Contents

About the Author xi

Foreword xiii

Preface xv

Acknowledgements xix

1 Introduction 1
1.1 Motivation 1
1.1.1 The ROF System 2
1.1.2 ROF for Millimeter Wave Bands 5
1.1.3 Serving Special Areas 6
1.1.4 Value-Added Use for Existing Fiber 6
1.1.5 Advancements in Microwave Photonics 7
1.1.6 Transparent System Enhancement 9
1.2 Basic Fi-Wi System Architecture 9
1.2.1 Two Types of Modulation 10
1.3 Major Issues 12
1.4 Other Fiber-Feeder Approaches 12
1.4.1 Digitized ROF 12
1.4.2 Intermediate Frequency over Fiber 13
1.5 Book Outline 13

2 Important Fi-Wi Link Elements 17
2.1 RF-Optical Modulation 17
2.1.1 Direct Intensity Modulation and the Laser Diode 17
2.1.2 External Intensity Modulation 25
2.2 The Fiber Channel 27
2.2.1 Attenuation 28
2.2.2 Multi-Mode Fiber for ROF 29
2.2.3 Single-Mode Fiber for ROF 30
2.2.4 Interferometric Noise 34
2.3 Optical Receiver 34
2.3.1 Photodetectors 35
2.3.2 Quantum Efficiency versus the Bandwidth 37

2.4 Brief Review of Baseband-RF Modulation Techniques 39
2.4.1 Phase-Shift Keying 39
2.4.2 Amplitude-Shift Keying 40
2.4.3 Quadrature Amplitude Modulation 40
2.5 The Wireless Channel 41
2.5.1 Indoor Propagation 42
2.5.2 Outdoor Propagation 42
2.5.3 Path-Loss Models 42
2.5.4 Multipath Propagation and Fading 44

3 Power Link Budget and Cumulating SNR **47**
3.1 Introduction 47
3.2 System Description 48
3.3 Optical SNR 49
3.3.1 Effect of Different Noise Dominations on OSNR 52
3.4 Cumulative SNR 54
3.4.1 Comparable Wireless and Optical Link Noise Powers 56
3.5 RAP Design Considerations 57
3.5.1 Optical Receiver Amplifier Gain 57
3.5.2 Cell Coverage Area 59
3.6 Summary 59

4 An Improved Expression for Relative Intensity Noise **61**
4.1 The Basics 61
4.2 The Fundamental Noise Processes in ROF Links 62
4.2.1 The Shot Noise 64
4.2.2 The Relative Intensity Noise 65
4.3 The Signal-to-Noise Ratio 67
4.4 Numerical Evaluation and Discussion 67
4.4.1 Noise Floor Increment in SCM ROF Systems 69
4.5 Summary 70

5 Subcarrier-Multiplexed ROF Downlink **71**
5.1 Introduction 71
5.1.1 Background 71
5.2 The ROF Downlink Channel 73
5.2.1 Higher-Order Terms 75
5.3 The Wireless Downlink Channel 84
5.4 Numerical Evaluation and Discussion 86

6 Subcarrier-Multiplexed ROF Uplink **89**
6.1 The Wireless Uplink Channel 89
6.2 The ROF Uplink Channel 92
6.2.1 Nonlinear Distortion 93
6.2.2 Higher-Order Terms 94
6.3 Signals to Distortion, Interference, and Noise Ratios 101

6.4 Numerical Evaluations and Discussion 103
6.5 Summary 107

7 Externally Modulated ROF Links **111**
7.1 Mach–Zehnder Modulator 112
7.1.1 Theory of MZI 113
7.2 Electro-Absorption Modulator 114
7.3 Reflective Semiconductor Optical Amplifier 117
7.4 Optimization of the MZI Bias Voltage 118
7.4.1 Maximizing RF Gain 118
7.4.2 Minimizing Noise Figure 120
7.4.3 Maximizing Spurious Free Dynamic Range 122
7.4.4 Combined Figure of Merit 123
7.5 Subcarrier-Multiplexed Signals in MZI 125

8 DSP Modeling of the ROF Link Nonlinearity **129**
8.1 Introduction 129
8.1.1 Linear Dynamic Range Requirement 130
8.1.2 Phase Nonlinearity 130
8.2 Various Attempts to Reduce NLD 130
8.2.1 Automatic Gain Controllers and Attenuators 130
8.2.2 Fixed Opto-Electronic Solutions 131
8.2.3 A few Novel Techniques 132
8.3 DSP Approaches 132
8.3.1 Baseband Compensation for Photonic Band Distortions 133
8.4 Basics of DSP for Nonlinear Systems 133
8.4.1 The Volterra Series Model 134
8.4.2 Discrete-Time-Domain Issue 135
8.5 Baseband Representation of a Passband Complex Nonlinear System 136
8.6 Nonlinear Modeling of Fi-Wi Link 137

9 Adaptive Compensation for the ROF Link Nonlinearity **139**
9.1 Adaptive Modeling of the ROF Link 139
9.1.1 Volterra Kernel Optimization 140
9.1.2 Filter Order and Memory 141
9.1.3 Case Study 144
9.2 Asymmetric Compensation 146
9.2.1 Pre-Compensation versus Post-Compensation 147
9.2.2 A Unified Look at the Asymmetric Compensation 149
9.2.3 Case Study of Adaptive DSP Compensation 152
9.2.4 Look-up Table versus Adaptive Filter Compensation 155
9.3 Summary 156

10 Joint Estimation of the Fi-Wi Channel **159**
10.1 The Wiener and Hammerstein System Model for Fi-Wi Links 159
10.2 Fi-Wi Channel Estimation 160

10.2.1 Input/Output Correlation Method 161
10.2.2 Estimation of the Linear Part 163
10.2.3 Estimation of the Nonlinear Part 165
10.3 Case Study 167
10.3.1 Linear System Identification 167
10.3.2 Nonlinear System Identification 169
10.4 Summary 169

11 Joint Equalization for the Fi-Wi Channel **171**
11.1 Equalization of the Wireless Channel 171
11.1.1 Nonlinearly Enhanced Decision Feedback Equalizers 172
11.1.2 The Hammerstein-Type DFE (HDFE) 173
11.1.3 Amplitude and Time-Domain Operations 173
11.2 Optimization of Polynomial Filter Parameters 174
11.2.1 Direct Generation of the Inverse Polynomial 174
11.3 Optimization of Linear Filter Parameters 176
11.3.1 Model Description 177
11.3.2 Parameter Optimization 180
11.4 Summary 182

12 Performance Evaluation of the Hammerstein-Type DFE **183**
12.1 Evaluation of the Polynomial Filter 183
12.1.1 Nonlinear Transformation of Time Dispersion 183
12.1.2 Inverse Polynomial Transformation 186
12.1.3 Expected Value of the Polynomial Filter Error 186
12.2 Evaluation of Linear Filters 189
12.2.1 Infinite-Length Results 189
12.2.2 Finite-Length Results 190
12.3 Case Study 190
12.3.1 Mean-Squared Error of the Polynomial Filter 190
12.3.2 Mean-Squared Error of Linear Filters 196
12.3.3 BER Performance of the HDFE 196
12.4 Summary 198

13 Multiuser CDMA Fi-Wi Systems **199**
13.1 Multiuser Fi-Wi Uplink Model 199
13.2 Correlation Relationships 201
13.2.1 Generalized Input–Output Correlation 201
13.2.2 Input-Kernel Correlation for Multiuser Case 203
13.3 ROF Channel Estimation 205
13.4 Case Study 206
13.4.1 Simulation Parameters 206
13.4.2 Wireless Channel Identification 207
13.4.3 Fiber Link Identification 208
13.5 Fi-Wi Uplink Equalization 209
13.5.1 Wireless Channel Equalization 210
13.5.2 Linearization by Series Reversion 210

13.6 Equalization: Simulation Results and Discussion 211
13.7 Summary 213

14 Fi-Wi for 4G, 5G, and OFDM Wireless Networks **215**
14.1 Brief History of Cellular Communication Systems 216
14.1.1 Worldwide Interoperability for Microwave Access 217
14.1.2 Long-Term Evolution 217
14.2 Wireless Access Schemes 218
14.2.1 Orthogonal Frequency Division Multiple Access 219
14.3 Peak-to-Average Power Ratio Reduction Techniques 221
14.4 OFDM ROF System Improvement 223
14.4.1 Adaptive Modulation Technique 224
14.4.2 Case Study 226
14.5 Combinations of OFDMA and CDMA 226
14.6 Summary 227

List of Abbreviations **229**

Important Symbols **233**

References **239**

Index **247**