# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>ix</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>xiii</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1 Spectrum Scarcity Issues and Optical Wireless Communications as a Solution</td>
<td>3</td>
</tr>
<tr>
<td>1.2 Organization</td>
<td>8</td>
</tr>
<tr>
<td>References</td>
<td>9</td>
</tr>
<tr>
<td>2 Fundamentals of Optical Wireless Communications</td>
<td>11</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>11</td>
</tr>
<tr>
<td>2.2 Communications Blocks in an OWC System</td>
<td>12</td>
</tr>
<tr>
<td>2.3 Intensity Modulation/Direct Detection (IM/DD)</td>
<td>14</td>
</tr>
<tr>
<td>2.4 Optical Transmitters</td>
<td>15</td>
</tr>
<tr>
<td>2.5 Optical Receivers</td>
<td>16</td>
</tr>
<tr>
<td>2.6 Optical Wireless Channel Propagation Characteristics</td>
<td>20</td>
</tr>
<tr>
<td>2.7 Conclusions</td>
<td>24</td>
</tr>
<tr>
<td>References</td>
<td>25</td>
</tr>
<tr>
<td>3 Indoor Optical Wireless Channel Modeling Methods</td>
<td>27</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>27</td>
</tr>
<tr>
<td>3.2 Source and Receiver Configurations</td>
<td>27</td>
</tr>
<tr>
<td>3.3 Steps for Modeling of Indoor OWC Environment</td>
<td>31</td>
</tr>
<tr>
<td>3.4 Models of the Room and Other Reflecting Surfaces</td>
<td>32</td>
</tr>
<tr>
<td>3.5 Radiation Patterns</td>
<td>32</td>
</tr>
<tr>
<td>3.5.1 Radiation Patterns of Point Sources</td>
<td>33</td>
</tr>
<tr>
<td>3.5.2 Radiation Patterns of Reflections</td>
<td>34</td>
</tr>
</tbody>
</table>
### Contents

3.6 Received Power from LOS Links 37

3.7 Received Power from NLOS Links 39

3.7.1 Barry’s Algorithm 39

3.7.2 MIMO Modeling Method 41

3.7.3 Modified Monte Carlo Algorithm and Variations 44

3.7.4 Combined Deterministic and MMC Algorithm 45

3.7.5 Other Approaches for Impulse Response Calculation 63

3.8 Conclusions 63

References 64

4 Analyses of Indoor Optical Wireless Channels Based on Channel Impulse Responses 67

4.1 Introduction 67

4.2 Analyses of Optical Wireless Channel Impulse Responses 67

4.2.1 Non-Directed LOS Links 70

4.2.2 Non-Directed NLOS Links 82

4.3 Effects of Furniture on Root-Mean-Square Delay Spread 89

4.4 SNR Calculations and BER Performance 93

4.5 Impact of Higher Order Reflections 96

4.6 Conclusions 107

References 109

5 Bit-Error-Rate Distribution and Outage of Indoor Optical Wireless Communications Systems 111

5.1 Introduction 111

5.2 Simulation Parameters 111

5.3 Optimal Detection and BER Outage Analysis 113

5.3.1 Optimal Detection 113

5.3.2 BER Analysis 115

5.4 Simulation Results (Receiver FOV = 60°) 117

5.4.1 BER Distribution and Outage 118

5.4.2 Impulse Response Distortion 121

5.5 Simulation Results (Receiver FOV = 30°) 123

5.6 Analytical Results and Comparisons 126

5.7 Conclusions 126

References 130

6 Orthogonal Frequency-Division Multiplexing (OFDM) for Indoor Optical Wireless Communications 131

6.1 Introduction 131

6.2 OFDM Overview 132

6.2.1 Basic OFDM System 132

6.2.2 System Operation 132

6.2.3 Discrete Time Implementation of OFDM 134

6.2.4 Drawbacks of OFDM 134
6.3 OFDM-Based OW Systems 136
   6.3.1 ACO-OFDM 137
   6.3.2 PAM-DMT 137
   6.3.3 DHT-OFDM 139

6.4 Precoding and PAPR Reduction in AC OFDM OW Systems 140
   6.4.1 Precoding-Based Optical OFDM System Model 140
   6.4.2 Precoding Schemes 143
   6.4.3 Simulation Results and Discussions 144

6.5 Performance of AC OFDM Systems in AWGN and Multipath Channel 149
   6.5.1 Precoding-Based OW OFDM System Model with AWGN 149
   6.5.2 Multipath Indoor Channel 150
   6.5.3 Frequency-Domain Equalization (FDE) 151
   6.5.4 Analytical BER Performance Results 152
   6.5.5 Electrical and Optical Performance Metrics 154
   6.5.6 Clipping and PAPR Reduction 154
   6.5.7 Simulation Results 155

6.6 Conclusions 164
References 167

7 MIMO Technology for Optical Wireless Communications using LED Arrays and Fly-Eye Receivers 169

7.1 Introduction 169
7.2 MIMO Configurations 169
   7.2.1 MIMO System Model 169
   7.2.2 Spatial Diversity 170
7.3 Angle-Diversity Receivers 171
   7.3.1 Angle-Diversity Receiver Overview 171
   7.3.2 Fly-Eye Receiver Design 171
7.4 Simulation Results and Discussions 173
   7.4.1 Simulation Parameters 173
   7.4.2 BER Spatial Distributions for MIMO OWC Systems 174
   7.4.3 Impact of Ambient Noise 182
7.5 Conclusions 189
References 190

8 Wireless Solutions for Aircrafts Based on Optical Wireless Communications and Power Line Communications 193

8.1 Introduction 193
8.2 Powerline Communications Channel Model 195
8.3 Optical Wireless Communications 196
   8.3.1 Simulation Configurations 196
   8.3.2 Illuminance Distribution Results 197
   8.3.3 Delay Spread Distribution Results 199
   8.3.4 Bit-Error-Rate Distribution and Outage Probability 200
8.4 Wireless Applications for Commercial Airplanes 204
  8.4.1 Reading Light Passenger Service Units 204
  8.4.2 Passenger Infotainment 205
  8.4.3 Cabin Interphones 205
  8.4.4 Interconnection of Line-Replaceable-Units Over Environmental Barrier 205

8.5 Conclusions 205
References 205

9 Multispot Diffusing Transmitters Using Holographic Diffusers for Infrared Beams and Receivers Using Holographic Mirrors 207
  9.1 Introduction 207
  9.2 CGH for Intensity-Weighted Spot Arrays 208
  9.3 Communication Cells for Multispot Diffusing Configuration 211
  9.4 Receiver Optical Front-End 214
    9.4.1 Holographic Mirrors 215
    9.4.2 Signal Effective Area 215
    9.4.3 Figure-of-Merit 216
  9.5 Wave Propagation through Materials and Metamaterials and Relation with Holography 218
  9.6 Conclusions 222
References 222

10 Indoor Positioning Methods Using VLC LEDs 225
  10.1 Motivation 225
  10.2 Positioning Algorithms and Solutions 228
    10.2.1 Triangulation 228
    10.2.2 Scene Analysis 234
    10.2.3 Proximity 234
    10.2.4 Comparison of Positioning Techniques 235
  10.3 An Asynchronous Indoor Positioning System based on VLC LED 237
    10.3.1 Basic Framed Slotted ALOHA Protocol 237
    10.3.2 System Design and DC Channel Gain 243
    10.3.3 Positioning Algorithm 244
    10.3.4 Signal-to-Noise Ratio Analysis 250
    10.3.5 Results and Discussions 252
    10.3.6 Extended Simulation and Results 256
  10.4 Conclusions 260
References 260

Index 263