *full duplex communication.*

Half Duplex

Half duplex communication

The form of two-way communication in which only one party transmits at a time is known as *half duplex communication* [see Fig. 1-4(*b*)]. The communication is two-way, but the direction alternates: the communicating parties take turns transmitting and receiving. Most radio transmissions, such as those used in the military, fire, police, aircraft, marine, and other services, are half duplex communication. Citizens band (CB), Family Radio, and amateur radio communication are also half duplex.

Analog Signals

Analog signal

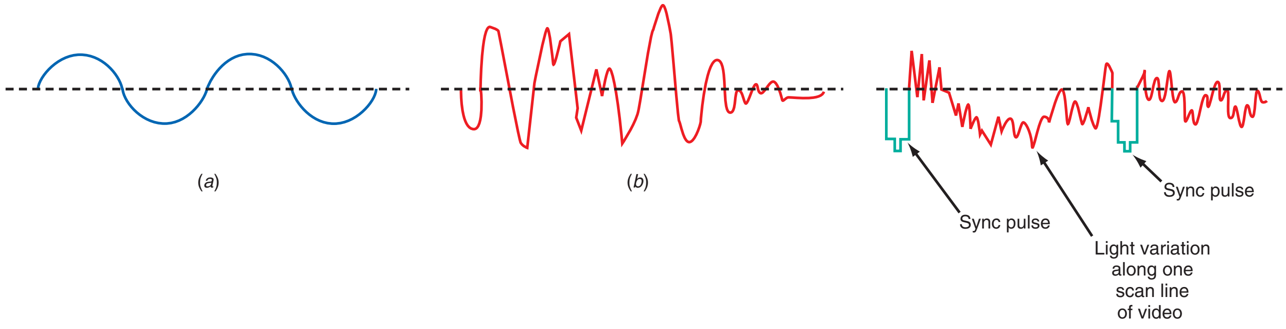
An *analog signal* is a smoothly and continuously varying voltage or current. Some typical analog signals are shown in Fig. 1-5. A sine wave is a single-frequency analog signal. Voice and video voltages are analog signals that vary in accordance with the sound or light variations that are analogous to the information being transmitted.

Digital Signals

Digital signal

Digital signals, in contrast to analog signals, do not vary continuously, but change in steps or in discrete increments. Most digital signals use binary or two-state codes. Some

Figure 1-5 Analog signals. (*a*) Sine wave "tone." (*b*) Voice. (*c*) Video (TV) signal.

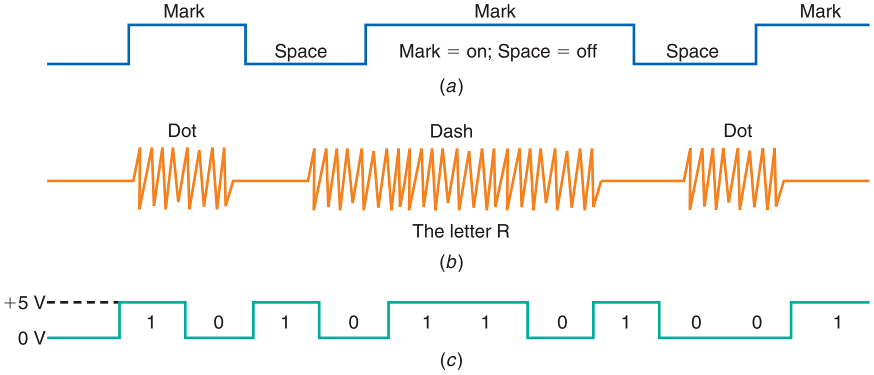


(*a*)

(*b*)

(*c*)

Figure 1-6 Digital signals. (*a*) Telegraph (Morse code). (*b*) Continuous-wave (CW) code. (*c*) Serial binary code.



(*a*) (*b*) (*c*)

examples are shown in Fig. 1-6. The earliest forms of both wire and radio communication used a type of on/off digital code. The telegraph used Morse code, with its system of short and long signals (dots and dashes) to designate letters and numbers. See Fig. 1-6(*a*). In radio telegraphy, also known as continuous-wave (CW) transmission, a sine wave signal is turned off and on for short or long durations to represent the dots and dashes. Refer to Fig. 1-6(*b*).

ASCII

Data used in computers is also digital. Binary codes representing numbers, letters, and special symbols are transmitted serially by wire, radio, or optical medium. The most commonly used digital code in communications is the *American Standard Code for Information Interchange* (*ASCII*, pronounced "ask key"). Fig. 1-6(*c*) shows a serial binary code.

Many transmissions are of signals that originate in digital form, e.g., telegraphy messages or computer data, but that must be converted to analog form to match the transmission medium. An example is the transmission of digital data over the telephone network, which was designed to handle analog voice signals only. If the digital data is converted to analog signals, such as tones in the audio frequency range, it can be transmitted over the telephone network.

Analog signals can also be transmitted digitally. It is very common today to take voice or video analog signals and digitize them with an analog-to-digital (A/D) converter. The data can then be transmitted efficiently in digital form and processed by computers and other digital circuits.

1-4 Modulation and Multiplexing

Modulation

Multiplexing

Modulation and multiplexing are electronic techniques for transmitting information efficiently from one place to another. *Modulation* makes the information signal more compatible with the medium, and *multiplexing* allows more than one signal to be transmitted concurrently over a single medium. Modulation and multiplexing techniques are basic to electronic communication. Once you have mastered the fundamentals of these techniques, you will easily understand how most modern communication systems work.

GOOD TO KNOW

Multiplexing has been used in the music industry to create stereo sound. In stereo radio, two signals are transmitted and received—one for the right and one for the left channel of sound. (For more information on multiplexing, see Chap. 10.)

Baseband Transmission

Before it can be transmitted, the information or intelligence must be converted to an electronic signal compatible with the medium. For example, a microphone changes voice signals (sound waves) into an analog voltage of varying frequency and amplitude. This signal is then passed over wires to a speaker or headphones. This is the way the telephone system works.

A video camera generates an analog signal that represents the light variations along one scan line of the picture. This analog signal is usually transmitted over a coaxial cable. Binary data is generated by a keyboard attached to a computer. The computer stores the data and processes it in some way. The data is then transmitted on cables to peripherals such as a printer or to other computers over a LAN. Regardless of whether the original information or intelligence signals are analog or digital, they are all referred to as baseband signals.

In a communication system, baseband information signals can be sent directly and unmodified over the medium or can be used to modulate a carrier for transmission over the medium. Putting the original voice, video, or digital signals directly into the medium is referred to as *baseband transmission.* For example, in many telephone and intercom systems, it is the voice itself that is placed on the wires and transmitted over some distance to the receiver. In most computer networks, the digital signals are applied directly to coaxial or twisted-pair cables for transmission to another computer.

Baseband transmission

In many instances, baseband signals are incompatible with the medium. Although it is theoretically possible to transmit voice signals directly by radio, realistically it is impractical. As a result, the baseband information signal, be it audio, video, or data, is normally used to modulate a high-frequency signal called a *carrier.* The higher-frequency carriers radiate into space more efficiently than the baseband signals themselves. Such wireless signals consist of both electric and magnetic fields. These electromagnetic signals, which are able to travel through space for long distances, are also referred to as *radio-frequency (RF) waves,* or just radio waves.

Carrier

Radio-frequency (RF) wave

Broadband Transmission

Modulation is the process of having a baseband voice, video, or digital signal modify another, higher-frequency signal, the carrier. The process is illustrated in Fig. 1-7. The information or intelligence to be sent is said to be *impressed* upon the carrier. The carrier is usually a sine wave generated by an oscillator. The carrier is fed to a circuit called a modulator along with the baseband intelligence signal. The intelligence signal changes the carrier in a unique way. The modulated carrier is amplified and sent to the antenna for transmission. This process is called *broadband transmission.*

Broadband transmission

Consider the common mathematical expression for a sine wave:

$$v = V_p \sin(2\pi f t + \theta) \qquad \text{or} \qquad v = V_p \sin(\omega t + \theta)$$

where v = instantaneous value of sine wave voltage
V_p = peak value of sine wave
f = frequency, Hz
ω = angular velocity $= 2\pi f$
t = time, s
$\omega t = 2\pi f t$ = angle, rad ($360° = 2\pi$ rad)
θ = phase angle

Figure 1-7 Modulation at the transmitter.

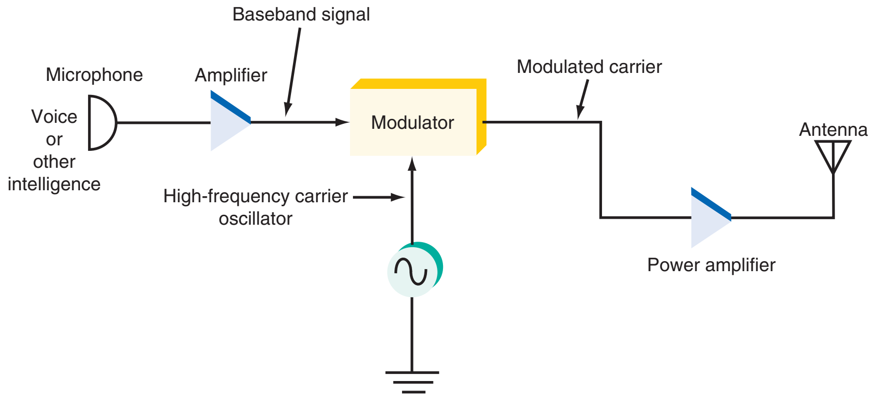
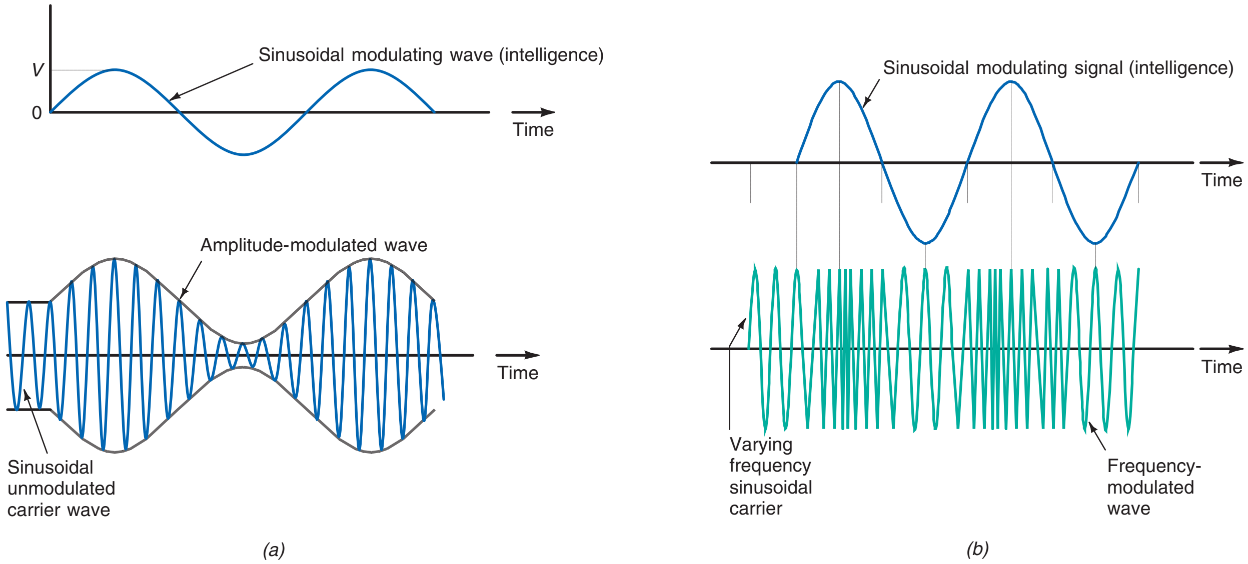


Figure 1-8 Types of modulation. (*a*) Amplitude modulation. (*b*) Frequency modulation.



Amplitude modulation (AM)

Frequency modulation (FM)

Phase modulation (PM)

Frequency-shift keying (FSK)

Phase-shift keying (PSK)

Modems

The three ways to make the baseband signal change the carrier sine wave are to vary its amplitude, vary its frequency, or vary its phase angle. The two most common methods of modulation are *amplitude modulation (AM)* and *frequency modulation (FM)*. In AM, the baseband information signal called the modulating signal varies the amplitude of the higher-frequency carrier signal, as shown in Fig. 1-8(*a*). It changes the V_p part of the equation. In FM, the information signal varies the frequency of the carrier, as shown in Fig. 1-8(*b*). The carrier amplitude remains constant. FM varies the value of f in the first angle term inside the parentheses. Varying the phase angle produces *phase modulation (PM)*. Here, the second term inside the parentheses (θ) is made to vary by the intelligence signal. Phase modulation produces frequency modulation; therefore, the PM signal is similar in appearance to a frequency-modulated carrier. Two common examples of transmitting digital data by modulation are given in Fig. 1-9. In Fig. 1-9(*a*), the data is converted to frequency-varying tones. This is called *frequency-shift keying (FSK)*. In Fig. 1-9(*b*), the data introduces a 180º-phase shift. This is called *phase-shift keying (PSK)*. Devices called *modems* (*mo*dulator-*dem*odulator) translate the data from digital to analog and back again. Both FM and PM are forms of angle modulation.

At the receiver, the carrier with the intelligence signal is amplified and then demodulated to extract the original baseband signal. Another name for the demodulation process is detection. (See Fig. 1-10.)

Figure 1-9 Transmitting binary data in analog form. (*a*) FSK. (*b*) PSK.

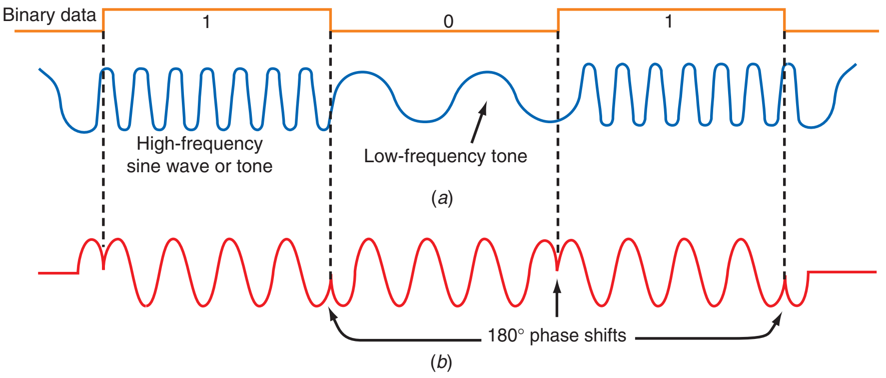
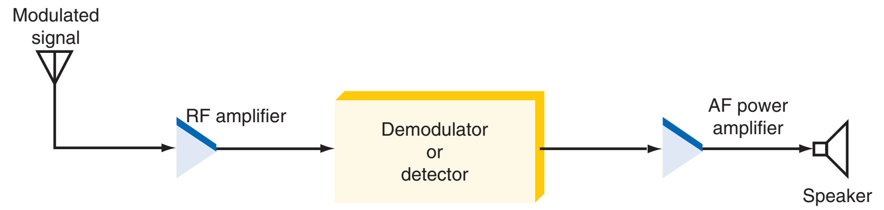


Figure 1-10 Recovering the intelligence signal at the receiver.



Multiplexing

The use of modulation also permits another technique, known as multiplexing, to be used. Multiplexing is the process of allowing two or more signals to share the same medium or channel; see Fig. 1-11. A multiplexer converts the individual baseband signals to a composite signal that is used to modulate a carrier in the transmitter. At the receiver, the composite signal is recovered at the demodulator, then sent to a demultiplexer where the individual baseband signals are regenerated (see Fig. 1-12).

Frequency-division multiplexing

There are three basic types of multiplexing: frequency division, time division, and code division. In *frequency-division multiplexing,* the intelligence signals modulate subcarriers on different frequencies that are then added together, and the composite signal is used to modulate the carrier. In optical networking, wavelength division multiplexing (WDM) is equivalent to frequency-division multiplexing for optical signal.

Time-division multiplexing

In *time-division multiplexing,* the multiple intelligence signals are sequentially sampled, and a small piece of each is used to modulate the carrier. If the information signals are sampled fast enough, sufficient details are transmitted that at the receiving end the signal can be reconstructed with great accuracy.

In code-division multiplexing, the signals to be transmitted are converted to digital data that is then uniquely coded with a faster binary code. The signals modulate a carrier on the same frequency. All use the same communications channel simultaneously. The unique coding is used at the receiver to select the desired signal.

Figure 1-11 Multiplexing at the transmitter.

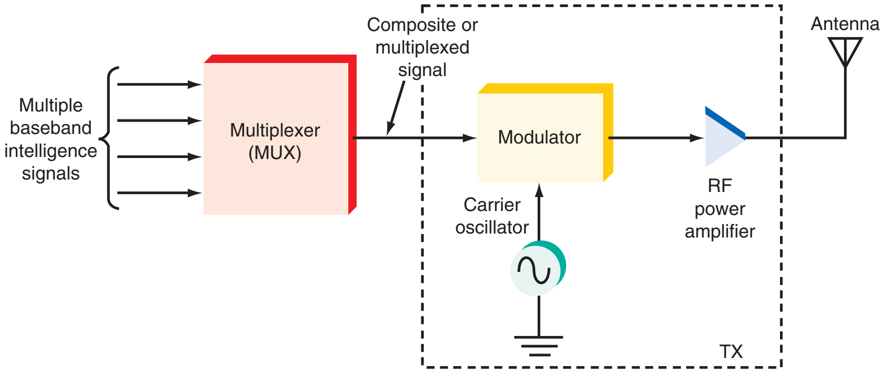
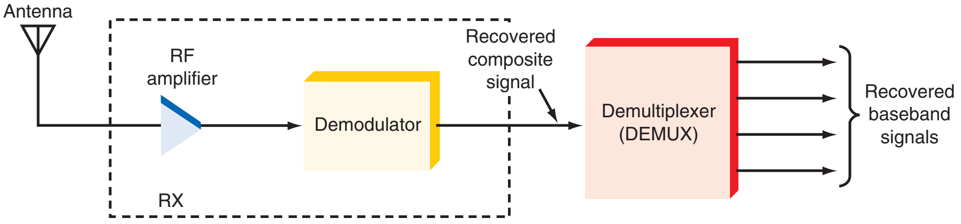


Figure 1-12 Demultiplexing at the receiver.



1-5 The Electromagnetic Spectrum

Electromagnetic waves are signals that oscillate; i.e., the amplitudes of the electric and magnetic fields vary at a specific rate. The field intensities fluctuate up and down, and the polarity reverses a given number of times per second. The electromagnetic waves vary sinusoidally. Their frequency is measured in cycles per second (cps) or hertz (Hz). These oscillations may occur at a very low frequency or at an extremely high frequency. The range of electromagnetic signals encompassing all frequencies is referred to as the *electromagnetic spectrum.*

Electromagnetic spectrum

All electrical and electronic signals that radiate into free space fall into the electromagnetic spectrum. Not included are signals carried by cables. Signals carried by cable may share the same frequencies of similar signals in the spectrum, but they are not radio signals. Fig. 1-13 shows the entire electromagnetic spectrum, giving both frequency and wavelength. Within the middle ranges are located the most commonly used radio frequencies for two-way communication, TV, cell phones, wireless LANs, radar, and other applications. At the upper end of the spectrum are infrared and visible light. Fig. 1-14 is a listing of the generally recognized segments in the spectrum used for electronic communication.

Frequency and Wavelength

A given signal is located on the frequency spectrum according to its frequency and wavelength.

Frequency

Frequency. *Frequency* is the number of times a particular phenomenon occurs in a given period of time. In electronics, frequency is the number of cycles of a repetitive wave that occurs in a given time period. A cycle consists of two voltage polarity reversals, current reversals, or electromagnetic field oscillations. The cycles repeat, forming a continuous but repetitive wave. Frequency is measured in cycles per second (cps). In electronics, the unit of frequency is the hertz, named for the German physicist Heinrich Hertz, who was a pioneer in the field of electromagnetics. One cycle per second is equal to one hertz, abbreviated (Hz). Therefore, 440 cps = 440 Hz.

Fig. 1-15(*a*) shows a sine wave variation of voltage. One positive alternation and one negative alternation form a cycle. If 2500 cycles occur in 1 s, the frequency is 2500 Hz.

Figure 1-13 The electromagnetic spectrum.

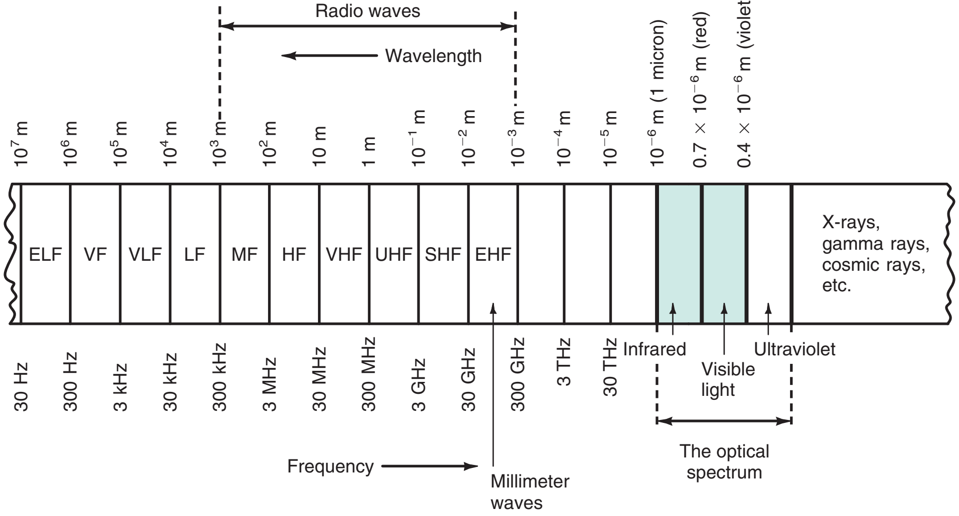


Figure 1-14 The electromagnetic spectrum used in electronic communication.

Name	Frequency	Wavelength
Extremely low frequencies (ELFs)	30–300 Hz	10^7–10^6 m
Voice frequencies (VFs)	300–3000 Hz	10^6–10^5 m
Very low frequencies (VLFs)	3–30 kHz	10^5–10^4 m
Low frequencies (LFs)	30–300 kHz	10^4–10^3 m
Medium frequencies (MFs)	300 kHz–3 MHz	10^3–10^2 m
High frequencies (HFs)	3–30 MHz	10^2–10^1 m
Very high frequencies (VHFs)	30–300 MHz	10^1–1 m
Ultra high frequencies (UHFs)	300 MHz–3 GHz	1–10^{-1} m
Super high frequencies (SHFs)	3–30 GHz	10^{-1}–10^{-2} m
Extremely high frequencies (EHFs)	30–300 GHz	10^{-2}–10^{-3} m
Infrared	—	0.7–10 μm
The visible spectrum (light)	—	0.4–0.8 μm

Units of Measure and Abbreviations:

kHz = 1000 Hz
MHz = 1000 kHz = 1×10^6 = 1,000,000 Hz
GHz = 1000 MHz = 1×10^6 = 1,000,000 kHz
= 1×10^9 = 1,000,000,000 Hz
m = meter
μm = micrometer = $\frac{1}{1,000,000}$ m = 1×10^{-6} m

Prefixes representing powers of 10 are often used to express frequencies. The most frequently used prefixes are as follows:

$$k = \text{kilo} = 1000 = 10^3$$
$$M = \text{mega} = 1{,}000{,}000 = 10^6$$
$$G = \text{giga} = 1{,}000{,}000{,}000 = 10^9$$
$$T = \text{tera} = 1{,}000{,}000{,}000{,}000 = 10^{12}$$

Thus, 1000 Hz = 1 kHz (kilohertz). A frequency of 9,000,000 Hz is more commonly expressed as 9 MHz (megahertz). A signal with a frequency of 15,700,000,000 Hz is written as 15.7 GHz (gigahertz).

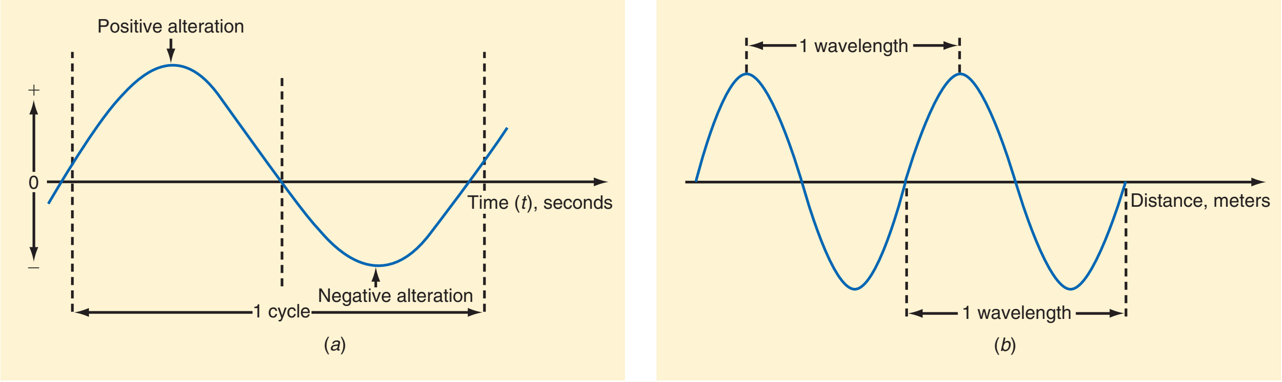
PIONEERS OF ELECTRONICS

In 1887 German physicist Heinrich Hertz was the first to demonstrate the effect of electromagnetic radiation through space. The distance of transmission was only a few feet, but this transmission proved that radio waves could travel from one place to another without the need for any connecting wires. Hertz also proved that radio waves, although invisible, travel at the same velocity as light waves. (Grob/Schultz, *Basic Electronics*, 9th ed., Glencoe/McGraw-Hill, 2003, p. 4)

Wavelength

Wavelength. *Wavelength* is the distance occupied by one cycle of a wave, and it is usually expressed in meters. One meter (m) is equal to 39.37 in (just over 3 ft, or

Figure 1-15 Frequency and wavelength. (*a*) One cycle. (*b*) One wavelength.



1 yd). Wavelength is measured between identical points on succeeding cycles of a wave, as Fig. 1-15(*b*) shows. If the signal is an electromagnetic wave, one wavelength is the distance that one cycle occupies in free space. It is the distance between adjacent peaks or valleys of the electric and magnetic fields making up the wave.

Wavelength is also the distance traveled by an electromagnetic wave during the time of one cycle. Electromagnetic waves travel at the speed of light, or 299,792,800 m/s. The speed of light and radio waves in a vacuum or in air is usually rounded off to 300,000,000 m/s (3×10^8 m/s), or 186,000 mi/s. The speed of transmission in media such as a cable is less.

The wavelength of a signal, which is represented by the Greek letter λ (lambda), is computed by dividing the speed of light by the frequency f of the wave in hertz: $\lambda = 300{,}000{,}000/f$. For example, the wavelength of a 4,000,000-Hz signal is

$$\lambda = 300{,}000{,}000/4{,}000{,}000 = 75 \text{ m}$$

If the frequency is expressed in megahertz, the formula can be simplified to $\lambda(\text{m}) = 300/f(\text{MHz})$ or $\lambda(\text{ft}) = 984\,f(\text{MHz})$.

The 4,000,000-Hz signal can be expressed as 4 MHz. Therefore $\lambda = 300/4 = 75$ m.

Very high frequency signal wavelength

A wavelength of 0.697 m, as in the second equation in Example 1-1, is known as a *very high frequency signal wavelength*. Very high frequency wavelengths are sometimes expressed in centimeters (cm). Since 1 m equals 100 cm, we can express the wavelength of 0.697 m in Example 1-1 as 69.7, or about 70 cm.

Example 1-1

Find the wavelengths of (*a*) a 150-MHz, (*b*) a 430-MHz, (*c*) an 8-MHz, and (*d*) a 750-kHz signal.

a. $\lambda = \dfrac{300{,}000{,}000}{150{,}000{,}000} = \dfrac{300}{150} = 2 \text{ m}$

b. $\lambda = \dfrac{300}{430} = 0.697 \text{ m}$

c. $\lambda = \dfrac{300}{8} = 37.5 \text{ m}$

d. For Hz (750 kHz = 750,000 Hz):

$$\lambda = \frac{300{,}000{,}000}{750{,}000} = 400 \text{ m}$$

For MHz (750 kHz = 0.75 MHz):

$$\lambda = \frac{300}{0.75} = 400 \text{ m}$$

If the wavelength of a signal is known or can be measured, the frequency of the signal can be calculated by rearranging the basic formula $f = 300/\lambda$. Here, f is in megahertz and λ is in meters. As an example, a signal with a wavelength of 14.29 m has a frequency of $f = 300/14.29 = 21$ MHz.

Example 1-2

A signal with a wavelength of 1.5 m has a frequency of

$$f = \frac{300}{1.5} = 200 \text{ MHz}$$

Example 1-3

A signal travels a distance of 75 ft in the time it takes to complete 1 cycle. What is its frequency?

$$1 \text{ m} = 3.28 \text{ ft}$$

$$\frac{75 \text{ ft}}{3.28} = 22.86 \text{ m}$$

$$f = \frac{300}{22.86} = 13.12 \text{ MHz}$$

Example 1-4

The maximum peaks of an electromagnetic wave are separated by a distance of 8 in. What is the frequency in megahertz? In gigahertz?

$$1 \text{ m} = 39.37 \text{ in}$$

$$8 \text{ in} = \frac{8}{39.37} = 0.203 \text{ m}$$

$$f = \frac{300}{0.203} = 1477.8 \text{ MHz}$$

$$\frac{1477.8}{10^3} = 1.4778 \text{ GHz}$$

Frequency Ranges from 30 Hz to 300 GHz

For the purpose of classification, the electromagnetic frequency spectrum is divided into segments, as shown in Fig. 1-13. The signal characteristics and applications for each segment are discussed in the following paragraphs.

Extremely low frequency (ELF)

Extremely Low Frequencies. *Extremely low frequencies (ELFs)* are in the 30- to 300-Hz range. These include ac power line frequencies (50 and 60 Hz are common), as well as those frequencies in the low end of the human audio range.