



ELECTRONIC COMMUNICATIONS

A SYSTEMS APPROACH

JEFFREY S. BEASLEY

JONATHAN D. HYMER

GARY M. MILLER

ELECTRONIC COMMUNICATIONS

A Systems Approach

JEFFREY S. BEASLEY

New Mexico State University

JONATHAN D. HYMER

Mt. San Antonio College

GARY M. MILLER

PEARSON

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Editorial Director: Vernon R. Anthony
Acquisitions Editor: Lindsey Prudhomme Gill
Editor, Digital Projects: Nichole Caldwell
Editorial Assistant: Amanda Cerreto
Director of Marketing: David Gesell
Marketing Manager: Stacey Martinez
Senior Marketing Coordinator: Alicia Wozniak
Senior Marketing Assistant: Les Roberts
Senior Managing Editor: JoEllen Gohr
Senior Project Manager: Rex Davidson
Senior Operations Supervisor: Pat Tonneman
Creative Director: Andrea Nix
Art Director: Jayne Conte
Cover Image: Fotolia
Full-Service Project Management: Peggy Kellar/iEnergizer Aptara®, Inc.
Composition: Aptara®, Inc.
Printer/Binder: R. R. Donnelley & Sons
Cover Printer: Lehigh/Phoenix Color Hagerstown
Text Font: Times Roman

Credits and acknowledgments for materials borrowed from other sources and reproduced, with permission, in this textbook appear on the credits page.

Copyright © 2014 by Pearson Education, Inc. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458, or you may fax your request to 201-236-3290.

Many of the designations by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed in initial caps or all caps.

Library of Congress Cataloging-in-Publication Data

Beasley, Jeffrey S., 1955–
Electronic communication : a systems approach / Jeffrey S. Beasley,
Gary M. Miller, Jonathan Hymer.
pages cm
Includes index.
ISBN-13: 978-0-13-298863-6
ISBN-10: 0-13-298863-1
1. Telecommunication. I. Miller, Gary M., 1941– II. Hymer, Jonathan.
III. Title.
TK5101.B3268 2014
621.382—dc23

2012049919

10 9 8 7 6 5 4 3 2 1

PEARSON

ISBN 10: 0-13-298863-1
ISBN 13: 978-0-13-298863-6

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

This page intentionally left blank

BRIEF CONTENTS

- 1 FUNDAMENTAL COMMUNICATIONS CONCEPTS 1
- 2 AMPLITUDE MODULATION 43
- 3 ANGLE MODULATION 64
- 4 COMMUNICATIONS CIRCUITS 95
- 5 TRANSMITTERS 131
- 6 RECEIVERS 156
- 7 DIGITAL COMMUNICATIONS TECHNIQUES 210
- 8 DIGITAL MODULATION AND DEMODULATION 255
- 9 TELEPHONE NETWORKS 305
- 10 WIRELESS COMMUNICATIONS SYSTEMS 337
- 11 COMPUTER COMMUNICATION AND THE INTERNET 384
- 12 TRANSMISSION LINES 416
- 13 WAVE PROPAGATION 465

14 ANTENNAS 497

15 WAVEGUIDES AND RADAR 536

16 FIBER OPTICS 562

APPENDIX A FCC General Radiotelephone Operator License (GROL) Requirements 599

ACRONYMS AND ABBREVIATIONS 602

GLOSSARY 610

INDEX 620

CONTENTS

1 FUNDAMENTAL COMMUNICATIONS CONCEPTS 1

- 1-1 Introduction 2
 - Communication Systems and Modulation 2
 - Characteristics of the Carrier* 3
 - The Electromagnetic Spectrum 5
 - Communications Systems 6
- 1-2 The Decibel in Communications Work 7
 - Logarithms 8
 - The Decibel as a Power Ratio 9
 - The Decibel as a Voltage or Current Ratio 10
 - Reference Levels 12
 - Approximating with Decibels 14
 - Stage Gains and Losses 16
- 1-3 Information and Bandwidth 17
 - Understanding Frequency Spectra 19
 - Time- and Frequency-Domain Representations 21
 - The Fast Fourier Transform 23
- 1-4 Noise 25
 - External Noise 26
 - Human-Made Noise* 26
 - Atmospheric Noise* 26
 - Space Noise* 26
 - Internal Noise 26
 - Thermal Noise* 27
 - Transistor Noise* 29
 - Frequency Noise Effects* 29
- 1-5 Noise Designation and Calculation 30
 - Signal-to-Noise Ratio 30
 - Noise Figure 30
 - Reactance Noise Effects 32
 - Noise Created by Amplifiers in Cascade 32
 - Equivalent Noise Temperature 34
 - Equivalent Noise Resistance 35
- 1-6 Troubleshooting 35
 - General Troubleshooting Techniques 36
 - Reasons Electronic Circuits Fail 37
 - Troubleshooting Plan 37

2 AMPLITUDE MODULATION 43

- 2-1 Overview of Amplitude Modulation 44
- 2-2 Double-Sideband AM 44
 - AM Waveforms 45
 - Modulation Index 46
 - Overmodulation 47
 - Amplitude Modulation and Mixing in the Frequency Domain 48
 - Amplitude Modulation in the Time Domain 52
 - Phasor Representation of AM 53
 - Power Distribution in Carrier and Sidebands 54
 - Importance of High-Percentage Modulation 54
 - Summary of Amplitude Modulation 57
- 2-3 Suppressed Carrier and Single-Sideband AM 58
 - Power Measurement 59
 - Advantages of SSB 59
 - Types of Sideband Transmission 60

3 ANGLE MODULATION 64

- 3-1 Introduction to Angle Modulation 65
- 3-2 Frequency Modulation in the Time Domain 66
 - A Simple FM Generator 66
 - The Concept of Deviation 66
 - Time-Domain Representation 68
 - The Two Major Concepts 68
 - Direct and Indirect FM* 69
- 3-3 FM in the Frequency Domain 70
 - Bandwidth Determination: Bessel Function Solutions 71
 - FM Spectrum Analysis 76
 - Power Distribution 78
 - Carson's Rule Approximation 79
 - Zero-Carrier Amplitude 80
 - Wideband and Narrowband FM 80
 - Percentage of Modulation and Deviation Ratio 81
- 3-4 Phase Modulation 83
- 3-5 Noise Suppression 87
 - FM Noise Analysis 88
 - Capture Effect 90
 - Preemphasis 91

4 COMMUNICATIONS CIRCUITS 95

- 4-1 Amplifiers 96
 - Classes of Amplification 96

- 4-2 Oscillators 100
 - LC* Oscillator 100
 - Hartley Oscillator 101
 - Colpitts Oscillator 102
 - Clapp Oscillator 103
 - Crystal Oscillator 103
- 4-3 Frequency-Selective Circuits 104
 - Reactance 105
 - Practical Inductors and Capacitors 106
 - Resonance 106
 - LC* Bandpass Filter 109
 - Parallel *LC* Circuits 111
 - Types of *LC* Filters 112
 - High-Frequency Effects 112
 - Crystal Filters 113
 - Ceramic Filters 114
 - Mechanical Filters 114
 - SAW Filters 116
- 4-4 Mixing and Multiplication Circuits 116
 - Balanced Modulator 118
 - LIC Balanced Modulator 119
 - Product Detector 120
- 4-5 The Phase-Locked Loop and Frequency Synthesis 120
 - Varactor Diodes 121
 - PLL Capture and Lock 121
 - Frequency Synthesis 122
 - Programmable Division 124
 - Two-Modulus Dividers 125
 - Direct Digital Synthesis 126

5 TRANSMITTERS 131

- 5-1 AM Transmitter Systems 132
 - Modulator Circuits 133
 - Neutralization 134
 - High- and Low-Level Modulation 135
 - Transistor High-Level Modulator 136
- 5-2 AM Transmitter Measurements 137
 - Trapezoid Patterns 137
 - Meter Measurement 138
 - Spectrum Analyzers 138
 - Harmonic Distortion Measurements 139
 - Special RF Signal Measurement Precautions 140
 - Measuring Transmitter Output Power 141

5-3	SSB Transmitters	141
	Filter Method	141
	Phase Method	143
5-4	FM Transmitters	144
	Direct FM Generation	145
	<i>Varactor Diodes</i>	145
	<i>Modulator Circuits</i>	145
	<i>Crosby Systems</i>	146
	Indirect FM Generation	148
	<i>Phase-Locked Loop FM Transmitter</i>	150
5-5	Stereo FM	151
	Modulating Signal	151
	Frequency-Domain Representation	151

6 RECEIVERS 156

6-1	Receiver Characteristics: Sensitivity and Selectivity	157
6-2	The Tuned Radio-Frequency Receiver	157
	TRF Selectivity	158
6-3	Superheterodyne Receivers	160
	Frequency Conversion	161
	Tuned-Circuit Adjustment	161
	Image Frequency	162
	Double Conversion	164
	Up-Conversion	166
	A Complete AM Receiver	167
	SSB Receivers	169
	FM Receivers	170
	<i>RF Amplifiers</i>	171
	<i>FET RF Amplifiers</i>	172
	<i>MOSFET RF Amplifiers</i>	172
	<i>Limiters</i>	173
	<i>Limiting and Sensitivity</i>	174
	Discrete Component FM Receiver	174
6-4	Direct Conversion Receivers	177
6-5	Demodulation and Detectors	178
	AM Diode Detector	178
	Detection of Suppressed-Carrier Signals	181
	Demodulation of FM and PM	184
	<i>Slope Detector</i>	184
	<i>Foster-Seeley Discriminator</i>	185
	<i>Ratio Detector</i>	187

- Quadrature Detector* 187
 - PLL FM Demodulator* 189
 - 6-6 Stereo Demodulation 189
 - SCA Decoder 190
 - 6-7 Receiver Noise, Sensitivity, and Dynamic Range Relationships 191
 - Noise and Receiver Sensitivity 191
 - SINAD* 192
 - Dynamic Range 194
 - Intermodulation Distortion Testing 196
 - 6-8 Automatic Gain Control and Squelch 197
 - Obtaining the AGC Level 197
 - Controlling the Gain of a Transistor 199
 - Delayed AGC 199
 - Auxiliary AGC 200
 - Variable Sensitivity 202
 - Variable Selectivity 202
 - Noise Limiter 202
 - Metering 203
 - Squelch 204

7 DIGITAL COMMUNICATIONS TECHNIQUES 210

- 7-1 Introduction to Digital Communications 211
- 7-2 Pulse Modulation and Multiplexing 212
 - Pulse-Amplitude Modulation 213
 - Pulse-Width Modulation 214
 - Class D Amplifier and PWM Generator* 215
 - Pulse-Position Modulation 216
 - Demodulation 217
- 7-3 Sample Rate and Nyquist Frequency 217
- 7-4 Pulse-Code Modulation 219
 - The Sample-and-Hold Circuit 220
 - Natural and Flat-Top Sampling 221
 - Quantization 222
 - Dynamic Range and Signal-to-Noise Calculations 226
 - Companding 227
 - Idle Channel Noise 227
 - Amplitude Companding 228
 - Coding and Analog-to-Digital Conversion 229
 - Digital-to-Analog Converters 232
- 7-5 Coding Principles 234
- 7-6 Code Error Detection and Correction 237
 - Parity 237

	Block Check Character	238
	Cyclic Redundancy Check	238
	CRC Code-Dividing Circuit	241
	Hamming Code	243
	Reed–Solomon Codes	244
7-7	Digital Signal Processing	244
	DSP Filtering	246

8 DIGITAL MODULATION AND DEMODULATION 255

8-1	Digital Modulation Techniques	256
	Amplitude-Shift Keying	257
	<i>Two-Tone Modulation</i>	258
	Frequency-Shift Keying	259
	<i>FSK Generation</i>	260
	Phase-Shift Keying	261
	Synchronization and Carrier	
	Reinsertion	263
	Differential Phase-Shift Keying	263
	Minimum Shift Keying	265
8-2	Bandwidth Considerations of Modulated	
	Signals	267
8-3	M-Ary Modulation Techniques	268
	M-Ary PSK	269
	Quadrature Amplitude Modulation	272
	Offset Modulation	273
8-4	Spectral Efficiency, Noise Performance,	
	and Filtering	274
	Spectral Efficiency	274
	Noise Performance	275
	Filtering	278
	<i>Raised-Cosine Filter</i>	279
8-5	The Complex Exponential and Analytic	
	Signals	281
	Complex Numbers	281
	Analytic Frequency	283
	DSP Modulation and Demodulation	285
8-6	Wideband Modulation	286
	Spread-Spectrum Techniques	287
	<i>Code Generation</i>	288
	<i>Frequency-Hopping Spread</i>	
	Spectrum	291
	<i>Direct-Sequence Spread Spectrum</i>	292

Orthogonal Frequency-Division Multiplexing (OFDM)	297
<i>HD Radio</i>	301
<i>HD Receivers</i>	302

9 TELEPHONE NETWORKS 305

9-1	Introduction	306
9-2	Basic Telephone Operation	306
	Telephone Systems	307
	Line Quality Considerations	309
	Attenuation Distortion	309
	Delay Distortion	310
	Telephone Traffic	311
	The Unit of Traffic	311
	Congestion	311
	Traffic Observation and Measurement	312
9-3	Digital Wired Networks	312
	Communication Links and Protocols	312
	<i>Protocols</i>	313
	Line Codes	314
	<i>NRZ Codes</i>	315
	<i>RZ Codes</i>	316
	<i>Biphase and Miller Codes</i>	317
	<i>Multilevel Binary Codes</i>	317
	<i>Synchronization and Bandwidth</i>	318
9-4	The T-Carrier System and Multiplexing	319
	Time-Division Multiplexing	319
	<i>T-Carrier Multiplexing</i>	320
	<i>The T1 Signal</i>	321
	<i>T1 Framing</i>	323
	<i>Loopbacks</i>	324
	<i>T1 Line Coding</i>	324
	<i>Bandwidth Considerations</i>	325
9-5	Packet-Switched Networks	327
	Frame Relay	327
	Asynchronous Transfer Mode	328
9-6	Signaling System 7	329
	Troubleshooting SS7 Networks	330
9-7	Troubleshooting	331
	The Digital Waveform	332
	Effects of Noise on the Pulse	332
	Effects of Impedance on the Pulse	333
	Effects of Frequency on the Pulse	333
	Eye Patterns	333

10 WIRELESS COMMUNICATIONS SYSTEMS 337

- 10-1 Wireless Computer Networks 338
 - Wireless Local-Area Networks 338
 - 802.11b* 338
 - 802.11a* 340
 - 802.11g* 341
 - 802.11n* 341
 - WiMAX 343
 - Bluetooth 344
 - ZigBee 345
 - Radio-Frequency Identification 346
 - Powering the Tag* 347
 - Frequency of Operation* 348
 - Communications (Air Interface) Protocol* 349
- 10-2 Cellular Phone Voice Systems 349
 - The Cellular Concept 350
 - Frequency Reuse 351
 - Cell Splitting 351
 - Rayleigh Fading 352
 - Cellular Frequency Bands 353
 - Global System for Mobile Communications 353
 - Vocoders* 355
 - Code-Division Multiple Access 357
 - Power Control* 361
 - Rake Receiver* 362
 - Troubleshooting and Interference Considerations 362
- 10-3 Mobile and Cellular Data Networks 367
 - Third-Generation Systems 367
 - Universal Mobile Telecommunications Service and Wideband CDMA* 368
 - Fourth-Generation Systems 368
 - Wireless Application Protocol 370
- 10-4 Wireless Security 371
- 10-5 Two-Way and Trunked Radio Systems 374
- 10-6 Software-Defined Radio 378

11 COMPUTER COMMUNICATION AND THE INTERNET 384

- 11-1 Alphanumeric Codes 385
 - The ASCII Code 385
 - The EBCDIC Code 386
 - The Baudot Code 386
 - The Gray Code 386

- 11-2 Computer Communication 389
 - Universal Serial Bus 389
 - IEEE 1394 390
 - RS-232 Standard 391
 - RS-232 Line Descriptions 392
 - RS-422, RS-485 395
- 11-3 Local-Area Networks 396
 - Ethernet LAN 399
- 11-4 Assembling a LAN 400
 - The Office LAN Example 401
 - Assembling a Building LAN 401
- 11-5 LAN Interconnection 402
 - Interconnecting LANs 403
- 11-6 Internet 404
 - Internet Protocol Addressing 405
- 11-7 IP Telephony 405
- 11-8 Interfacing the Networks 406
 - Modem Technologies 407
 - Cable Modems 407
 - Integrated Services Digital Network 407
 - xDSL Modems 408
- 11-9 Troubleshooting 411
 - Troubleshooting a LAN 411
 - Troubleshooting Unshielded Twisted-Pair Networks 412*
 - Some Cabling Tips 413*

12 TRANSMISSION LINES 416

- 12-1 Introduction 417
- 12-2 Types of Transmission Lines 417
 - Two-Wire Open Line 417
 - Twisted Pair 418
 - Unshielded Twisted Pair (UTP) 418
 - Shielded Pair 420
 - Coaxial Lines 420
 - Balanced/Unbalanced Lines 421
- 12-3 Electrical Characteristics of Transmission Lines 421
 - Two-Wire Transmission Line 421
 - Characteristic Impedance 422
 - Transmission Line Losses 425
- 12-4 Propagation of DC Voltage Down a Line 426
 - Physical Explanation of Propagation 426
 - Velocity of Propagation 426

- Delay Line 427
- Wavelength 428
- 12-5 Nonresonant Line 429
 - Traveling DC Waves 429
 - Traveling AC Waves 430
- 12-6 Resonant Transmission Line 431
 - DC Applied to an Open-Circuited Line 431
 - Incident and Reflected Waves 432
 - DC Applied to a Short-Circuited Line 433
 - Standing Waves: Open Line 434
 - Standing Waves: Shorted Line 435
 - Quarter-Wavelength Sections 437
- 12-7 Standing Wave Ratio 439
 - Effect of Mismatch 441
 - Quarter-Wavelength Transformer 443
 - Electrical Length 443
- 12-8 The Smith Chart 444
 - Transmission Line Impedance 444
 - Smith Chart Introduction 445
 - Using the Smith Chart 446
 - Corrections for Transmission Loss 449
 - Matching Using the Smith Chart 449
 - Stub Tuners 450
- 12-9 Transmission Line Applications 453
 - Discrete Circuit Simulation 453
 - Baluns 454
 - Transmission Lines as Filters 454
 - Slotted Lines 455
 - Time-Domain Reflectometry 455
- 12-10 Impedance Matching and Network Analysis 456
 - Vector Network Analysis and S Parameters 458

13 WAVE PROPAGATION 465

- 13-1 Electrical to Electromagnetic Conversion 466
- 13-2 Electromagnetic Waves 466
 - Wavefronts 468
 - Characteristic Impedance of Free Space 469
- 13-3 Waves Not in Free Space 469
 - Reflection 469
 - Refraction 470
 - Diffraction 471
- 13-4 Ground- and Space-Wave Propagation 471
 - Ground-Wave Propagation 471
 - Space-Wave Propagation 472

- 13-5 Sky-Wave Propagation 473
 - Ionospheric Layers 474
 - Effects of the Ionosphere on the Sky Wave 475
 - Critical Frequency* 475
 - Critical Angle* 475
 - Maximum Usable Frequency* 476
 - Skip Zone* 476
 - Fading* 477
 - Tropospheric Scatter 478
- 13-6 Satellite Communications 479
 - Orbital Patterns 481
 - Azimuth and Elevation Calculations 482
 - Global Positioning System 483
 - Multiplexing Techniques 484
 - Earth Station Distance to and from the Satellites 485
 - VSAT and MSAT Systems 487
 - Satellite Radio 487
- 13-7 Figure of Merit and Satellite Link Budget
 - Analysis 488
 - Figure of Merit 489
 - Satellite Link Budget Calculation 490

14 ANTENNAS 497

- 14-1 Basic Antenna Theory 498
- 14-2 Half-Wave Dipole Antenna 499
 - Development of the Half-Wave Dipole Antenna 499
 - Half-Wave Dipole Antenna Impedance 499
 - Radiation and Induction Field 500
 - Resonance 502
 - Radiation Patterns 502
 - Antenna Gain 503
 - Effective Radiated Power* 504
 - Received Power* 504
 - Polar Plots 505
- 14-3 Radiation Resistance 507
 - Effects of Antenna Length 507
 - Ground Effects 508
 - Electrical versus Physical Length 509
 - Effects of Nonideal Length 509
- 14-4 Antenna Feed Lines 510
 - Resonant Feed Line 510
 - Nonresonant Feed Line 511
 - Delta Match 511
 - Quarter-Wave Matching 512

- 14-5 Monopole Antenna 512
 - Effects of Ground Reflection 512
 - The Counterpoise 513
 - Radiation Pattern 513
 - Loaded Antennas 513
- 14-6 Antenna Arrays 514
 - Half-Wave Dipole Antenna with Parasitic Element 514
 - Yagi–Uda Antenna 515
 - Driven Collinear Array 516
 - Broadside Array 516
 - Vertical Array 517
- 14-7 Special-Purpose Antennas 517
 - Log-Periodic Antenna 517
 - Small-Loop Antenna 518
 - Ferrite Loop Antenna 519
 - Folded Dipole Antenna 519
 - Slot Antenna 520
- 14-8 Microwave Antennas 520
 - Horn Antenna 521
 - The Parabolic Reflector Antenna 522
 - Lens Antenna 525
 - Patch Antenna 526
- 14-9 Microwave System Link Budget and Path-Loss Calculations 527

15 WAVEGUIDES AND RADAR 536

- 15-1 Comparison of Transmission Systems 537
- 15-2 Types of Waveguides 538
 - Waveguide Operation 538
 - Dominant Mode of Operation 540
- 15-3 Physical Picture of Waveguide Propagation 541
- 15-4 Other Types of Waveguides 542
 - Circular 542
 - Ridged 543
 - Flexible 543
- 15-5 Other Waveguide Considerations 544
 - Waveguide Attenuation 544
 - Bends and Twists 544
 - Tees 545
 - Tuners 546
- 15-6 Termination and Attenuation 546
 - Variable Attenuators 547
- 15-7 Directional Coupler 547

- 15-8 Coupling Waveguide Energy and Cavity Resonators 548
 - Cavity Resonators 549
 - Cavity Tuning 550
- 15-9 Radar 550
 - Radar Waveform and Range Determination 551
 - Radar System Parameters 551
 - Basic Radar Block Diagram 553
 - Doppler Effect 554
- 15-10 Microintegrated Circuit Waveguiding 554
 - Microstrip Circuit Equivalents 555
 - Dielectric Waveguide 555
- 15-11 Troubleshooting 556
 - Some Common Problems 556
 - Test Equipment 557

16 FIBER OPTICS 562

- 16-1 Introduction 563
- 16-2 The Nature of Light 564
 - Construction of the Fiber Strand 566
- 16-3 Optical Fibers 568
 - Multimode Step-Index Fiber 568
 - Multimode Graded-Index Fiber 569
 - Single-Mode Fibers 569
 - Fiber Classification 570
 - Plastic Optical Fiber 571
- 16-4 Fiber Attenuation and Dispersion 572
 - Attenuation 572
 - Dispersion 573
 - Dispersion Compensation 575
- 16-5 Optical Components 576
 - Modulating the Light Source 577
 - Intermediate Components 578
 - Isolators* 578
 - Attenuators* 578
 - Branching Devices* 579
 - Splitters* 579
 - Couplers* 579
 - Wavelength Division Multiplexers* 579
 - Optical-Line Amplifiers* 579
 - Detectors 579
- 16-6 Fiber Connections and Splices 581
 - Fiber Connectorization 582
- 16-7 System Design and Operational Issues 583

16-8	Cabling and Construction	587	
	Exterior (Outdoor) Installations	587	
	Interior (Indoor) Installations	587	
	Testing the Fiber Installation	587	
16-9	Optical Networking	589	
	Defining Optical Networking	589	
	Air Fiber	592	
	Fiber Distributed Data Interface	592	
16-10	Safety	592	
16-11	Troubleshooting	593	
	System Testing	594	
	General Guidelines	594	
	Losses in an Optical-Fiber System	594	
	Calculating Power Requirements	595	
	Connector and Cable Problems	595	
	Characteristics of Light-Emitting Diodes and Diode Lasers	595	
	A Simple Test Tool	595	
APPENDIX A		FCC General Radiotelephone Operator License (GROL) Requirements	599
ACRONYMS AND ABBREVIATIONS			602
GLOSSARY		610	
INDEX		620	

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

Jemma Blake-Judd, all of Mt. San Antonio College, also provided invaluable assistance by reviewing portions of the manuscript, for which I am also deeply grateful. Of course, any errors are mine alone. Finally, no acknowledgment section is complete unless I recognize my mentor, Mr. Clarence E. “Pete” Davis, who, over the years, really taught me what I know about radio and who helped me get to where I am today. Thank you.

JONATHAN D. HYMER
Mt. San Antonio College
Walnut, California

CHAPTER 1

FUNDAMENTAL COMMUNICATIONS CONCEPTS

CHAPTER OUTLINE

- 1-1 Introduction
- 1-2 The Decibel in Communications Work
- 1-3 Information and Bandwidth
- 1-4 Noise
- 1-5 Noise Designation and Calculation
- 1-6 Troubleshooting

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

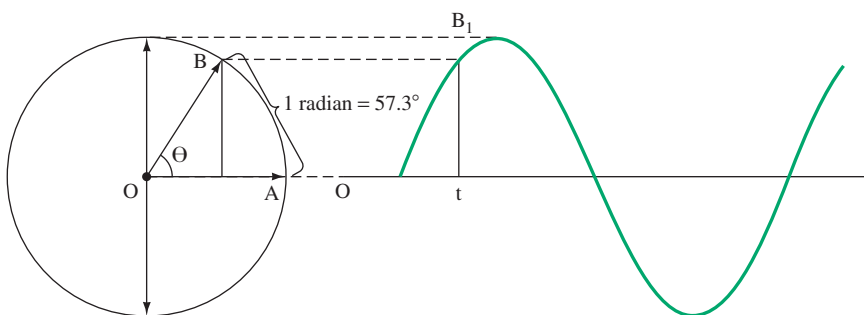


FIGURE 1-1 Sine wave represented as a rotating phasor.

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:

$$v = V_p \sin(\omega t + \Phi), \quad (1-1)$$

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.

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.

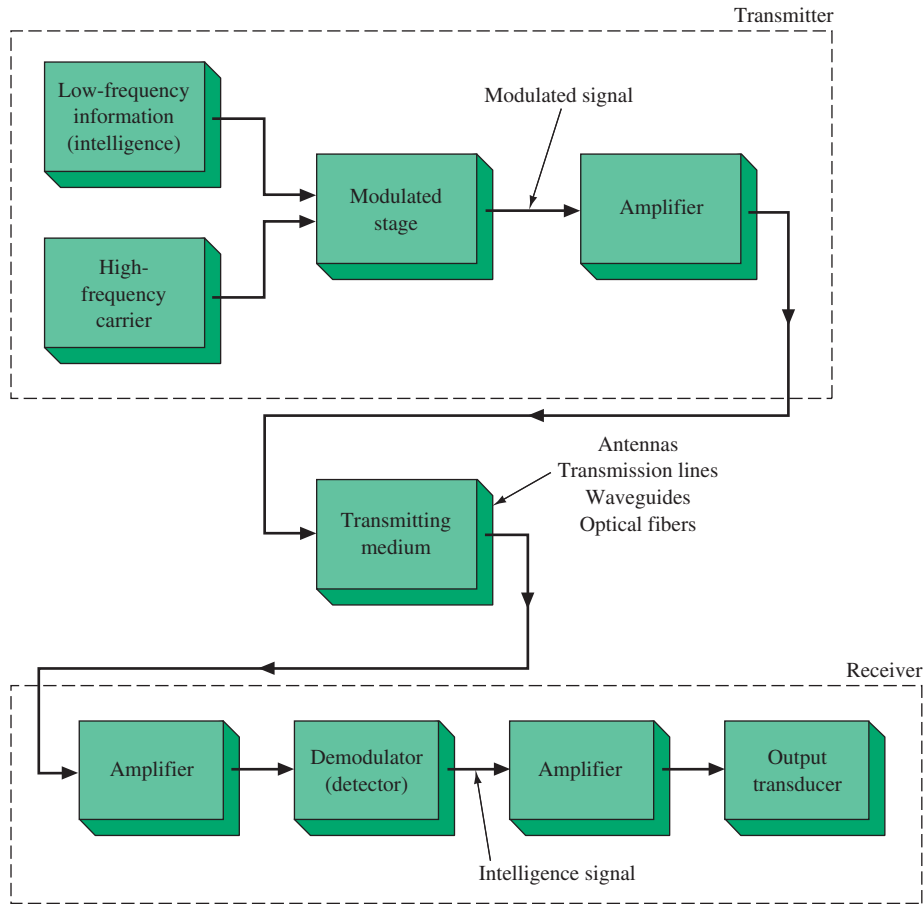


FIGURE 1-2 Communication system block diagram.

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), $\text{antilog } 2 = 10^2$, 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:

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

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

^{*} 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.