ELECTRONIC COMMUNICATIONS

A SYSTEMS APPROACH

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To the experimenter, tinkerer, and lifelong
learner in all of us.

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PREFACE

The electronic communications field, the largest business sector in the industry and the original application from which the discipline has evolved, is undergoing a fundamental transformation. Thanks to the computer revolution and advances in large-scale integration, functions traditionally performed by analog circuits built from discrete components are now largely carried out within integrated circuits executing digital signal-processing operations. Such wholesale changes in system implementation bring with them an increasing need for a new approach to study. In contrast with the traditional emphasis on individual circuits embodied by many texts, the primary objective of this book is to foster an in-depth understanding of communications systems by providing a comprehensive description of how functional blocks work together to perform their intended tasks.

Notwithstanding the shift to digitally implemented systems, however, the underlying concepts, constraints, and themes that have informed the communications art for the last century have remained the same. A comprehensive introduction to communications technology in all its forms must emphasize thematic elements that highlight relationships among seemingly isolated concepts. To this end, the early chapters in particular have a narrative structure that provides readers with an overall conceptual framework for the development of foundational concepts and major themes. For example, all communications systems can be examined in terms of certain overriding characteristics, such as bandwidth and power distribution, as well as in terms of constraints on system operation such as noise. When viewing systems from the twin perspectives of characteristics and constraints, readers can begin to forge relationships among concepts that initially may seem very disconnected. The inevitable conclusion is that even the most advanced, highly integrated systems are composed of subsystems employing well-established ideas that are often familiar from the analog context. For this reason, the early chapters are largely given over to a study of modulation techniques and analog circuits, even as the conversion from the analog to the digital realm continues at an accelerating pace. A solid understanding of analog fundamentals provides the platform for a conceptual understanding of how equivalent actions are carried out in the digital domain. With such a foundation, the conceptual leap from analog to digital is less daunting than it may first appear.

Features and Audience

This text is intended for a one- or two-semester course sequence in electronic communications, wireless communications, communications maintenance technology, or introductory telecommunications. The text is suitable for students in two-year programs at community colleges or technical institutes as well as for students in some four-year programs in electronics engineering technology or industrial technology. Math analysis has been kept to the level of algebra and trigonometry but is sufficient to enhance understanding of key, underlying concepts. For completeness, a discussion of Fourier series and complex-exponential representations, topics not often found in books intended for two-year programs, has been included in Chapters 1 and 8, respectively. I have tried throughout to strike a middle ground between calculus-intensive communications texts intended for four-year engineering programs and the math-avoidance path followed by some texts intended for two-year programs.

Several chapters, many illustrations, and most end-of-chapter problems have been adapted from *Modern Electronic Communication* by Jeff Beasley and Gary Miller. This venerable text, now in its 9th edition, has been a standard in its field for over 25 years. As such, it provides an outstanding foundation for the systems-level approach of this book. I am deeply grateful to the authors for entrusting me with the task of adapting their exemplary work for students entering the communications field in the second decade of the 21st century. Students today are entering a field in which entire communications systems are now on single integrated circuits, rather than consisting of multiple stages with many integrated circuits and discrete components. The trend over the past five years has been to the widespread adoption of digital signal processing (DSP) techniques and software-defined radio. Both topics are given more extensive coverage in this text than is the case in competing texts or in previous editions of *Modern Electronic Communication*. As recently as five years ago, many of these techniques were more akin to laboratory curiosities rather than mainstream consumer products. In short, this text takes a top-down view of the discipline rather than a "bottom-up" view implied by a text focusing on circuits built from discrete components.

Topics covered include modulation; communications circuits; transmitters and receivers; digital communications techniques, including digital modulation and demodulation; telephone and wired computer networks; wireless communications systems, both short-range and wide area; transmission lines, impedance matching, and Smith charts; wave propagation; antennas; waveguides and radar; and fiber-optic systems. Considerable attention has been given to providing a narrative structure throughout, and particularly in the fundamentals chapters, to allow readers to put the many facts and concepts encountered into a larger, coherent whole. By explicitly tying together concepts that may have been left unstated before, I hope to help students see the big picture and make sense of topics at a conceptual level, rather than asking them to rely on rote memorization of a large number of seemingly unrelated facts.

Other key features are as follows:

- Review of some basic electronics concepts. Scheduling constraints or differences in curriculum policies may cause students to take the communications courses some significant amount of time after completing the fundamental electronics (dc/ac) and circuits courses. Recognizing this reality, I have expanded coverage of some concepts initially introduced in electronics fundamentals and devices (circuits) courses, including the nature of a sine wave, reactance and resonance, and classes of amplification, to allow opportunities for instructor-led or self-paced review.
- Inclusion of topics and end-of-chapter questions specifically directed at preparation for the U.S. Federal Communications Commission's (FCC) General Radiotelephone Operator License (GROL) exam. The FCC GROL is still valued in industry; many employers use it as a resume filter to screen applicants, and in some industries (particularly avionics) possession of the GROL is mandatory.
- Enhanced coverage of digital communications and DSP. This text has the most up-to-date treatment of enabling technologies behind latest-generation wireless systems, including third- and fourth-generation (3G and 4G) wireless data networks. In addition, sections on the following topics have been significantly expanded and enhanced: digital modulation, DSP, finite-impulse response filters, spread-spectrum implementations, orthogonal frequency-division multiplexing, and multiple-input/multiple-output configurations.
- Discussions of topics not found in other communications texts. The following topics, which are either covered superficially or not at all in other texts, have been included or significantly expanded: SINAD (receiver sensitivity) testing, squelch system operation, DSP modulation/demodulation, spread-spectrum techniques, wireless networks including 802.11n, Bluetooth and ZigBee, enhanced coverage of digital cellular voice networks (GSM and CDMA), coverage of two-way and trunked radio systems, software-defined and cognitive radio, cavity filters/duplexers/combiners, impedance matching and network analysis (including S parameters), Maxwell's equations, and system link budgeting and path-loss calculations.
- Introduction to the concept of analytic frequency and the complex exponential. A section has been added describing some mathematical concepts behind many DSP-based implementations of digital modulation and demodulation that are now becoming mainstream implementations.

Every discipline has as a core part of its narrative the concepts, constraints, and challenges that define it as an intellectual endeavor and a field of inquiry. Electronic communications is no exception. I hope to have conveyed in the pages of this text some sense of the magnitude of ingenuity and scientific accomplishment that is embodied in the technologies described herein, for it is the simple, overriding need of people to be able to talk to each other that has not only brought us to where we are today but that also represents what is surely a transformative achievement of human civilization.

Supplements

- Laboratory Manual to accompany *Electronic Communications* (ISBN: 0-13-301066-X)
- TestGen (Computerized Test Bank): This electronic bank of test questions can be used to develop customized quizzes, tests, and/or exams.
- Online PowerPoint® Presentation
- Online Instructor's Resource Manual

To access supplementary materials online, instructors need to request an instructor access code. Go to **www.pearsonhighered.com/irc**, where you can register for an instructor access code. Within 48 hours after registering, you will receive a confirming e-mail, including an instructor access code. Once you have received your code, go to the site and log on for full instructions on downloading the materials you wish to use.

A Note to the Student

Over the years, as I have taught communications electronics, I have noticed that many students approach the subject with a sense of trepidation, perhaps because the subject matter may seem overly mathematical, esoteric, or just plain "hard." I have also noticed that many students treat the subject strictly as one they are learning in school rather than as one with which they engage outside the classroom as an avocation or hobby. The joy of electronics, however, is in its hands-on nature and in the opportunities it provides for tinkering and experimentation. The opportunity to work with my hands, to explore and to experiment, is what initially attracted me to electronics as a vocation and a field of study. To this end, I encourage you to explore on your own the many opportunities you will have outside of class time to engage with electronic communications systems. There are many well designed radio and communications kits from vendors such as Elenco, TenTec, and Elecraft that will not only allow you to explore the fundamental communications concepts described in this text on your own but that will also give you the opportunity to experience the thrill of seeing something you created with your own hands work the first time you turn it on. In addition, radio amateurs or "hams" experience the enjoyment of worldwide communication with others, often using radios and antennas of their own design. The national organization of amateur radio operators in the United States is the American Radio Relay League (ARRL), located in Newington, Connecticut, and reachable on the internet at www.arrl.org. ARRL publications rank among the best anywhere for providing a rich introduction to communications systems design and operation. I encourage students using this text to explore the field outside the classroom as well, for it is this personal engagement with the subject matter that will make the topic come alive in a way that no book or classroom lecture possibly can.

Acknowledgments

I would again like to acknowledge Jeff Beasley and Gary Miller, authors of *Modern Electronic Communication,* for entrusting me with stewardship of their text. I trained with the 3rd edition of this standard work, never thinking for a moment that I would some day become part of the "MEC family." I am humbled to carry on the tradition it established and can only hope to maintain its standards of excellence. I would also like to thank my colleague, Steve Harsany, for his in-depth review of the end-of-chapter problems and for contributing Appendix A on GROL preparation, as well as former student Scott Cook for his invaluable research assistance. Colleagues Ken Miller, Joe Denny, Sarah Daum, and

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CHAPTER 1

FUNDAMENTAL COMMUNICATIONS CONCEPTS

CHAPTER OUTLINE

KEY TERMS

channel
modulation
carrier
intelligence
demodulation
detection
frequency-division multiplexing
amplitude modulation (AM)
frequency modulation (FM)
phase modulation (PM)
transducer
transceiver
dBm
bandwidth
Hartley's law
information theory
fundamental
harmonic
time domain
frequency domain
spectrum analyzer
fast Fourier transform (FFT)
digitized
noise
external noise
internal noise
atmospheric noise
space noise
solar noise
cosmic noise
ionosphere
Johnson noise
thermal noise
white noise
low-noise resistor
shot noise
excess noise
transit-time noise
signal-to-noise ratio (*S/N* ratio)
noise figure (NF)
noise ratio (NR)
octave
Friiss's formula

1-1 INTRODUCTION

The harnessing of electrical energy to enable long-distance communication represents not only a milestone in technological progress but also a transformative achievement of human civilization. This foundational application of electronics technology continues to be as dynamic and exciting today as it ever was, for societies all over the world are in the midst of yet another communications revolution. The ongoing transition away from exclusively analog technologies toward digital systems promises to continue unabated. Advances in digital communications are key to satisfying the seemingly never-ending demand for ever-higher rates of information transfer in ever more portable devices. The explosion in demand for latest-generation smart phones and other wireless devices, as well as the widespread availability of high-definition television sets, are but two recent entries in a never-ending parade of advances in communications technology.

This book provides a comprehensive overview of wireless and wired, analog and digital electronic communications technologies at the systems level. As with any discipline, the study of communication systems is informed by underlying principles and recurring themes. These themes will become apparent in the first three chapters of this text and will manifest themselves fully in the chapters that follow. Further, all electronic communication systems, whether analog or digital, can be analyzed in terms of certain overriding characteristics such as power distribution and bandwidth, as well as in terms of the fundamental constraints that bound their operation, among them noise. Those commonalities and constraints are the focus of this first chapter.

Communications Systems and Modulation

The function of any communication system is to transfer information from one point to another. All systems fundamentally consist of three elements: a transmitter, a receiver, and a **channel**, or link for information transfer. The channel can be, and often is, wireless. Either the Earth's atmosphere or free space—a vacuum—can form the path between transmitter and receiver. Alternatively, channels can be formed from physical media such as copper wires, transmission lines, waveguides, or optical fibers. As we shall soon see, the characteristics of the channel largely determine the maximum information capacity of the system.

Radio and television stations, whose transmitters use "the airwaves" to broadcast programs to widely dispersed receivers, are familiar examples of communications systems. Other systems make use of both wired and wireless links at the same time. For example, the link between a cellular phone and the base station serving it is wireless, but that interface is only one part of a much larger infrastructure consisting of many base stations, switching centers, and monitoring facilities. Links between base stations and the carrier's mobile switching centers, where equipment that routes calls within and outside the carrier's network is located, may be wired or wireless. Interconnections between switching centers belonging to different wireless and wireline carriers that, taken together, form the global telephone system are most likely made with fiber optic cable; other possibilities include copper wires or satellite interconnections. Other familiar examples abound. For example, subscription-based satellite television and radio services convey information wirelessly through outer space and the atmosphere to Earth-based receivers. Broadband internet capability to the home is provided through networks consisting of either copper wires or coaxial cables, or, in some areas, fiber-optic links. Regardless of their simplicity or complexity, however, all systems can be considered as consisting of the fundamental elements of transmitter, link, and receiver.

Basic to the field of communications is the concept of modulation. **Modulation** is the process of impressing relatively low-frequency voltages that represent information, such as voices, images, or data, onto a high-frequency signal called a **carrier** for transmission. The carrier does just what its name implies: It "carries" the information from the transmitter through the channel to the receiver. The low-frequency information, often termed the **intelligence**, is placed onto the carrier in such a way that its meaning is preserved but that it occupies a band of frequencies much higher than it did before modulation took place. Once received, the intelligence must be recovered, that is, separated, from the high-frequency carrier, a process known as **demodulation** or **detection**.

At this point, you may be thinking: "Why bother to go through this modulation/demodulation process? Why not just transmit the information directly?" As an example, if we wanted to use radio waves to send voice messages to receivers in the surrounding area, could we not just use a microphone to convert the messages from acoustical vibrations to electrical signals and then apply these signals to an antenna for transmission? Though theoretically possible, direct transmission of signals at such low frequencies presents two practical problems: first, the inability to share, and second, the size of the antenna that would be needed. The frequency range of the human voice is from about 20 to 3000 Hz. If more than one party in a given geographic area attempted at the same time to transmit those frequencies directly as radio waves, interference between the transmissions would cause them all to be ineffective. Also, for reasons that will become clear in Chapter 14, the antennas required for efficient propagation of radio signals at such low frequencies would be hundreds if not thousands of miles long—far too impractical for use.

The solution is modulation, in which a high-frequency carrier is used to propagate the low-frequency intelligence through a transmission medium. Through a process known as **frequency-division multiplexing**, in which each transmitter in a given area is assigned exclusive use of a carrier frequency, communications channels (in this case, bands of radio frequencies) are allocated for simultaneous use by multiple transmitters. Modulation enables multiplexing, thereby allowing access to a single communication medium by many different users at the same time. Also, and equally important, the frequencies employed by the modulated signal are high enough to permit the use of antennas of reasonable length. Among the recurring themes in the study of communications is certainly the concept of modulation, and it is for this reason that Chapters 2 and 3 are largely given over to an in-depth analysis of this important topic.

CHARACTERISTICS OF THE CARRIER

Because the carrier is often a sine wave, a review of the characteristics of such waves is in order. Recall from fundamental AC theory that a sine wave looks like the waveform shown in Figure 1-1. A periodic waveform, such as that produced by an electronic oscillator or by a mechanical generator whose armature is rotating within a magnetic field, can be represented by a vector *OB* whose length represents the peak voltage produced within the conductor. In the case of the generator, this would be the voltage created as the conductor cuts across the magnetic lines of force produced by the field. If we assume that the vector *OB* started at the location represented by the line *OA*, we see that a continuously increasing angle θ is created as vector *OB* moves counterclockwise around the circle from *OA*; the speed or velocity at which the vector rotates is directly related to the frequency of rotation: the faster the speed of rotation, the higher the frequency of the resulting waveform.

Why is this waveform called a sine wave? Referring back to Figure 1-1, we place a point t along a horizontal line extended from point *OA* that is the same distance that point B moved along a circle from A. Extending a line horizontally from point B to a point directly above t and calling it point B_1, we see that the point B_1t is the same height as an imaginary vertical line drawn from the end of radius point B to the line defined by *OA*. Put another way, by drawing a perpendicular line from B to the line *OA*, we have formed a right triangle, the hypotenuse of which is the line *OB* and which is equivalent in length to B_1t. The line B_1t represents the magnitude of the instantaneous voltage produced by our

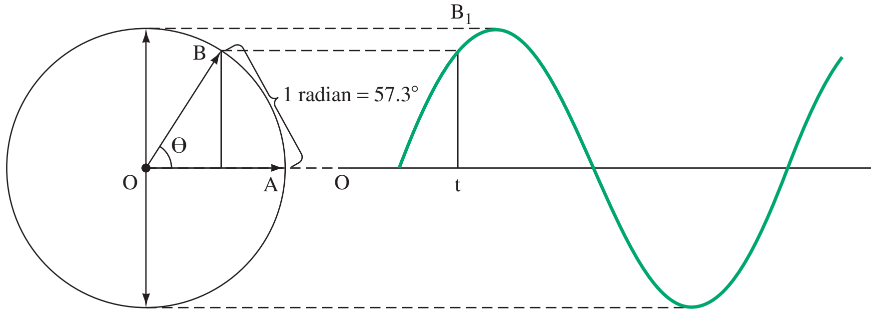

FIGURE 1-1 Sine wave represented as a rotating phasor.

rotating vector at the point B. Since, by definition, the sine of the angle θ is the ratio of the length of the side of a right triangle opposite to that of θ divided by the hypotenuse of that triangle, it follows that, if we define the length of OB to have an arbitrary length of 1 unit, the vertical line B_1t, and therefore the instantaneous voltage at point t, will have a value defined by the sine of θ. The familiar sine-wave representation of an alternating voltage is thus traced out by creating a vertical line created from each point where the vector OB intersects with the circle created by its counterclockwise rotation to the line OA and projecting that vertical line onto a time representation whose horizontal axis is represented by the length from A_1 to A_2. Each trip that the rotating vector makes around the circle represents one complete cycle of the alteration.

If in Figure 1-1 the vector OB is placed such that the distance along the curve from A to B equals the length OB, the size of the angle θ is said to equal 1 unit of angular measurement known as a radian. By definition, the radian is the angle that subtends an arc equal to the radius of the circle and is equal to approximately 57.3 degrees. Because the circumference of a circle equals 2π times the radius of the circle, it follows that there are 2π radians around the circle. (The quantity π is defined as the ratio of the circumference of a circle to its diameter and is a constant.) Therefore, if the vector OB has completed one cycle, it has swept through 2π radians of angle. The frequency of the alternating voltage is the number of cycles that occur in one second; alternatively, it is also the number of times per second that the vector OB goes around the circle. Therefore, the number of radians per second that the vector goes through the circle will be 2π times the frequency. This quantity, called the *angular frequency* or *angular velocity*, is customarily represented by ω, the Greek letter omega. Thus,

$$\omega = 2\pi f.$$

In general, the angular velocity has units of radians per second or degrees per second, and, in Figure 1-1, the distance from points A_1 to A_2 represents a time scale.

When applied to an electrical quantity such as voltage, the angular velocity specifies the time rate of change of the quantity under consideration. Put another way, ω indicates that the total variation of that quantity (such as voltage or current) will be 2π times the cyclic frequency, f, or number of cycles completed per second. Angular velocity and cyclic frequency are clearly related: the higher the angular velocity, the higher the frequency. The concept of angular velocity is useful because many electrical phenomena (in particular, capacitive and inductive reactance) involve rates of change and, therefore, their formulas each contain a π term. In addition, by expressing waveforms in terms of rates of change, we can invoke a number of trigonometric principles to describe the behavior of sine waves both singly and in combination. Since the essence of modulation is the analysis of combinations of sine waves, the ability to express the results of such combinations as trigonometric relationships will become very useful.

From the foregoing, it follows that any sine wave can be represented by the following expression:

$$v = V_P \sin(\omega t + \Phi), \tag{1-1}$$

where v = instantaneous value
V_P = peak value
ω = angular velocity = $2\pi f$
Φ = phase angle.

The cyclic frequency is contained within the ω term, but the Φ term for phase angle may not yet be familiar. The *phase angle* represents the instantaneous number of electrical degrees by which a sine wave is advanced or delayed from some arbitrary starting time $t = 0$. As we shall see in Chapter 3, frequency and phase angle are interrelated: an instantaneous frequency change will create a change in the phase angle, and vice versa.

If the expression of Equation (1-1) represents a carrier, it follows that for modulation to take place, one or more characteristics of the carrier must be modified. **Amplitude modulation (AM)** occurs when the amplitude term, V_P, is varied. **Frequency modulation (FM)** occurs when the frequency term (contained within ω) is varied. Varying the phase angle, Φ, results in **phase modulation (PM)**. Because of the relationship between frequency and phase, these latter two forms of modulation are sometimes classified under the umbrella of "angle" modulation. One overriding fact should be kept in mind at all times: amplitude, frequency, and phase are the only characteristics of a sine-wave carrier that can be modified. The essence of modulation in any system, no matter how outwardly complex it appears, ultimately involves modifying one or more of those three parameters.

Though modulation is certainly not exclusive to wireless systems, the concept is perhaps most familiar in the context of AM and FM broadcast radio. In large part, electronics as a discipline within the field of physical science emerged from the discovery of radio waves, and many core ideas are adapted from those first developed for radio communications. Wireless systems will be the primary focus of many chapters of this text not only because of their historical importance but also because many circuits first developed for early radio systems are used in modified form in other areas of electronics even today.

The Electromagnetic Spectrum

What actually travels between transmitter and receiver in a wireless system? Recall from your study of electrical fundamentals that electricity and magnetism are intertwined. One gives rise to the other. Magnetic fields surround moving electric charges (i.e., currents); likewise, currents are generated in a circuit whenever relative motion occurs between magnetic fields and conductors. Electric and magnetic fields both result from voltage potentials and current flows. In ordinary conductors as well as in "free space," that is, in a vacuum, the electric and magnetic fields form at right angles to each other as well as at right angles to the direction of travel. This form of energy is therefore *electromagnetic* energy. For nonvarying—that is, direct—currents and voltages, the magnitudes of both the electric and magnetic fields are constant, and, therefore, do not reproduce in free space, whereas for alternating currents, the electric and magnetic fields take on the characteristics of the voltages and currents that generated them. A sinusoidal source, therefore, generates at its operating frequency both electric (voltage) and magnetic (current) fields that are sinusoidal in shape as well as at right angles to each other.

Electromagnetic energy is present as the result of electric charge moving within a conductor, but, in the case of alternating currents, the energy also exists outside the confines of the conductor and, indeed, propagates away from its source. With an appropriate **transducer**, a device that converts energy from one form to another, alternating currents flowing in a conductor are converted into waves that continue to exist beyond the physical confines of the conductor. (A wave is a mechanism for the transfer of energy that does not depend on matter.) As in a conductor, the electromagnetic wave in free space exists as both electric and magnetic fields. The voltage potentials defining the electric field and created by accelerating electric charges also create current flows, which in turn give rise to a moving magnetic field at right angles to the electric field. The moving magnetic field so created begets another electric field, and so on. The wave that is created from the moving electric and magnetic fields thereby propagates from its point of origin through space to its ultimate destination. In a wireless system, the transducers are antennas at the transmitter and receiver. Currents generated by the transmitter and applied to its antenna are converted to electromagnetic energy, whereas at the destination, the moving electromagnetic field impinging upon the conductors of the receiving antenna will generate currents within that antenna for subsequent application to the receiver input.

Electromagnetic energy exists at all frequencies from DC (0 Hz) to the frequencies represented by visible light and beyond. Indeed, light is an electromagnetic wave. The *electromagnetic spectrum*, therefore, is composed of the entire range of signals occupying all frequencies. Many familiar activities and services reside along the electromagnetic spectrum. *Audio frequencies*, those that can be heard by the human ear when converted to acoustical form, range from about 20 Hz up to approximately 20 kHz. Frequencies above 50 kHz or so are termed *radio frequencies*, for it is here that electromagnetic energy can be produced and radiated using antennas of reasonable length. The AM radio broadcast band occupies the frequency range from 540 kHz to 1.7 MHz; FM broadcasting is assigned the 20 MHz band of frequencies from 88 to 108 MHz. Cellular telephones use bands of frequencies at either 800 MHz or 1.8 to 2.1 GHz, depending on carrier and geographic region.

Household microwave ovens operate at 2.4 GHz, as do wireless networks of personal computers. Other household wireless devices, among them some cordless phones and newer-vintage local-area networks, operate at 5.8 GHz. These frequencies are well within the microwave region, characterized by very short wavelengths and necessitating specialized techniques that will be covered in subsequent chapters.

Among the ways communication systems can be categorized is by the frequency of the carrier. Table 1-1 shows the designations commonly applied to services within the radio-frequency portion of the electromagnetic spectrum. Note, however, that the electromagnetic spectrum extends beyond even the highest frequencies shown in the table. Above the extra-high-frequency range shown in the table reside the so-called "millimeter wave" bands, which are of particular interest to physicists and astronomers. Above that resides the optical spectrum, consisting of infrared, visible light, and ultraviolet waves. At the very highest frequencies are found X rays, gamma rays, and cosmic rays.

TABLE 1-1 • Radio-Frequency Spectrum

FREQUENCY	DESIGNATION	ABBREVIATION
30–300 Hz	Extremely low frequency	ELF
300–3000 Hz	Voice frequency	VF
3–30 kHz	Very low frequency	VLF
30–300 kHz	Low frequency	LF
300 kHz–3 MHz	Medium frequency	MF
3–30 MHz	High frequency	HF
30–300 MHz	Very high frequency	VHF
300 MHz–3 GHz	Ultra high frequency	UHF
3–30 GHz	Super high frequency	SHF
30–300 GHz	Extra high frequency	EHF

Communications Systems

Figure 1-2 represents a simple communication system in block diagram form. The modulated stage accepts two inputs—the carrier and the information (intelligence) signal—and combines them to produce the modulated signal. This signal is subsequently amplified—often by a factor of thousands, in the case of high-power wireless systems—before transmission. Transmission of the modulated signal can be wireless, or it can involve physical media such as copper wire, coaxial cable, or optical fibers. The receiving unit picks up the transmitted signal and reamplifies it to compensate for attenuation that occurred during transmission. The amplified signal is then applied to the demodulator (often referred to as a detector), where the information is extracted from the high-frequency carrier. The demodulated intelligence is then fed to the amplifier and raised to a level enabling it to drive a speaker or any other output transducer.

All communications systems, from the most basic to the most complex, are fundamentally limited by two factors: bandwidth and noise. For this reason, we will devote considerable space to the study of these important considerations, for these are the themes that inform and unify the development of the communications art. Also, one of the overriding themes of this text is that all communications systems, from the most basic to the most complex, make use of certain principles that have formed the building blocks of communications engineering for over a century, and, particularly in the first three chapters, much space will be given over to the study of these themes because they inform discussion of the system-level topics covered in following chapters. First, however, we must discuss decibel units because of their extreme utility in addressing issues that are common to all communications systems.

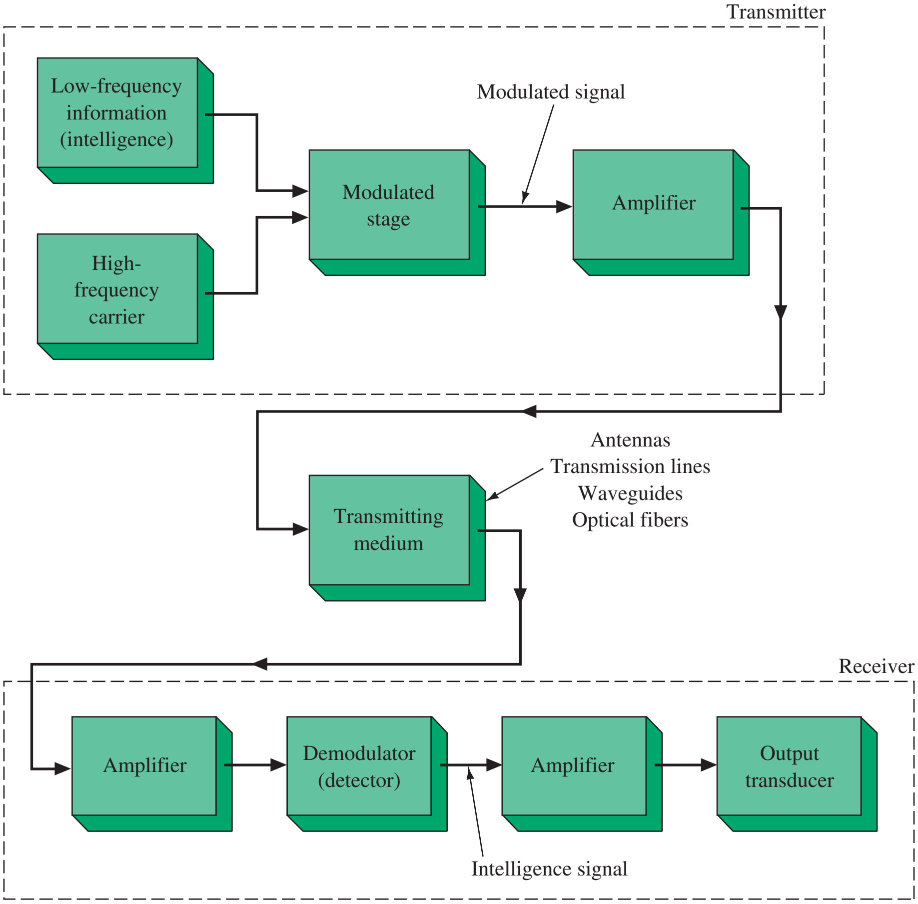

FIGURE 1-2 Communication system block diagram.

1-2 THE DECIBEL IN COMMUNICATIONS WORK

A defining characteristic of any communication system is the wide range of power levels it will encounter. For example, a broadcast station's transmitter might supply tens of thousands of watts to its antenna, but a receiver within the station's coverage area would encounter a power level in the picowatt range at its antenna input. (One picowatt is 10^{-12} watts.) A single **transceiver** (combination transmitter and receiver, such as a mobile two-way radio) will have power levels from femtowatts (10^{-15} W) within the receiver to a substantial fraction of a kilowatt (10^3 W) or more at the transmitter output. Within a receiver, signal voltages are at the millivolt (10^{-3}) or microvolt (10^{-6}) level. Such wide differences in any quantity under consideration are conceptually difficult to envision with ordinary units of measure, yet expansive ranges of powers and voltages, along with the need to make computations involving very large and very small numbers at the same time, are routinely encountered in the analysis of communications systems. For these reasons, we employ units of measure that not only compress an extremely wide range of quantities to a more manageable span but that also make computations involving the multiplication and division of very large or very small quantities easier to manage. Such measurements can be made with relative ease when quantities of interest—power, voltage, or current—are represented as ratios in logarithmic form.

The term *decibel* (dB) may be familiar as a unit of sound intensity. In acoustics, decibels represent ratios related to sound pressure levels, where 0 dB is considered to be absolute silence, and the range from 140 to 160 dB represents the sound pressures encountered in the immediate vicinity of a jet engine. The term is derived from a unit called the

Bel, named in honor of Alexander Graham Bell, the inventor of the telephone. The historical relationship between telephones and sound levels is no accident. Telephone engineers and others realized early on that the ear does not perceive changes in volume in a linear fashion. Amplifiers and other signal-handling equipment deployed in telephone systems must be capable of preserving the natural sound of the human voice over long distances. Researchers learned that human perception of increased volume is more accurately modeled as an exponential relationship, where an apparent doubling of volume or loudness results from a ten-times increase, rather than a doubling, of power. The decibel ($\frac{1}{10}$ Bel) was originally defined to represent the smallest perceivable change in sound level in acoustic or electronic systems.

Decibel notation is by no means exclusively used to represent sound levels or other signals for eventual conversion to acoustic form. As used in electronics, the term simply allows for easy comparison of two, perhaps widely divergent, quantities of interest. Though derived from power ratios, decibels are also used to represent ratios of voltages and currents. Decibel-based calculations are found in noise analysis, audio systems, microwave system gain calculations, satellite system link-budget analysis, antenna power gains, light-budget calculations, and many other communications system measurements. Expressed as ratios, decibels represent system gains and losses; when referenced to absolute levels, decibel units can be used in conjunction with those levels to represent absolute powers, voltages, or currents.

As we shall see shortly, the decibel is defined in terms of, and derives much of its utility from, the properties of logarithms. Because these properties may not be familiar, we shall first describe their characteristics in some detail.

Logarithms

Simply put, logarithms are exponents. You are most likely familiar with "powers-of-10" notation, in which the number 10 is multiplied by itself one or more times to produce a result that increases by a factor of 10 each time the operation is carried out. (You may also have heard the term *order of magnitude*; when properly used in scientific contexts, this expression refers to a power-of-10 relationship.) A raised (superscript) number termed the *exponent* denotes the number of times 10 appears in such expressions. Thus, the expression $10 \times 10 = 100$ can be represented as $10^2 = 100$ because the number 10 has to be multiplied once by itself to produce the answer, 100. Likewise, $10 \times 10 \times 10 = 1000$ is represented in exponential form as $10^3 = 1000$, and so on. As mentioned, in the expression $10^2 = 100$, the raised 2 is called the *exponent*. In that same expression, the 10 is called the *base*, and the result, 100, is the *number*. The exponent (2) can also be called the *logarithm* of the number 100 to the base 10. Such an expression would be expressed in writing as $\log_{10} 100 = 2$ and would be read aloud as "the logarithm to the base 10 of the number 100 is 2." Put in general terms, the logarithm (log) of a number to a given base is the power to which the base must be raised to give the number. While any number could appear as a base in logarithms, those used in decibel expressions are always base-10, or *common,* logarithms. For common logarithms, the base may not be expressed explicitly. Thus, the above expression could be written simply as $\log 100 = 2$ and read aloud as "the log of 100 is 2."

Following the same line of reasoning as for an exponent of 2, the expression $10^3 = 1000$ could be expressed as "$\log 1000 = 3$." The common logarithm of any number between 100 and 1000—that is, the power to which the base, 10, has to be raised to give a result between 100 and 1000—will fall between 2 and 3. Stated another way, the logarithm of a number between 100 and 1000 will be 2 plus some decimal fraction. The whole-number part is called the *characteristic*, and the decimal fraction is the *mantissa;* both of these values historically have been available in published tables of logarithms but are now most easily determined with scientific calculators. The common logarithm is denoted with the "log" key on scientific calculators, and it is distinct from the *natural logarithm,* which has as its base a number denoted as e, equal to 2.71828 . . . . The natural logarithm, represented by the "ln" key on scientific calculators, is the exponent of the function e^x. These terms describe a number of natural phenomena, among them the charge and discharge rates of capacitors and the rates at which magnetic fields expand and collapse around inductors. The natural logarithm is *not* used in decibel calculations.

Conversion of very large and very small numbers into exponential form allows for two very useful properties of exponents, known as the *product rule* and the *quotient rule,* to come into play. The product rule states that when two numbers in exponential form are multiplied, the result is the *product* of the multipliers but the *sum* of the exponents. That is,

$$(A \times 10^n)(B \times 10^m) = (A)(B) \times 10^{n+m}$$

In the above expression, note that, to find the answer, one would add the exponents n and m. There is no need to multiply very large numbers if those numbers are converted to their exponential equivalents. Likewise, division of large numbers in exponential form follows the quotient rule:

$$\frac{A \times 10^n}{B \times 10^m} = \frac{A}{B} \times 10^{n-m}$$

The quotient rule allows for the division of large and small numbers to be reduced to the simple subtraction of their exponents. These properties, though still extremely useful, were indispensable when all calculations had to be carried out with nothing more than a pencil and paper.

Because logarithms are based on exponents, it follows that rules pertaining to exponents apply also to logarithms. Indeed they do, and these useful "log rules" can be summarized as follows:

$$\log ab = \log a + \log b, \quad \text{(Rule 1)}$$
$$\log a/b = \log a - \log b, \quad \text{(Rule 2)}$$

and

$$\log a^b = b \log a. \quad \text{(Rule 3)}$$

Such it is with logarithms that we are able to accomplish our original objective of stating and comparing either very large or very small numbers in a more convenient form. Another advantage is expressed in the above rules: Because quantities in decibel units are expressed as logarithms of power, voltage, or current ratios, these decibel results can simply be added and subtracted. Multiplication and division of very large and very small numbers is thus reduced to the addition or subtraction of their logarithmic, that is, decibel, equivalents.

The inverse of a logarithm is the *antilogarithm.* The antilogarithm (antilog) of a number to a given base is simply the base raised to that number. Therefore, for common logarithms, the antilog is the expression 10^x. For example (again, assuming common logarithms), antilog $2 = 10^2$, or 100. Both the log and antilog can be easily determined with a calculator. On some calculators, the antilog is indeed denoted as 10^x, while others may have an INV key that provides the antilog function when paired with the log key.

The Decibel as a Power Ratio

In electronics, the decibel is fundamentally defined as a power ratio:

$$\text{dB} = 10 \log \frac{P_2}{P_1}. \quad \text{(1-2)}$$

In words, Equation (1-2) states that one decibel is equal to 10 times the logarithm of the ratio of two power levels, P_1 and P_2.* By convention, the numerator of the expression, P_2, is the higher power level so that the result is expressed as a positive number. This convention made determining the logarithm easier when published tables were the norm, but it is no longer absolutely necessary now that calculators are commonplace. Note, however, that if

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* Astute readers may note an apparent contradiction between the prefix "deci-," which means "$\frac{1}{10}$," and the definition in Equation (1-2), in which the Bel ratio, originally defined as $\log(P_2/P_1)$ is multiplied, rather than divided, by 10. It would appear at first that the Bel should be multiplied by 0.1 to create the decibel. The original problem was one of scale: Use of the Bel ratio without modification would cause the very large range of numbers from 0.00000001 to 100,000,000 to be represented by a range of only −8 to +8 Bels. The original ratio produced results that were far too compressed to represent small changes reasonably. Multiplying the log ratio by 10 gives a range of −80 to +80, with each whole-number change representing an increment $\frac{1}{10}$ as large as before (hence the term "deci-"), and allowing for much smaller changes to be represented with numbers of reasonable size.