

Contents

	<i>Preface</i>	<i>page</i> xix
	<i>Acknowledgements</i>	xxiii
	<i>Notation</i>	xxv
	<i>Primary Symbols</i>	xxvii
	<i>List of Symbols</i>	xxviii
1	Introduction	1
	1.1 Digital Lightwave Communication Systems	2
	1.1.1 Channel Coding	2
	1.1.2 Modulation	3
	1.1.3 Types of Lightwave Channels	3
	1.1.4 Demodulation	4
	1.1.5 Detection and Decoding	5
	1.1.6 Error Probabilities	5
	1.2 Lightwave Signal Models	6
	1.2.1 Relationship of Wave Optics to Photon Optics	8
	1.2.2 Choosing a Signal Model	10
	1.3 Modulation and Demodulation	11
	1.3.1 Phase-Synchronous Systems	12
	1.3.2 Phase-Asynchronous Systems	14
	1.4 Codes and Coded-Modulation	15
	1.5 Multiplexing	15
	1.6 Communication Channels	17
	1.6.1 Common Wave-Optics Communication Channels	18
	1.6.2 Channel Capacity	20
	1.7 References	22
	1.8 Historical Notes	23
	1.9 Problems	24
2	Background	27
	2.1 Linear Systems	27
	2.1.1 Bandwidth and Timewidth	34
	2.1.2 Passband and Complex-Baseband Signals	39
	2.1.3 Signal Space	41
	2.2 Random Signals	52
	2.2.1 Probability Distribution Functions	53
	2.2.2 Random Processes	67

2.3	Electromagnetics	79
2.3.1	Material Properties	80
2.3.2	The Wave Equation	83
2.3.3	Geometrical Optics	91
2.3.4	Polarization	93
2.3.5	Random Lightwave Fields	97
2.4	References	99
2.5	Problems	99
3	The Guided Lightwave Channel	110
3.1	Characteristics of an Optical Fiber	110
3.1.1	Fiber Structure	110
3.1.2	Optical Fiber Attenuation	112
3.2	Guided Signal Propagation	115
3.2.1	Guided Rays	115
3.2.2	Guided Waves	121
3.2.3	Guided Photon Streams	122
3.3	Waveguide Geometries	123
3.3.1	Modes in a Slab Waveguide	125
3.3.2	Modes in a Step-Index Fiber	132
3.3.3	Modes in a Graded-Index Fiber	144
3.4	Mode Coupling	146
3.4.1	Derivation of the Coupled Equations	147
3.4.2	Solution of the Coupled Equations	149
3.5	References	149
3.6	Historical Notes	149
3.7	Problems	150
4	The Linear Lightwave Channel	155
4.1	Ray Dispersion	156
4.2	Wave Dispersion	157
4.2.1	Dispersion in a Slab Waveguide	157
4.2.2	Dispersion for a Linearly Polarized Mode	159
4.3	Narrowband-Signal Dispersion	159
4.3.1	Narrowband Dispersion	161
4.3.2	Material Dispersion	163
4.3.3	Narrowband Signal Propagation	166
4.4	Group Delay	167
4.4.1	Mode-Groups in a Step-Index Fiber	168
4.4.2	Mode-Groups in a Graded-Index Fiber	169
4.4.3	Step-Index Multimode Fiber	171
4.4.4	Wavelength-Dependent Group Delay	173
4.5	Linear Distortion	175
4.5.1	Distortion from Mode-Dependent Group Delay	175

	4.5.2	Distortion from Wavelength-Dependent Group Delay	179
	4.5.3	Dispersion-Controlled Optical Fiber	180
	4.5.4	Independent Sources of Distortion	181
4.6		Polarization-Mode Dispersion	182
	4.6.1	Jones Representation	183
	4.6.2	Stokes Representation	186
	4.6.3	Distortion from Polarization-Dependent Group Delay	187
	4.6.4	Distortion from Polarization-Dependent Loss	189
4.7		References	190
4.8		Historical Notes	191
4.9		Problems	191
5		The Nonlinear Lightwave Channel	201
	5.1	Anharmonic Material Response	202
	5.1.1	Wave-Optics Description	202
	5.1.2	Photon-Optics Description	203
5.2		Kinds of Nonlinearities	204
	5.2.1	The Kerr Nonlinearity	204
	5.2.2	Raman Scattering	205
	5.2.3	Brillouin Scattering	206
5.3		Signal Propagation in a Nonlinear Fiber	208
	5.3.1	Phase Matching	208
	5.3.2	Intensity-Dependent Index Change	209
	5.3.3	Nonlinear Propagation Constant	210
	5.3.4	Characteristic Lengths	213
	5.3.5	Classification of Nonlinear Channels	215
5.4		Single-Carrier Nonlinear Schrödinger Equation	216
	5.4.1	Nonlinear Narrowband Signal Propagation	217
	5.4.2	Nonlinear Distortion for a Single Pulse	219
5.5		Interference in a Nonlinear Fiber	223
	5.5.1	Cross-Phase Modulation	224
	5.5.2	Nonlinear Schrödinger Equation for Multiple Subcarriers	224
	5.5.3	Nonlinear Interference	226
5.6		Computational Methods	229
5.7		References	231
5.8		Historical Notes	231
5.9		Problems	231
6		Random Signals	237
	6.1	The Physics of Randomness and Noise	238
	6.1.1	Randomness and Entropy	239
	6.1.2	Photon–Matter Interactions	244
	6.1.3	Expected Energy	247
6.2		Probability Distribution Functions	250

6.2.1	Thermal Noise	250
6.2.2	Spontaneous Emission Noise	256
6.2.3	Photon Noise	257
6.3	The Poisson Transform	262
6.3.1	The Direct Poisson Transform	262
6.3.2	The Inverse Poisson Transform	262
6.3.3	Forms of Uncertainty	264
6.3.4	The Gordon Distribution	265
6.4	Power Density Spectra	267
6.4.1	Power Density Spectrum of the Lightwave Noise Power	267
6.4.2	Power Density Spectrum of the Photodetected Signal with Additive Noise	268
6.4.3	Power Density Spectrum of the Photodetected Signal with Shot Noise	269
6.5	Direct Photodetection with Gaussian Noise	271
6.5.1	Continuous Probability Density Functions	272
6.5.2	Discrete Probability Mass Functions	275
6.6	Balanced Photodetection with Gaussian Noise	277
6.6.1	Orthogonal Expansion	277
6.6.2	Special Cases	279
6.6.3	Direct Photodetection	281
6.6.4	Spatially Correlated Modes	284
6.7	Bandlimited Shot Noise	285
6.7.1	Approximate Analysis	286
6.7.2	General Analysis	287
6.8	References	291
6.9	Historical Notes	291
6.10	Problems	292
7	Lightwave Components	298
7.1	Passive Lightwave Components	298
7.1.1	Lightwave Couplers	298
7.1.2	Delay-Line Interferometers	301
7.1.3	Multipath Interference	302
7.1.4	Optical Filters	302
7.2	Semiconductors	302
7.3	Lightwave Receivers	304
7.3.1	Photodetectors	304
7.3.2	Lightwave Demodulators	307
7.4	Lightwave Amplifiers	312
7.4.1	Doped-Fiber Lightwave Amplifiers	313
7.4.2	Gain in a Doped-Fiber Amplifier	315
7.4.3	Semiconductor Lightwave Amplifiers	318
7.4.4	Wavelength Dependence of the Gain	320

	7.4.5	Noise from Multiple Amplifiers	321
7.5		Lightwave Transmitters	323
	7.5.1	Light-Emitting Diodes	323
	7.5.2	Laser Diodes	326
	7.5.3	External Modulators	329
7.6		Noise in Lightwave Receivers	331
	7.6.1	Dark-Current Noise	331
	7.6.2	Internal-Gain Noise	331
7.7		Noise in Lightwave Amplifiers	334
	7.7.1	Power Density Spectrum	334
	7.7.2	Probability Distribution Functions	336
	7.7.3	Noise Figure	338
	7.7.4	Nonlinear Phase Noise	339
7.8		Noise in Laser Transmitters	342
	7.8.1	Power Density Spectra	342
	7.8.2	Probability Density Functions	347
7.9		References	349
7.10		Historical Notes	350
7.11		Problems	350
8		The Electrical Channel	361
	8.1	The Lightwave Channel	363
		8.1.1 Linear Single-Input Single-Output Lightwave Channels	363
		8.1.2 Multiplex Channels	368
		8.1.3 Multi-input Multi-output Channels	372
		8.1.4 Channel Statistics in Time and Space	374
	8.2	Lightwave Demodulation	377
		8.2.1 Demodulation of the Lightwave Complex Amplitude	378
		8.2.2 Demodulation of the Lightwave Intensity	387
		8.2.3 Demodulation of Pulse Intensity in Multiple Modes	391
		8.2.4 Demodulation of Pulse Intensity in a Single Mode	392
		8.2.5 Cumulative Electrical Power Density Spectrum	395
	8.3	Discrete-Time Electrical Channels	397
		8.3.1 Interpolation and Sampling	399
		8.3.2 Conventional Discrete-Time Channels	400
	8.4	References	402
	8.5	Historical References	403
	8.6	Problems	403
9		The Information Channel	410
	9.1	Prior and Posterior Distributions	412
	9.2	Methods of Modulation	413
		9.2.1 Signal Constellations	414
		9.2.2 Nyquist Pulses	416

	9.2.3	Detection	417
	9.2.4	Partial-Response Signaling	418
	9.2.5	Sampler Response	419
9.3		Methods of Reception	422
9.4		Detection Filters	423
	9.4.1	Linear Detection Filters	424
	9.4.2	Detection Filters for Additive White Noise	425
	9.4.3	Detection Filters for Signal-Dependent Noise	427
	9.4.4	Detection Filters for General Noise	429
9.5		Detection of a Binary Signal	430
	9.5.1	Detection of a Binary Wave-Optics Signal	430
	9.5.2	Detection of a Binary Photon-Optics Signal	439
	9.5.3	Binary Detection for a Dispersive Channel	444
	9.5.4	Displacement Detection of a Binary Signal	445
9.6		Detection of a Multilevel Signal	447
	9.6.1	Detection of a Multilevel Wave-Optics Signal	447
	9.6.2	Detection of a Multilevel Photon-Optics Signal	451
9.7		Noise Models for Intensity Detection	453
	9.7.1	Additive Electrical-Noise Model	454
	9.7.2	Signal-Dependent Shot-Noise Model	454
	9.7.3	Signal-Noise Mixing Model	454
9.8		References	455
9.9		Historical Notes	455
9.10		Problems	455
10		Modulation and Demodulation	463
	10.1	Modulation Formats	464
		10.1.1 Complex Signal Constellations	464
		10.1.2 Complex-Baseband Modulation	465
		10.1.3 Binary Modulation Formats	466
		10.1.4 Multisymbol Modulation Formats	471
		10.1.5 Efficiency of Modulation Formats	474
	10.2	Phase-Synchronous Demodulation	476
		10.2.1 Demodulation of Binary Formats	476
		10.2.2 Demodulation of Multilevel Real-Valued Formats	476
		10.2.3 Detection of Multilevel Complex-Valued Formats	477
		10.2.4 Demodulation with Phase Noise	484
		10.2.5 Demodulation with Shot Noise	486
	10.3	Dual-Polarization Signaling	491
		10.3.1 Constellations in Four-Dimensional Signal Space	491
		10.3.2 Dual-Polarization Modulation and Demodulation	493
	10.4	Constellations in Signal Space	496
		10.4.1 General Signal Constellations	497
		10.4.2 Constellations on the Complex Plane	497

		10.4.3 Orthogonal Constellations	498
		10.4.4 Nonorthogonal Constellations	499
	10.5	Noncoherent Demodulation	500
		10.5.1 Detection of Noncoherent Orthogonal Signals	501
		10.5.2 Detection of Differential-Phase-Shift-Keyed Signals	503
		10.5.3 Detection of Noncoherent On–Off-Keyed Intensity Signals	504
	10.6	Energy Demodulation	509
		10.6.1 Sample Statistic	510
	10.7	References	512
	10.8	Historical Notes	513
	10.9	Problems	513
11	Interference		522
	11.1	Intersymbol Interference	523
	11.2	Equalization	527
		11.2.1 Zero-Forcing Equalization	528
		11.2.2 Matched Filter Equalization	528
		11.2.3 Minimum-Error Linear Equalizer	529
		11.2.4 Detection Filters for Additive White Noise	530
		11.2.5 Decision Feedback	533
		11.2.6 Prefiltering and Precoding	533
	11.3	Sequence Detection	535
		11.3.1 Trellis Diagrams	537
		11.3.2 Minimum-Distance Sequence Detection	538
		11.3.3 Maximum-Likelihood Sequence Detection	542
		11.3.4 Maximum-Posterior Sequence Detection	544
	11.4	Interchannel Interference	551
		11.4.1 Uncompensated Linear Interchannel Interference	551
		11.4.2 Uncompensated Nonlinear Interchannel Interference	553
		11.4.3 Linear Equalization of Polarization Interference	553
		11.4.4 Linear Equalization of Interchannel Interference	555
	11.5	Equalization of Intensity Modulation	556
		11.5.1 Intensity Interference	556
		11.5.2 Intensity Equalization with Shot Noise	558
	11.6	Interference in Nonlinear Channels	559
		11.6.1 Sequence Detection for a Nonlinear Channel	560
		11.6.2 Equalization of a Nonlinear Channel	563
	11.7	References	565
	11.8	Historical Notes	565
	11.9	Problems	566
12	Channel Estimation		572
	12.1	Channel Parameters	572
	12.2	Carrier-Phase Estimation	574

12.2.1	Maximum-Likelihood Phase Estimation	574
12.2.2	Phase-Locked Loops	576
12.2.3	Phase Estimation of a Data-Modulated Waveform	581
12.2.4	Generalized Likelihood Function	583
12.3	Clock-Phase Estimation	586
12.4	Frame Synchronization	588
12.5	Channel-State Estimation	590
12.5.1	Impulse Response Estimation	591
12.5.2	Detection-Filter Estimation	595
12.5.3	Constant-Modulus Objective Function	598
12.5.4	Adaptive Estimation	599
12.6	Polarization-State Estimation	600
12.7	Estimation of Spatial Modes	601
12.7.1	Channel Matrix Estimation for Multiple Spatial Modes	602
12.7.2	Modal Detection-Filter Estimation	603
12.8	References	603
12.9	Historical Notes	604
12.10	Problems	604
13	Channel Codes	608
13.1	Code Structure and Code Rate	609
13.1.1	Decoding	610
13.1.2	Classes of Codes	611
13.1.3	Nesting of Codes	611
13.2	Algebraic Block Codes	612
13.2.1	Galois Fields	612
13.2.2	Linear Codes	613
13.2.3	Matrix Description of Linear Codes	613
13.2.4	Binary Block Codes	617
13.2.5	Nonbinary Block Codes	618
13.2.6	Spherical Decoding	621
13.2.7	Performance Analysis	623
13.2.8	Descriptions of Linear Codes as Graphs	625
13.2.9	Limits of Spherical Decoding	627
13.3	Convolutional Codes	628
13.3.1	Convolutional Encoders	629
13.3.2	Decoding on a Trellis	632
13.3.3	Sequential Decoding	633
13.3.4	Performance Analysis	634
13.4	Cutoff Rate and Critical Rate	635
13.5	Composite Codes	639
13.5.1	Componentwise Marginalization	640
13.5.2	Berrou Codes	642
13.5.3	Turbo Decoding	643

13.5.4	Gallager Codes	646
13.5.5	Message-Passing Decoders	648
13.6	Trellis-Coded Modulation	655
13.7	Modulation Codes	659
13.7.1	Runlength-Limited Codes	660
13.7.2	Spectral-Notch Codes	663
13.7.3	Partial-Response Codes	663
13.8	References	664
13.9	Historical Notes	664
13.10	Problems	665
14	The Information Capacity of a Lightwave Channel	669
14.1	Entropy, Mutual Information, and Channel Capacity	671
14.1.1	Types of Information Channels	672
14.1.2	Entropy	673
14.1.3	Mutual Information	674
14.1.4	Fano Inequality	675
14.1.5	Channel Capacity	676
14.1.6	Signal and Channel Models	679
14.2	Photon-Optics Capacity	680
14.2.1	The Discrete Memoryless Photon-Optics Channel	682
14.2.2	The Continuous Photon-Optics Channel	685
14.2.3	The Ideal Photon-Optics Channel	685
14.2.4	The Additive-Noise-Limited Photon-Optics Channel	688
14.3	Wave-Optics Capacity	696
14.3.1	Capacities and Priors for Waves and Photons	697
14.3.2	Soft-Decision Capacity and Hard-Decision Capacity Using Wave Optics	698
14.3.3	Intensity Modulation	701
14.3.4	Phase Modulation	703
14.4	Capacity of a Product Channel	706
14.4.1	Capacity of a Gaussian MIMO Channel	707
14.4.2	Capacity of a Random MIMO Channel	709
14.4.3	Capacity of a Bandlimited Wave-Optics Channel	710
14.4.4	Capacity of a Bandlimited Photon-Optics Channel	713
14.5	Spectral Rate Efficiency	718
14.5.1	Wave-Optics Spectral Rate Efficiency	718
14.5.2	Photon-Optics Spectral Rate Efficiency	719
14.5.3	Spectral Rate Efficiency for Constrained Modulation Formats	720
14.6	Nonlinear Lightwave Channels	722
14.6.1	The Full Kerr Lightwave Channel	723
14.6.2	The Memoryless Kerr Information Channel	724
14.6.3	Dispersionless Channel	724
14.6.4	Kerr Wavelength-Multiplex Information Channel	726

	14.6.5	Kerr Wavelength MIMO Channel	728
	14.6.6	The Capacity Using the Envelope Method	729
14.7		References	729
14.8		Historical Notes	730
14.9		Problems	731
15		The Quantum-Optics Model	736
	15.1	An Operational View of Quantum Optics	736
	15.1.1	Lightwave Signal States	737
	15.1.2	Modulation	741
	15.1.3	Measurements	742
	15.1.4	State Detection	747
	15.1.5	Gaussian Signal States	748
	15.2	A Formal View of Quantum Optics	750
	15.2.1	Signal States	750
	15.2.2	Operators	751
	15.2.3	Time Dependence	752
	15.2.4	Quantum Wave Functions	752
	15.2.5	Measurements	754
	15.3	Coherent States	761
	15.3.1	Operators for Coherent States	761
	15.3.2	Canonical Commutation Relationship	763
	15.3.3	Position–Momentum Representation	765
	15.3.4	Minimum-Uncertainty Coherent States	766
	15.3.5	The Coherent-State Operator	768
	15.3.6	Representation of a Coherent State	772
	15.3.7	The Pairwise Nonorthogonality of Coherent States	774
	15.3.8	Antipodal Coherent States	775
	15.4	Statistical Quantum Optics	776
	15.4.1	Derivation of the Density Matrix	777
	15.4.2	Representation of a Density Matrix	781
	15.4.3	Decoherence	783
	15.4.4	Quantum Entropy	784
	15.4.5	Measurements on Density Matrices	786
	15.5	Classical Methods for Quantum-Lightwave Signals	789
	15.5.1	Lightwave Couplers for Coherent States	789
	15.5.2	Homodyne Demodulation to Real Baseband	790
	15.5.3	Joint Demodulation	792
	15.6	Quantum-Lightwave Signal Distributions	797
	15.6.1	The P Quasi-probability Distribution	797
	15.6.2	The Wigner Quasi-probability Distribution	799
	15.6.3	The Husimi Quasi-probability Distribution	801
	15.6.4	Representations of Classical Signals	802
	15.6.5	Gaussian Signal States	806

	15.7	References	807
	15.8	Historical Notes	808
	15.9	Problems	808
16	The Quantum-Lightwave Channel		815
	16.1	Methods of Quantum-Optics State Detection	816
	16.1.1	Classical Channels and Detection	817
	16.1.2	Quantum-Lightwave Channels and State Detection	818
	16.1.3	Detection Operators	820
	16.1.4	Detection for Pure Symbol States	823
	16.2	State Detection for Binary Modulation Formats	827
	16.2.1	Detection for Binary Mixed-Signal-State Modulation	827
	16.2.2	Detection for Binary Pure-State Modulation	829
	16.2.3	Detection for Antipodal Coherent-State Modulation	831
	16.2.4	Detection for On–Off-Keyed Coherent-State Modulation	834
	16.2.5	Other Methods of State Detection	835
	16.2.6	Binary State Detection in Additive Noise	837
	16.3	State Detection for Multilevel Modulation Formats	839
	16.3.1	Square-Root Detection Basis	840
	16.4	Quantum-Lightwave Information Channels	843
	16.4.1	Signal-Dependent Information Channels	843
	16.4.2	Component-Symbol State Preparation and Detection	844
	16.4.3	Block-Symbol-State Preparation and Detection	846
	16.5	Classical Channel Capacity of a Quantum-Lightwave Channel	853
	16.5.1	An Ideal Classical Channel	854
	16.5.2	Holevo Information	856
	16.5.3	A Noiseless Product-State Channel	858
	16.5.4	A Noisy Product-State Channel	860
	16.5.5	The General Quantum-Lightwave Channel	861
	16.6	The Ideal Quantum-Lightwave Channel	862
	16.6.1	Capacity for Conventional Binary Modulation Formats	863
	16.6.2	Capacity using Component-Symbol-State Detection	867
	16.6.3	Capacity Using Block-Symbol-State Detection	869
	16.7	The Gaussian Quantum-Lightwave Information Channel	871
	16.7.1	Gaussian Channels	871
	16.7.2	Phase-Insensitive Gaussian Channels	871
	16.7.3	Capacity for a Phase-Insensitive Gaussian Channel	875
	16.8	References	878
	16.9	Historical Notes	879
	16.10	Problems	879
		<i>Bibliography</i>	883
		<i>Index</i>	902