
CONTENTS

Preface	xix
1 Introduction	1
1-1 Elements of a Digital Communication System	1
1-2 Communication Channels and Their Characteristics	3
1-3 Mathematical Models for Communication Channels	11
1-4 A Historical Perspective in the Development of Digital Communications	13
1-5 Overview of the Book	16
1-6 Bibliographical Notes and References	16
2 Probability and Stochastic Processes	17
2-1 Probability	17
2-1-1 Random Variables, Probability Distributions, and Probability Densities	22
2-1-2 Functions of Random Variables	28
2-1-3 Statistical Averages of Random Variables	33
2-1-4 Some Useful Probability Distributions	37
2-1-5 Upper bounds on the Tail Probability	53
2-1-6 Sums of Random Variables and the Central Limit Theorem	58
2-2 Stochastic Processes	62
2-2-1 Statistical Averages	64
2-2-2 Power Density Spectrum	67
2-2-3 Response of a Linear Time-Invariant System to a Random Input Signal	68
2-2-4 Sampling Theorem for Band-Limited Stochastic Processes	72
2-2-5 Discrete-Time Stochastic Signals and Systems	74
2-2-6 Cyclostationary Processes	75
2-3 Bibliographical Notes and References	77
Problems	77

3	Source Coding	82
3-1	Mathematical Models for Information	82
3-2	A Logarithmic Measure of Information	84
3-2-1	Average Mutual Information and Entropy	87
3-2-2	Information Measures for Continuous Random Variables	91
3-3	Coding for Discrete Sources	93
3-3-1	Coding for Discrete Memoryless Sources	94
3-3-2	Discrete Stationary Sources	103
3-3-3	The Lempel-Ziv Algorithm	106
3-4	Coding for Analog Sources—Optimum Quantization	108
3-4-1	Rate-Distortion Function	108
3-4-2	Scalar Quantization	113
3-4-3	Vector Quantization	118
3-5	Coding Techniques for Analog Sources	125
3-5-1	Temporal Waveform Coding	125
3-5-2	Spectral Waveform Coding	136
3-5-3	Model-Based Source Coding	138
3-6	Bibliographical Notes and References	144
	Problems	144
4	Characterization of Communication Signals and Systems	
4-1	Representation of Bandpass Signals and Systems	152
4-1-1	Representation of Bandpass Signals	153
4-1-2	Representation of Linear Bandpass Systems	157
4-1-3	Response of a Bandpass System to a Bandpass Signal	157
4-1-4	Representation of Bandpass Stationary Stochastic Processes	159
4-2	Signal Space Representation	163
4-2-1	Vector Space Concepts	163
4-2-2	Signal Space Concepts	165
4-2-3	Orthogonal Expansions of Signals	165
4-3	Representation of Digitally Modulated Signals	173
4-3-1	Memoryless Modulation Methods	174
4-3-2	Linear Modulation with Memory	186
4-3-3	Nonlinear Modulation Methods with Memory	190
4-4	Spectral Characteristics of Digitally Modulated Signals	203
4-4-1	Power Spectra of Linearly Modulated Signals	204
4-4-2	Power Spectra of CPM and CFSK Signals	209
4-4-3	Power Spectra of Modulated Signals with Memory	220
4-5	Bibliographical Notes and References	223
	Problems	224
5	Optimum Receivers for the Additive White Gaussian Noise Channel	233
5-1	Optimum Receiver for Signals Corrupted by AWGN	233
5-1-1	Correlation Demodulator	234
5-1-2	Matched-Filter Demodulator	238

5-1-3	The Optimum Detector	244
5-1-4	The Maximum-Likelihood Sequence Detector	249
5-1-5	A Symbol-by-Symbol MAP Detector for Signals with Memory	254
5-2	Performance of the Optimum Receiver for Memoryless Modulation	257
5-2-1	Probability of Error for Binary Modulation	257
5-2-2	Probability of Error for M -ary Orthogonal Signals	260
5-2-3	Probability of Error for M -ary Biorthogonal Signals	264
5-2-4	Probability of Error for Simplex Signals	266
5-2-5	Probability of Error for M -ary Binary-Coded Signals	266
5-2-6	Probability of Error for M -ary PAM	267
5-2-7	Probability of Error for M -ary PSK	269
5-2-8	Differential PSK (DPSK) and its Performance	274
5-2-9	Probability of Error for QAM	278
5-2-10	Comparison of Digital Modulation Methods	282
5-3	Optimum Receiver for CPM Signals	284
5-3-1	Optimum Demodulation and Detection of CPM	285
5-3-2	Performance of CPM Signals	290
5-3-3	Symbol-by-Symbol Detection of CPM Signals	296
5-4	Optimum Receiver for Signals with Random Phase in AWGN Channel	301
5-4-1	Optimum Receiver for Binary Signals	302
5-4-2	Optimum Receiver for M -ary Orthogonal Signals	308
5-4-3	Probability of Error for Envelope Detection of M -ary Orthogonal Signals	308
5-4-4	Probability of Error for Envelope Detection of Correlated Binary Signals	312
5-5	Regenerative Repeaters and Link Budget Analysis	313
5-5-1	Regenerative Repeaters	314
5-5-2	Communication Link Budget Analysis	316
5-6	Bibliographical Notes and References	319
	Problems	320

6	Carrier and Symbol Synchronization	333
6-1	Signal Parameter Estimation	333
6-1-1	The Likelihood Function	335
6-1-2	Carrier Recovery and Symbol Synchronization in Signal Demodulation	336
6-2	Carrier Phase Estimation	337
6-2-1	Maximum-Likelihood Carrier Phase Estimation	339
6-2-2	The Phase-Locked Loop	341
6-2-3	Effect of Additive Noise on the Phase Estimate	343
6-2-4	Decision-Directed Loops	347
6-2-5	Non-Decision-Directed Loops	350
6-3	Symbol Timing Estimation	358
6-3-1	Maximum-Likelihood Timing Estimation	359
6-3-2	Non-Decision-Directed Timing Estimation	361

6-4	Joint Estimation of Carrier Phase and Symbol Timing	365
6-5	Performance Characteristics of ML Estimators	367
6-6	Bibliographical Notes and References	370
	Problems	371
7	Channel Capacity and Coding	374
7-1	Channel Models and Channel Capacity	375
7-1-1	Channel Models	375
7-1-2	Channel Capacity	380
7-1-3	Achieving Channel Capacity with Orthogonal Signals	387
7-1-4	Channel Reliability Functions	389
7-2	Random Selection of Codes	390
7-2-1	Random Coding Based on M -ary Binary-Coded Signals	390
7-2-2	Random Coding Based on M -ary Multiamplitude Signals	397
7-2-3	Comparison of R_0^* with the Capacity of the AWGN Channel	399
7-3	Communication System Design Based on the Cutoff Rate	400
7-4	Bibliographical Notes and References	406
	Problems	406
8	Block and Convolutional Channel Codes	413
8-1	Linear Block Codes	413
8-1-1	The Generator Matrix and the Parity Check Matrix	417
8-1-2	Some Specific Linear Block Codes	421
8-1-3	Cyclic Codes	423
8-1-4	Optimum Soft-Decision Decoding of Linear Block Codes	436
8-1-5	Hard-Decision Decoding	445
8-1-6	Comparison of Performance between Hard-Decision and Soft-Decision Decoding	456
8-1-7	Bounds on Minimum Distance of Linear Block Codes	461
8-1-8	Nonbinary Block Codes and Concatenated Block Codes	464
8-1-9	Interleaving of Coded Data for Channels with Burst Errors	468
8-2	Convolutional Codes	470
8-2-1	The Transfer Function of a Convolutional Code	477
8-2-2	Optimum Decoding of Convolutional Codes— The Viterbi Algorithm	483
8-2-3	Probability of Error for Soft-Decision Decoding	486
8-2-4	Probability of Error for Hard-Decision Decoding	489
8-2-5	Distance Properties of Binary Convolutional Codes	492
8-2-6	Nonbinary Dual- k Codes and Concatenated Codes	492
8-2-7	Other Decoding Algorithms for Convolutional Codes	500
8-2-8	Practical Considerations in the Application of Convolutional Codes	506
8-3	Coded Modulation for Bandwidth-Constrained Channels	511
8-4	Bibliographical Notes and References	526
	Problems	528

9	Signal Design for Band-Limited Channels	534
9-1	Characterization of Band-Limited Channels	534
9-2	Signal Design for Band-Limited Channels	540
9-2-1	Design of Band-Limited Signals for No Intersymbol Interference—The Nyquist Criterion	542
9-2-2	Design of Band-Limited Signals with Controlled ISI—Partial-Response Signals	548
9-2-3	Data Detection for Controlled ISI	551
9-2-4	Signal Design for Channels with Distortion	557
9-3	Probability of Error in Detection of PAM	561
9-3-1	Probability of Error for Detection of PAM with Zero ISI	561
9-3-2	Probability of Error for Detection of Partial-Response Signals	562
9-3-3	Probability of Error for Optimum Signals in Channel with Distortion	565
9-4	Modulation Codes for Spectrum Shaping	566
9-5	Bibliographical Notes and References	576
	Problems	576
10	Communication through Band-Limited Linear Filter Channels	583
10-1	Optimum Receiver for Channels with ISI and AWGN	584
10-1-1	Optimum Maximum-Likelihood Receiver	584
10-1-2	A Discrete-Time Model for a Channel with ISI	586
10-1-3	The Viterbi Algorithm for the Discrete-Time White Noise Filter Model	589
10-1-4	Performance of MLSE for Channels with ISI	593
10-2	Linear Equalization	601
10-2-1	Peak Distortion Criterion	602
10-2-2	Mean Square Error (MSE) Criterion	607
10-2-3	Performance Characteristics of the MSE Equalizer	612
10-2-4	Fractionally Spaced Equalizer	617
10-3	Decision-Feedback Equalization	621
10-3-1	Coefficient Optimization	621
10-3-2	Performance Characteristics of DFE	622
10-3-3	Predictive Decision-Feedback Equalizer	626
10-4	Bibliographical Notes and References	628
	Problems	628
11	Adaptive Equalization	636
11-1	Adaptive Linear Equalizer	636
11-1-1	The Zero-Forcing Algorithm	637
11-1-2	The LMS algorithm	639
11-1-3	Convergence Properties of the LMS Algorithm	642
11-1-4	Excess MSE Due to Noisy Gradient Estimates	644
11-1-5	Baseband and Passband Linear Equalizers	648
11-2	Adaptive Decision-Feedback Equalizer	649
11-2-1	Adaptive Equalization of Trellis-Coded Signals	650

11-3	An Adaptive Channel Estimator for ML Sequence Detection	652
11-4	Recursive Least-Squares Algorithms for Adaptive Equalization	654
11-4-1	Recursive Least-Squares (Kalman) Algorithm	656
11-4-2	Linear Prediction and the Lattice Filter	660
11-5	Self-Recovering (Blind) Equalization	664
11-5-1	Blind Equalization Based on Maximum-Likelihood Criterion	664
11-5-2	Stochastic Gradient Algorithms	668
11-5-3	Blind Equalization Algorithms Based on Second- and Higher-Order Signal Statistics	673
11-6	Bibliographical Notes and References	675
	Problems	676
12	Multichannel and Multicarrier Systems	680
12-1	Multichannel Digital Communication in AWGN Channels	680
12-1-1	Binary Signals	682
12-1-2	M -ary Orthogonal Signals	684
12-2	Multicarrier Communications	686
12-2-1	Capacity of a Non-Ideal Linear Filter Channel	687
12-2-2	An FFT-Based Multicarrier System	689
12-3	Bibliographical Notes and References	692
	Problems	693
13	Spread Spectrum Signals for Digital Communications	695
13-1	Model of Spread Spectrum Digital Communication System	697
13-2	Direct Sequence Spread Spectrum Signals	698
13-2-1	Error Rate Performance of the Decoder	702
13-2-2	Some Applications of DS Spread Spectrum Signals	712
13-2-3	Effect of Pulsed Interference on DS Spread Spectrum Systems	717
13-2-4	Generation of PN Sequences	724
13-3	Frequency-Hopped Spread Spectrum Signals	729
13-3-1	Performance of FH Spread Spectrum Signals in AWGN Channel	732
13-3-2	Performance of FH Spread Spectrum Signals in Partial-Band Interference	734
13-3-3	A CDMA System Based on FH Spread Spectrum Signals	741
13-4	Other Types of Spread Spectrum Signals	743
13-5	Synchronization of Spread Spectrum Signals	744
13-6	Bibliographical Notes and References	752
	Problems	753
14	Digital Communication through Fading Multipath Channels	758
14-1	Characterization of Fading Multipath Channels	759
14-1-1	Channel Correlation Functions and Power Spectra	762
14-1-2	Statistical Models for Fading Channels	767

14-2	The Effect of Characteristics on the Choice of a Channel Model	770
14-3	Frequency-Nonselective, Slowly Fading Channel	772
14-4	Diversity Techniques for Fading Multipath Channels	777
14-4-1	Binary Signals	778
14-4-2	Multiphase Signals	785
14-4-3	M -ary Orthogonal Signals	787
14-5	Digital Signaling over a Frequency-Selective, Slowly Fading Channel	795
14-5-1	A Tapped-Delay-Line Channel Model	795
14-5-2	The RAKE Demodulator	797
14-5-3	Performance of RAKE Receiver	798
14-6	Coded Waveforms for Fading Channels	806
14-6-1	Probability of Error for Soft-Decision Decoding of Linear Binary Block Codes	808
14-6-2	Probability of Error for Hard-Decision Decoding of Linear Binary Block Codes	811
14-6-3	Upper Bounds on the Performance of Convolutional Codes for a Raleigh Fading Channel	811
14-6-4	Use of Constant-Weight Codes and Concatenated Codes for a Fading Channel	814
14-6-5	System Design Based on the Cutoff Rate	825
14-6-6	Trellis-Coded Modulation	830
14-7	Bibliographical Notes and References	832
	Problems	833
15	Multisuser Communications	840
15-1	Introduction to Multiple Access Techniques	840
15-2	Capacity of Multiple Access Methods	843
15-3	Code-Division Multiple Access	849
15-3-1	CDMA Signal and Channel Models	849
15-3-2	The Optimum Receiver	851
15-3-3	Suboptimum Detectors	854
15-3-4	Performance Characteristics of Detectors	859
15-4	Random Access Methods	862
15-4-1	ALOHA System and Protocols	863
15-4-2	Carrier Sense Systems and Protocols	867
15-5	Bibliographical Notes and References	872
	Problems	873
Appendix A	The Levinson-Durbin Algorithm	879
Appendix B	Error Probability for Multichannel Binary Signals	882

Appendix C	Error Probabilities for Adaptive Reception of M-phase Signals	887
C-1	Mathematical Model for an M -phase Signaling Communications System	887
C-2	Characteristic Function and Probability Density Function of the Phase	889
C-3	Error Probabilities for Slowly Rayleigh Fading Channels	891
C-4	Error Probabilities for Time-Invariant and Ricean Fading Channels	893
Appendix D	Square-Root Factorization	897
	References and Bibliography	899
	Index	917

INTRODUCTION

In this book, we present the basic principles that underlie the analysis and design of digital communication systems. The subject of digital communications involves the transmission of information in digital form from a source that generates the information to one or more destinations. Of particular importance in the analysis and design of communication systems are the characteristics of the physical channels through which the information is transmitted. The characteristics of the channel generally affect the design of the basic building blocks of the communication system. Below, we describe the elements of a communication system and their functions.

1-1 ELEMENTS OF A DIGITAL COMMUNICATION SYSTEM

Figure 1-1-1 illustrates the functional diagram and the basic elements of a digital communication system. The source output may be either an analog signal, such as audio or video signal, or a digital signal, such as the output of a teletype machine, that is discrete in time and has a finite number of output characters. In a digital communication system, the messages produced by the source are converted into a sequence of binary digits. Ideally, we should like to represent the source output (message) by as few binary digits as possible. In other words, we seek an efficient representation of the source output that results in little or no redundancy. The process of efficiently converting the output of either an analog or digital source into a sequence of binary digits is called *source encoding* or *data compression*.

The sequence of binary digits from the source encoder, which we call the

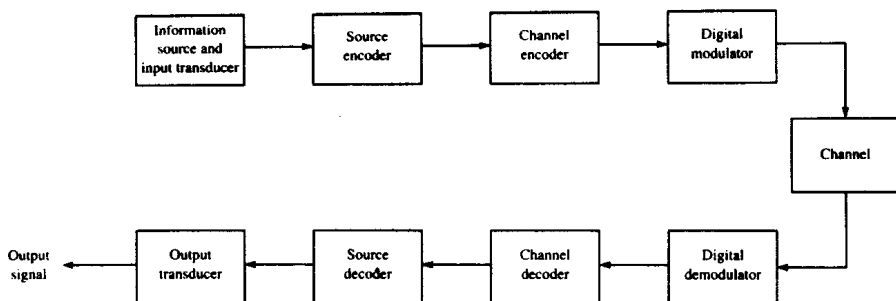


FIGURE 1-1-1 Basic elements of a digital communication system.

information sequence, is passed to the *channel encoder*. The purpose of the channel encoder is to introduce, in a controlled manner, some redundancy in the binary information sequence that can be used at the receiver to overcome the effects of noise and interference encountered in the transmission of the signal through the channel. Thus, the added redundancy serves to increase the reliability of the received data and improves the fidelity of the received signal. In effect, redundancy in the information sequence aids the receiver in decoding the desired information sequence. For example, a (trivial) form of encoding of the binary information sequence is simply to repeat each binary digit m times, where m is some positive integer. More sophisticated (nontrivial) encoding involves taking k information bits at a time and mapping each k -bit sequence into a unique n -bit sequence, called a *code word*. The amount of redundancy introduced by encoding the data in this manner is measured by the ratio n/k . The reciprocal of this ratio, namely k/n , is called the rate of the code or, simply, the *code rate*.

The binary sequence at the output of the channel encoder is passed to the *digital modulator*, which serves as the interface to the communications channel. Since nearly all of the communication channels encountered in practice are capable of transmitting electrical signals (waveforms), the primary purpose of the digital modulator is to map the binary information sequence into signal waveforms. To elaborate on this point, let us suppose that the coded information sequence is to be transmitted one bit at a time at some uniform rate R bits/s. The digital modulator may simply map the binary digit 0 into a waveform $s_0(t)$ and the binary digit 1 into a waveform $s_1(t)$. In this manner, each bit from the channel encoder is transmitted separately. We call this *binary modulation*. Alternatively, the modulator may transmit b coded information bits at a time by using $M = 2^b$ distinct waveforms $s_i(t)$, $i = 0, 1, \dots, M - 1$, one waveform for each of the 2^b possible b -bit sequences. We call this *M-ary modulation* ($M > 2$). Note that a new b -bit sequence enters the modulator

every b/R seconds. Hence, when the channel bit rate R is fixed, the amount of time available to transmit one of the M waveforms corresponding to a b -bit sequence is b times the time period in a system that uses binary modulation.

The *communication channel* is the physical medium that is used to send the signal from the transmitter to the receiver. In wireless transmission, the channel may be the atmosphere (free space). On the other hand, telephone channels usually employ a variety of physical media, including wire lines, optical fiber cables, and wireless (microwave radio). Whatever the physical medium used for transmission of the information, the essential feature is that the transmitted signal is corrupted in a random manner by a variety of possible mechanisms, such as additive *thermal noise* generated by electronic devices, man-made noise, e.g., automobile ignition noise, and atmospheric noise, e.g., electrical lightning discharges during thunderstorms.

At the receiving end of a digital communications system, the *digital demodulator* processes the channel-corrupted transmitted waveform and reduces the waveforms to a sequence of numbers that represent estimates of the transmitted data symbols (binary or M -ary). This sequence of numbers is passed to the channel decoder, which attempts to reconstruct the original information sequence from knowledge of the code used by the channel encoder and the redundancy contained in the received data.

A measure of how well the demodulator and decoder perform is the frequency with which errors occur in the decoded sequence. More precisely, the average probability of a bit-error at the output of the decoder is a measure of the performance of the demodulator-decoder combination. In general, the probability of error is a function of the code characteristics, the types of waveforms used to transmit the information over the channel, the transmitter power, the characteristics of the channel, i.e., the amount of noise, the nature of the interference, etc., and the method of demodulation and decoding. These items and their effect on performance will be discussed in detail in subsequent chapters.

As a final step, when an analog output is desired, the source decoder accepts the output sequence from the channel decoder and, from knowledge of the source encoding method used, attempts to reconstruct the original signal from the source. Due to channel decoding errors and possible distortion introduced by the source encoder and, perhaps, the source decoder, the signal at the output of the source decoder is an approximation to the original source output. The difference or some function of the difference between the original signal and the reconstructed signal is a measure of the distortion introduced by the digital communication system.

1-2 COMMUNICATION CHANNELS AND THEIR CHARACTERISTICS

As indicated in the preceding discussion, the communication channel provides the connection between the transmitter and the receiver. The physical channel

may be a pair of wires that carry the electrical signal, or an optical fiber that carries the information on a modulated light beam, or an underwater ocean channel in which the information is transmitted acoustically, or free space over which the information-bearing signal is radiated by use of an antenna. Other media that can be characterized as communication channels are data storage media, such as magnetic tape, magnetic disks, and optical disks.

One common problem in signal transmission through any channel is additive noise. In general, additive noise is generated internally by components such as resistors and solid-state devices used to implement the communication system. This is sometimes called *thermal noise*. Other sources of noise and interference may arise externally to the system, such as interference from other users of the channel. When such noise and interference occupy the same frequency band as the desired signal, its effect can be minimized by proper design of the transmitted signal and its demodulator at the receiver. Other types of signal degradations that may be encountered in transmission over the channel are signal attenuation, amplitude and phase distortion, and multipath distortion.

The effects of noise may be minimized by increasing the power in the transmitted signal. However, equipment and other practical constraints limit the power level in the transmitted signal. Another basic limitation is the available channel bandwidth. A bandwidth constraint is usually due to the physical limitations of the medium and the electronic components used to implement the transmitter and the receiver. These two limitations result in constraining the amount of data that can be transmitted reliably over any communications channel as we shall observe in later chapters. Below, we describe some of the important characteristics of several communication channels.

Wireline Channels The telephone network makes extensive use of wire lines for voice signal transmission, as well as data and video transmission. Twisted-pair wire lines and coaxial cable are basically guided electromagnetic channels that provide relatively modest bandwidths. Telephone wire generally used to connect a customer to a central office has a bandwidth of several hundred kilohertz (kHz). On the other hand, coaxial cable has a usable bandwidth of several megahertz (MHz). Figure 1-2-1 illustrates the frequency range of guided electromagnetic channels, which include waveguides and optical fibers.

Signals transmitted through such channels are distorted in both amplitude and phase and further corrupted by additive noise. Twisted-pair wireline channels are also prone to crosstalk interference from physically adjacent channels. Because wireline channels carry a large percentage of our daily communications around the country and the world, much research has been performed on the characterization of their transmission properties and on methods for mitigating the amplitude and phase distortion encountered in signal transmission. In Chapter 9, we describe methods for designing optimum transmitted signals and their demodulation; in Chapters 10 and 11, we

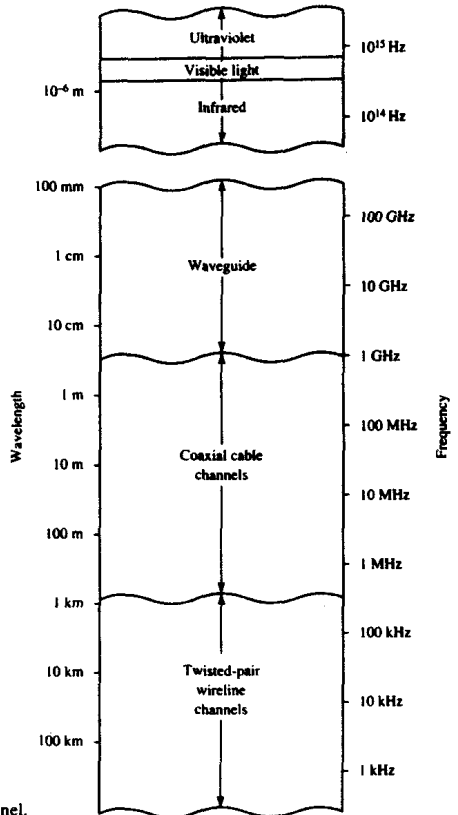


FIGURE 1-2-1 Frequency range for guided wire channel.

consider the design of channel equalizers that compensate for amplitude and phase distortion on these channels.

Fiber Optic Channels Optical fibers offer the communications system designer a channel bandwidth that is several orders of magnitude larger than coaxial cable channels. During the past decade, optical fiber cables have been developed that have a relatively low signal attenuation, and highly reliable photonic devices have been developed for signal generation and signal detection. These technological advances have resulted in a rapid deployment of optical fiber channels, both in domestic telecommunication systems as well as for trans-Atlantic and trans-Pacific communications. With the large bandwidth

available on fiber optic channels, it is possible for telephone companies to offer subscribers a wide array of telecommunication services, including voice, data, facsimile, and video.

The transmitter or modulator in a fiber optic communication system is a light source, either a light-emitting diode (LED) or a laser. Information is transmitted by varying (modulating) the intensity of the light source with the message signal. The light propagates through the fiber as a light wave and is amplified periodically (in the case of digital transmission, it is detected and regenerated by repeaters) along the transmission path to compensate for signal attenuation. At the receiver, the light intensity is detected by a photodiode, whose output is an electrical signal that varies in direct proportion to the power of the light impinging on the photodiode. Sources of noise in fiber optic channels are photodiodes and electronic amplifiers.

It is envisioned that optical fiber channels will replace nearly all wireline channels in the telephone network by the turn of the century.

Wireless Electromagnetic Channels In wireless communication systems, electromagnetic energy is coupled to the propagation medium by an antenna which serves as the radiator. The physical size and the configuration of the antenna depend primarily on the frequency of operation. To obtain efficient radiation of electromagnetic energy, the antenna must be longer than $\frac{1}{10}$ of the wavelength. Consequently, a radio station transmitting in the AM frequency band, say at $f_c = 1$ MHz (corresponding to a wavelength of $\lambda = c/f_c = 300$ m), requires an antenna of at least 30 m. Other important characteristics and attributes of antennas for wireless transmission are described in Chapter 5.

Figure 1-2-2 illustrates the various frequency bands of the electromagnetic spectrum. The mode of propagation of electromagnetic waves in the atmosphere and in free space may be subdivided into three categories, namely, ground-wave propagation, sky-wave propagation, and line-of-sight (LOS) propagation. In the VLF and audio frequency bands, where the wavelengths exceed 10 km, the earth and the ionosphere act as a waveguide for electromagnetic wave propagation. In these frequency ranges, communication signals practically propagate around the globe. For this reason, these frequency bands are primarily used to provide navigational aids from shore to ships around the world. The channel bandwidths available in these frequency bands are relatively small (usually 1–10% of the center frequency), and hence the information that is transmitted through these channels is of relatively slow speed and generally confined to digital transmission. A dominant type of noise at these frequencies is generated from thunderstorm activity around the globe, especially in tropical regions. Interference results from the many users of these frequency bands.

Ground-wave propagation, as illustrated in Fig. 1-2-3, is the dominant mode of propagation for frequencies in the MF band (0.3–3 MHz). This is the frequency band used for AM broadcasting and maritime radio broadcasting. In AM broadcasting, the range with groundwave propagation of even the more

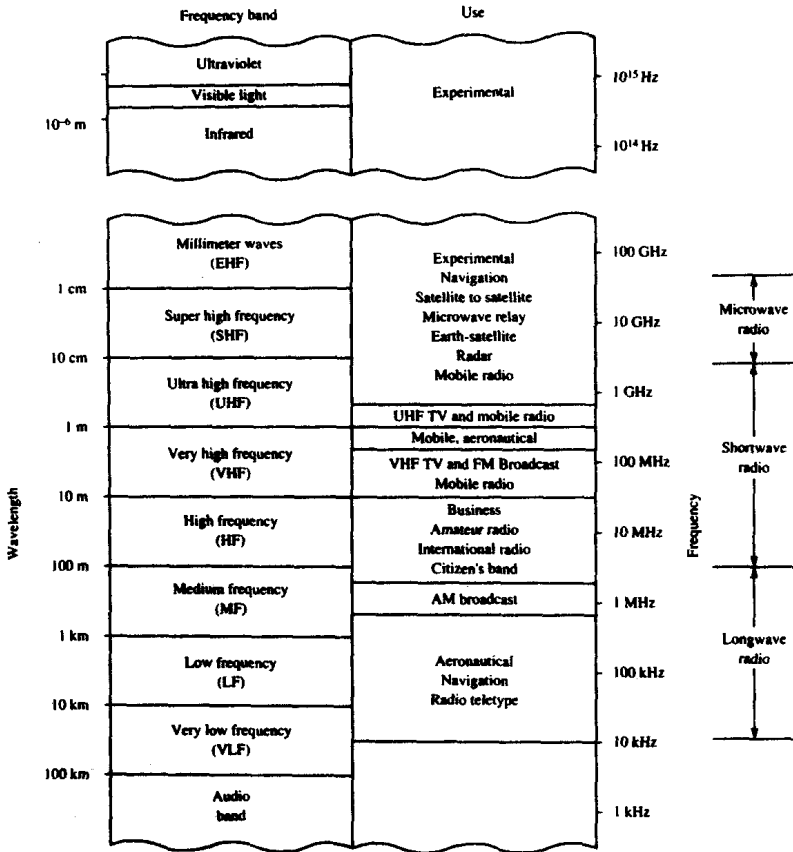


FIGURE 1-2-2 Frequency range for wireless electromagnetic channels. [Adapted from Carlson (1975), 2nd edition, © McGraw-Hill Book Company Co. Reprinted with permission of the publisher.]

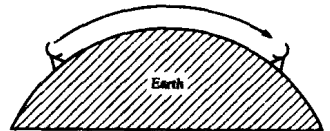


FIGURE 1-2-3 Illustration of ground-wave propagation.

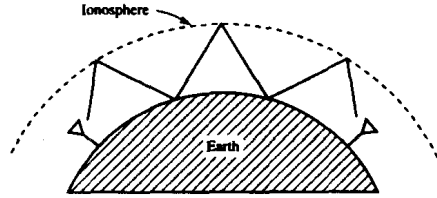


FIGURE 1-2-4 Illustration of sky-wave propagation.

powerful radio stations is limited to about 150 km. Atmospheric noise, man-made noise, and thermal noise from electronic components at the receiver are dominant disturbances for signal transmission in the MF band.

Sky-wave propagation, as illustrated in Fig. 1-2-4 results from transmitted signals being reflected (bent or refracted) from the ionosphere, which consists of several layers of charged particles ranging in altitude from 50 to 400 km above the surface of the earth. During the daytime hours, the heating of the lower atmosphere by the sun causes the formation of the lower layers at altitudes below 120 km. These lower layers, especially the D-layer, serve to absorb frequencies below 2 MHz, thus severely limiting sky-wave propagation of AM radio broadcast. However, during the night-time hours, the electron density in the lower layers of the ionosphere drops sharply and the frequency absorption that occurs during the daytime is significantly reduced. As a consequence, powerful AM radio broadcast stations can propagate over large distances via sky wave over the F-layer of the ionosphere, which ranges from 140 to 400 km above the surface of the earth.

A frequently occurring problem with electromagnetic wave propagation via sky wave in the HF frequency range is *signal multipath*. Signal multipath occurs when the transmitted signal arrives at the receiver via multiple propagation paths at different delays. It generally results in intersymbol interference in a digital communication system. Moreover, the signal components arriving via different propagation paths may add destructively, resulting in a phenomenon called *signal fading*, which most people have experienced when listening to a distant radio station at night when sky wave is the dominant propagation mode. Additive noise at HF is a combination of atmospheric noise and thermal noise.

Sky-wave ionospheric propagation ceases to exist at frequencies above approximately 30 MHz, which is the end of the HF band. However, it is possible to have ionospheric scatter propagation at frequencies in the range 30–60 MHz, resulting from signal scattering from the lower ionosphere. It is also possible to communicate over distances of several hundred miles by use of tropospheric scattering at frequencies in the range 40–300 MHz. Troposcatter results from signal scattering due to particles in the atmosphere at altitudes of 10 miles or less. Generally, ionospheric scatter and tropospheric scatter

involve large signal propagation losses and require a large amount of transmitter power and relatively large antennas.

Frequencies above 30 MHz propagate through the ionosphere with relatively little loss and make satellite and extraterrestrial communications possible. Hence, at frequencies in the VHF band and higher, the dominant mode of electromagnetic propagation is line-of-sight (LOS) propagation. For terrestrial communication systems, this means that the transmitter and receiver antennas must be in direct LOS with relatively little or no obstruction. For this reason, television stations transmitting in the VHF and UHF frequency bands mount their antennas on high towers to achieve a broad coverage area.

In general, the coverage area for LOS propagation is limited by the curvature of the earth. If the transmitting antenna is mounted at a height h m above the surface of the earth, the distance to the radio horizon, assuming no physical obstructions such as mountains, is approximately $d = \sqrt{15h}$ km. For example, a TV antenna mounted on a tower of 300 m in height provides a coverage of approximately 67 km. As another example, microwave radio relay systems used extensively for telephone and video transmission at frequencies above 1 GHz have antennas mounted on tall towers or on the top of tall buildings.

The dominant noise limiting the performance of a communication system in VHF and UHF frequency ranges is thermal noise generated in the receiver front end and cosmic noise picked up by the antenna. At frequencies in the SHF band above 10 GHz, atmospheric conditions play a major role in signal propagation. For example, at 10 GHz, the attenuation ranges from about 0.003 dB/km in light rain to about 0.3 dB/km in heavy rain. At 100 GHz, the attenuation ranges from about 0.1 dB/km in light rain to about 6 dB/km in heavy rain. Hence, in this frequency range, heavy rain introduces extremely high propagation losses that can result in service outages (total breakdown in the communication system).

At frequencies above the EHF (extremely high frequency) band, we have the infrared and visible light regions of the electromagnetic spectrum, which can be used to provide LOS optical communication in free space. To date, these frequency bands have been used in experimental communication systems, such as satellite-to-satellite links.

Underwater Acoustic Channels Over the past few decades, ocean exploration activity has been steadily increasing. Coupled with this increase is the need to transmit data, collected by sensors placed under water, to the surface of the ocean. From there, it is possible to relay the data via a satellite to a data collection center.

Electromagnetic waves do not propagate over long distances under water except at extremely low frequencies. However, the transmission of signals at such low frequencies is prohibitively expensive because of the large and powerful transmitters required. The attenuation of electromagnetic waves in water can be expressed in terms of the *skin depth*, which is the distance a signal is attenuated by $1/e$. For sea water, the skin depth $\delta = 250/\sqrt{f}$, where f is