
Contents

Preface.....	xv
Authors.....	xix
List of Figures.....	xxiii
List of Tables.....	xxxvii
Abbreviations.....	xxxix
Chapter 1 Introduction: Optical Wireless Communication Systems.....	1
1.1 Wireless Access Schemes.....	1
1.2 A Brief History of OWC.....	7
1.3 OWC/Radio Comparison.....	8
1.4 Link Configuration.....	11
1.5 OWC Application Areas.....	19
1.6 Safety and Regulations.....	21
1.6.1 Maximum Permissible Exposures.....	25
1.7 OWC Challenges.....	25
References.....	30
Chapter 2 Optical Sources and Detectors.....	35
2.1 Light Sources.....	35
2.2 Light-Emitting Diode.....	38
2.2.1 LED Structure.....	41
2.2.2 Planar and Dome LED.....	42
2.2.3 Edge-Emitting LED.....	43
2.2.4 LED Efficiencies.....	44
2.2.4.1 Internal Quantum Efficiency.....	44
2.2.4.2 External Quantum Efficiency.....	45
2.2.4.3 Power Efficiency.....	45
2.2.4.4 Luminous Efficiency.....	46
2.2.4.5 LED Modulation Bandwidth.....	47
2.3 The Laser.....	48
2.3.1 Operating Principle of a Laser.....	48
2.3.2 Stimulated Emission.....	49
2.3.2.1 Population Inversion.....	50
2.3.3 Optical Feedback and Laser Oscillation.....	50
2.3.4 Basic Semiconductor Laser Structure.....	51
2.3.5 The Structure of Common Laser Types.....	53
2.3.5.1 Fabry–Perot Laser.....	53
2.3.5.2 Distributed Feedback Laser.....	54

	2.3.5.3	Vertical-Cavity Surface-Emitting Laser.....	55
	2.3.5.4	Superluminescent Diodes	56
	2.3.6	Comparison of LED and Laser Diodes	57
2.4		Photodetectors	57
	2.4.1	PIN Photodetector	59
	2.4.2	APD Photodetector.....	61
2.5		Photodetection Techniques.....	62
	2.5.1	Direct Detection	63
	2.5.2	Coherent Detection.....	63
		2.5.2.1 Heterodyne Detection	64
		2.5.2.2 Homodyne Detection	66
2.6		Photodetection Noise	66
	2.6.1	Photon Fluctuation Noise	67
	2.6.2	Dark Current and Excess Noise	68
	2.6.3	Background Radiation.....	70
	2.6.4	Thermal Noise.....	70
	2.6.5	Intensity Noise.....	71
	2.6.6	Signal-to-Noise Ratio	72
2.7		Optical Detection Statistics	72
		References	74
Chapter 3		Channel Modelling.....	77
	3.1	Indoor Optical Wireless Communication Channel	77
		3.1.1 LOS Propagation Model.....	81
		3.1.2 Non-LOS Propagation Model.....	84
		3.1.3 Ceiling Bounce Model	95
		3.1.4 Hayasaka–Ito Model	96
		3.1.5 Spherical Model	97
	3.2	Artificial Light Interference	99
		3.2.1 Incandescent Lamp	100
		3.2.2 Fluorescent Lamp Driven by Conventional Ballast	101
		3.2.3 Fluorescent Lamp Model	102
	3.3	Outdoor Channel	107
		3.3.1 Atmospheric Channel Loss	107
		3.3.2 Fog and Visibility	111
		3.3.3 Beam Divergence	120
		3.3.4 Optical and Window Loss.....	125
		3.3.5 Pointing Loss.....	125
		3.3.6 The Atmospheric Turbulence Models	126
		3.3.6.1 Log-Normal Turbulence Model.....	131
		3.3.6.2 Spatial Coherence in Weak Turbulence	135
		3.3.6.3 Limit of Log-Normal Turbulence Model....	137
		3.3.6.4 The Gamma–Gamma Turbulence Model ...	138
		3.3.6.5 The Negative Exponential Turbulence Model.....	142

3.3.7	Atmospheric Effects on OWC Test Bed	143
3.3.7.1	Demonstration of Scintillation Effect on Data Carrying Optical Radiation.....	146
	References	154
Chapter 4	Modulation Techniques	161
4.1	Introduction	161
4.2	Analogue Intensity Modulation.....	164
4.3	Digital Baseband Modulation Techniques.....	167
4.3.1	Baseband Modulations	167
4.3.2	On–Off Keying	168
4.3.3	Error Performance on Gaussian Channels	172
4.4	Pulse Position Modulation.....	178
4.4.1	Error Performance on Gaussian Channels	182
4.4.2	PPM Variants	186
4.4.2.1	Multilevel PPM.....	187
4.4.2.2	Differential PPM.....	188
4.4.2.3	Differential Amplitude Pulse Position Modulation.....	189
4.5	Pulse Interval Modulation	189
4.5.1	Error Performance on Gaussian Channels	195
4.5.1.1	DPIM with No Guard Band.....	199
4.5.1.2	DPIM with One Guard Slot.....	200
4.5.2	Optimum Threshold Level	202
4.6	Dual-Header PIM (DH-PIM)	206
4.6.1	Spectral Characteristics.....	209
4.6.2	Error Performance on Gaussian Channels	211
4.7	Multilevel DPIM.....	215
4.8	Comparisons of Baseband Modulation Schemes	217
4.8.1	Power Efficiency.....	217
4.8.2	Transmission Bandwidth Requirements.....	219
4.8.3	Transmission Capacity	222
4.8.4	Transmission Rate	223
4.8.5	Peak-to-Average Power Ratio.....	224
4.9	Subcarrier Intensity Modulation.....	225
4.10	Orthogonal Frequency Division Multiplexing.....	229
4.11	Optical Polarization Shift Keying	233
4.11.1	Binary PolSK.....	234
4.11.2	Bit Error Rate Analysis	239
4.11.3	MPolSK	241
4.11.4	Differential Circle Polarization Shift Keying	245
4.11.5	Error Probability Analysis	247
Appendix 4.A	.....	248
4.A.1	Derivation of Slot Autocorrelation Function of DPIM(1GS).....	248

Appendix 4.B	252
4.B.1 PSD of DH-PIM	252
4.B.1.1 Fourier Transform of DH-PIM	252
4.B.1.2 Power Spectral Density of DH-PIM	252
4.B.1.3 Further Discussion on the PSD Expression.....	260
References	261
Chapter 5 System Performance Analysis: Indoor	267
5.1 Effect of Ambient Light Sources on Indoor OWC Link Performance.....	267
5.2 Effect of FLI without Electrical High-Pass Filtering	268
5.2.1 Matched Filter Receiver	269
5.3 Effect of Baseline Wander without FLI	277
5.4 Effect of FLI with Electrical High-Pass Filtering.....	286
5.5 Wavelet Analysis	293
5.5.1 The Continuous Wavelet Transform.....	294
5.5.2 The Discrete Wavelet Transform.....	297
5.5.3 DWT-Based Denoising.....	298
5.5.4 Comparative Study of DWT and HPF	303
5.5.5 Experimental Investigations.....	305
5.6 Link Performance for Multipath Propagation	310
5.6.1 OOK	310
5.6.2 PPM.....	317
5.6.3 DPIM.....	319
5.7 Mitigation Techniques	320
5.7.1 Filtering	321
5.7.2 Equalization	323
5.7.2.1 The Zero Forcing Equalizer	323
5.7.2.2 Minimum Mean Square Error Equalizer.....	325
5.7.2.3 Decision Feedback Equalizer	326
5.8 Equalization as a Classification Problem	327
5.9 Introduction to Artificial Neural Network	327
5.9.1 Neuron.....	328
5.9.2 ANN Architectures	329
5.10 Training Network	330
5.10.1 Backpropagation Learning.....	331
5.11 The ANN-Based Adaptive Equalizer.....	332
5.11.1 Comparative Study of the ANN- and FIR-Based Equalizers.....	340
5.11.2 Diversity Techniques	341
References	342

Chapter 6	FSO Link Performance under the Effect of Atmospheric Turbulence	347
6.1	On–Off Keying.....	348
6.1.1	OOK in a Poisson Atmospheric Optical Channel.....	348
6.1.2	OOK in a Gaussian Atmospheric Optical Channel	350
6.2	Pulse Position Modulation.....	354
6.3	Subcarrier Intensity Modulation.....	358
6.3.1	SIM Generation and Detection.....	359
6.3.2	SIM-FSO Performance in Log-Normal Atmospheric Channel.....	362
6.3.3	Bit Error Probability Analysis of SIM-FSO.....	366
6.3.3.1	BPSK-Modulated Subcarrier	367
6.3.3.2	M-Ary PSK-Modulated Subcarrier	373
6.3.3.3	DPSK-Modulated Subcarrier.....	374
6.3.3.4	Multiple SIM Performance Analysis	376
6.3.3.5	Outage Probability in Log-Normal Atmospheric Channels.....	377
6.3.4	SIM-FSO Performance in Gamma–Gamma and Negative Exponential Atmospheric Channels.....	380
6.3.5	Outage Probability in Negative Exponential Model Atmospheric Channels.....	383
6.4	Atmospheric Turbulence-Induced Penalty	384
Appendix 6.A	.....	388
Appendix 6.B	.....	388
6.B.1	MATLAB Scripts for Sections 6.3.2, 6.3.3.2 and 6.3.3.3	388
6.B.1.1	Section 6.3.2	388
6.B.1.2	Sections 6.3.3.2 and 6.3.3.3	389
References	.....	394
Chapter 7	Outdoor OWC Links with Diversity Techniques	397
7.1	Atmospheric Turbulence Mitigation Techniques	397
7.2	Receiver Diversity in Log-Normal Atmospheric Channels	400
7.2.1	Maximum Ratio Combining	402
7.2.2	Equal Gain Combining	404
7.2.3	Selection Combining	406
7.2.4	Effect of Received Signal Correlation on Error Performance	407
7.2.5	Outage Probability with Receiver Diversity in a Log-Normal Atmospheric Channel.....	408

7.3	Transmitter Diversity in a Log-Normal Atmospheric Channel.....	409
7.4	Transmitter–Receiver Diversity in a Log-Normal Atmospheric Channel.....	410
7.5	Results and Discussions of SIM-FSO with Spatial Diversity in a Log-Normal Atmospheric Channel.....	411
7.6	SIM-FSO with Receiver Diversity in Gamma–Gamma and Negative Exponential Atmospheric Channels.....	416
7.6.1	BER and Outage Probability of BPSK-SIM with Spatial Diversity.....	416
7.6.2	BER and Outage Probability of DPSK-SIM in Negative Exponential Channels.....	419
7.7	Terrestrial Free Space Optical Links with Subcarrier Time Diversity.....	425
7.7.1	Error Performance with STDD.....	425
7.7.1.1	Error Performance of Short-Range Links.....	427
7.7.1.2	Error Performance of Long-Range Links.....	428
7.7.1.3	Results and Discussion for Short-Range Links.....	429
7.7.1.4	Results and Discussion for Long-Range Links.....	430
7.8	Aperture Averaging.....	432
7.8.1	Plane Wave.....	432
7.8.2	Spherical Wave.....	433
7.8.3	Gaussian Beam Wave.....	434
Appendix 7.A	.....	435
7.A.1	Sum of Log-Normal Distribution Mean and Variance Calculation.....	435
Appendix 7.B	.....	437
7.B.1	PDF of $I_{\max} = \max\{I_i\}_{i=1}^N$ for Log-Normal-Distributed Variables.....	437
Appendix 7.C	.....	438
7.C.1	PDF of $I_{\max} = \max\{I_i\}_{i=1}^N$ for Negative Exponential Distributed Variables.....	438
References	.....	438
Chapter 8	Visible Light Communications.....	443
8.1	Introduction.....	443
8.2	System Description.....	448
8.2.1	VLC System Model.....	452
8.2.2	SNR Analysis.....	463
8.2.3	Channel Delay Spread.....	464

8.3	System Implementations.....	467
8.3.1	Bit Angle Modulation.....	469
8.3.2	Pulse Modulation Schemes	470
8.3.3	PWM with Discrete Multitone Modulation	472
8.3.4	Multilevel PWM-PPM.....	474
8.3.5	PWM with NRZ-OOK.....	476
8.4	Multiple-Input–Multiple-Output VLC	477
8.5	Home Access Network	486
	References	493
Index	.....	497