Digital Communication over Fading Channels

A Unified Approach to Performance Analysis

Marvin K. Simon
Mohamed-Slim Alouini

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

Digital Communication over Fading Channels: A Unified Approach to Performance Analysis.
Marvin K. Simon, Mohamed-Slim Alouini
Copyright © 2000 John Wiley & Sons, Inc.
Print ISBN 0-471-31779-9 Electronic ISBN 0-471-20069-7

CONTENTS

Preface **xv**

PART 1 FUNDAMENTALS

Chapter 1 Introduction **3**
1.1 System Performance Measures 4
1.1.1 Average Signal-to-Noise Ratio 4
1.1.2 Outage Probability 5
1.1.3 Average Bit Error Probability 6
1.2 Conclusions 12
References 13

Chapter 2 Fading Channel Characterization and Modeling **15**
2.1 Main Characteristics of Fading Channels 15
2.1.1 Envelope and Phase Fluctuations 15
2.1.2 Slow and Fast Fading 16
2.1.3 Frequency-Flat and Frequency-Selective Fading 16
2.2 Modeling of Flat Fading Channels 17
2.2.1 Multipath Fading 18
2.2.2 Log-Normal Shadowing 23
2.2.3 Composite Multipath/Shadowing 24
2.2.4 Combined (Time-Shared) Shadowed/Unshadowed Fading 25
2.3 Modeling of Frequency-Selective Fading Channels 26
References 28

Chapter 3 Types of Communication **31**
3.1 Ideal Coherent Detection 31
3.1.1 Multiple Amplitude-Shift-Keying or Multiple Amplitude Modulation 33
3.1.2 Quadrature Amplitude-Shift-Keying or Quadrature Amplitude Modulation 34
3.1.3 M-ary Phase-Shift-Keying 35
3.1.4 Differentially Encoded M-ary Phase-Shift-Keying 39
3.1.5 Offset QPSK or Staggered QPSK 41
3.1.6 M-ary Frequency-Shift-Keying 43
3.1.7 Minimum-Shift-Keying 45
3.2 Nonideal Coherent Detection 47
3.3 Noncoherent Detection 53
3.4 Partially Coherent Detection 55
3.4.1 Conventional Detection: One-Symbol Observation 55
3.4.2 Multiple Symbol Detection 57
3.5 Differentially Coherent Detection 59
3.5.1 M-ary Differential Phase Shift Keying 59
3.5.2 $\pi/4$-Differential QPSK 65
References 65

PART 2 MATHEMATICAL TOOLS

Chapter 4 Alternative Representations of Classical Functions **69**
4.1 Gaussian Q-Function 70
4.1.1 One-Dimensional Case 70
4.1.2 Two-Dimensional Case 72
4.2 Marcum Q-Function 74
4.2.1 First-Order Marcum Q-Function 74
4.2.2 Generalized (mth-Order) Marcum Q-Function 81
4.3 Other Functions 90
References 94
Appendix 4A: Derivation of Eq. (4.2) 95

Chapter 5 Useful Expressions for Evaluating Average Error Probability Performance **99**
5.1 Integrals Involving the Gaussian Q-Function 99
5.1.1 Rayleigh Fading Channel 101

5.1.2 Nakagami-q (Hoyt) Fading Channel 101
5.1.3 Nakagami-n (Rice) Fading Channel 102
5.1.4 Nakagami-m Fading Channel 102
5.1.5 Log-Normal Shadowing Channel 104
5.1.6 Composite Log-Normal Shadowing/Nakagami-m Fading Channel 104
5.2 Integrals Involving the Marcum Q-Function 107
5.2.1 Rayleigh Fading Channel 108
5.2.2 Nakagami-q (Hoyt) Fading Channel 109
5.2.3 Nakagami-n (Rice) Fading Channel 109
5.2.4 Nakagami-m Fading Channel 109
5.2.5 Log-Normal Shadowing Channel 109
5.2.6 Composite Log-Normal Shadowing/Nakagami-m Fading Channel 110
5.3 Integrals Involving the Incomplete Gamma Function 111
5.3.1 Rayleigh Fading Channel 112
5.3.2 Nakagami-q (Hoyt) Fading Channel 112
5.3.3 Nakagami-n (Rice) Fading Channel 112
5.3.4 Nakagami-m Fading Channel 113
5.3.5 Log-Normal Shadowing Channel 114
5.3.6 Composite Log-Normal Shadowing/Nakagami-m Fading Channel 114
5.4 Integrals Involving Other Functions 114
5.4.1 M-PSK Error Probability Integral 114
5.4.2 Arbitrary Two-Dimensional Signal Constellation Error Probability Integral 116
5.4.3 Integer Powers of the Gaussian Q-Function 117
5.4.4 Integer Powers of M-PSK Error Probability Integrals 121
References 124
Appendix 5A: Evaluation of Definite Integrals Associated with Rayleigh and Nakagami-m Fading 124

Chapter 6 New Representations of Some PDF's and CDF's for Correlative Fading Applications 141
6.1 Bivariate Rayleigh PDF and CDF 142
6.2 PDF and CDF for Maximum of Two Rayleigh Random Variables 146
6.3 PDF and CDF for Maximum of Two Nakagami-m Random Variables 149
References 152

PART 3 OPTIMUM RECEPTION AND PERFORMANCE EVALUATION

Chapter 7 Optimum Receivers for Fading Channels 157

7.1 Case of Known Amplitudes, Phases, and Delays: Coherent Detection 159

7.2 The Case of Known Phases and Delays, Unknown Amplitudes 163

7.2.1 Rayleigh Fading 163

7.2.2 Nakagami-*m* Fading 164

7.3 Case of Known Amplitudes and Delays, Unknown Phases 166

7.4 Case of Known Delays and Unknown Amplitudes and Phases 168

7.4.1 One-Symbol Observation: Noncoherent Detection 168

7.4.2 Two-Symbol Observation: Conventional Differentially Coherent Detection 181

7.4.3 *N*-Symbol Observation: Multiple Symbol Differentially Coherent Detection 186

7.5 Case of Unknown Amplitudes, Phases, and Delays 188

7.5.1 One-Symbol Observation: Noncoherent Detection 188

7.5.2 Two-Symbol Observation: Conventional Differentially Coherent Detection 190

References 191

Chapter 8 Performance of Single Channel Receivers 193

8.1 Performance Over the AWGN Channel 193

8.1.1 Ideal Coherent Detection 194

8.1.2 Nonideal Coherent Detection 206

8.1.3 Noncoherent Detection 209

8.1.4 Partially Coherent Detection 210

8.1.5 Differentially Coherent Detection 213

8.1.6 Generic Results for Binary Signaling 218

8.2 Performance Over Fading Channels 219

8.2.1 Ideal Coherent Detection 220

8.2.2 Nonideal Coherent Detection 234

8.2.3 Noncoherent Detection 239

8.2.4 Partially Coherent Detection 242

8.2.5 Differentially Coherent Detection 243

References 251

Appendix 8A: Stein's Unified Analysis of the Error Probability Performance of Certain Communication Systems 253

Chapter 9 Performance of Multichannel Receivers 259

9.1 Diversity Combining 260
9.1.1 Diversity Concept 260
9.1.2 Mathematical Modeling 260
9.1.3 Brief Survey of Diversity Combining Techniques 261
9.1.4 Complexity–Performance Trade-offs 264
9.2 Maximal-Ratio Combining 265
9.2.1 Receiver Structure 265
9.2.2 PDF-Based Approach 267
9.2.3 MGF-Based Approach 268
9.2.4 Bounds and Asymptotic SER Expressions 275
9.3 Coherent Equal Gain Combining 278
9.3.1 Receiver Structure 279
9.3.2 Average Output SNR 279
9.3.3 Exact Error Rate Analysis 281
9.3.4 Approximate Error Rate Analysis 288
9.3.5 Asymptotic Error Rate Analysis 289
9.4 Noncoherent Equal-Gain Combining 290
9.4.1 DPSK, DQPSK, and BFSK: Exact and Bounds 290
9.4.2 M-ary Orthogonal FSK 304
9.5 Outage Probability Performance 311
9.5.1 MRC and Noncoherent EGC 312
9.5.2 Coherent EGC 313
9.5.3 Numerical Examples 314
9.6 Impact of Fading Correlation 316
9.6.1 Model A: Two Correlated Branches with Nonidentical Fading 320
9.6.2 Model B: D Identically Distributed Branches with Constant Correlation 323
9.6.3 Model C: D Identically Distributed Branches with Exponential Correlation 324
9.6.4 Model D: D Nonidentically Distributed Branches with Arbitrary Correlation 325
9.6.5 Numerical Examples 329
9.7 Selection Combining 333
9.7.1 MGF of Output SNR 335

9.7.2 Average Output SNR 336
9.7.3 Outage Probability 338
9.7.4 Average Probability of Error 340
9.8 Switched Diversity 348
9.8.1 Performance of SSC over Independent Identically Distributed Branches 348
9.8.2 Effect of Branch Unbalance 362
9.8.3 Effect of Branch Correlation 366
9.9 Performance in the Presence of Outdated or Imperfect Channel Estimates 370
9.9.1 Maximal-Ratio Combining 370
9.9.2 Noncoherent EGC over Rician Fast Fading 371
9.9.3 Selection Combining 373
9.9.4 Switched Diversity 374
9.9.5 Numerical Results 377
9.10 Hybrid Diversity Schemes 378
9.10.1 Generalized Selection Combining 378
9.10.2 Generalized Switched Diversity 403
9.10.3 Two-Dimensional Diversity Schemes 408
References 411
Appendix 9A: Alternative Forms of the Bit Error Probability for a Decision Statistic that is a Quadratic Form of Complex Gaussian Random Variables 421
Appendix 9B: Simple Numerical Techniques for the Inversion of the Laplace Transform of Cumulative Distribution Functions 427
9B.1 Euler Summation-Based Technique 427
9B.2 Gauss–Chebyshev Quadrature-Based Technique 428
Appendix 9C: Proof of Theorem 1 430
Appendix 9D: Direct Proof of Eq. (9.331) 431
Appendix 9E: Special Definite Integrals 432

PART 4 APPLICATION IN PRACTICAL COMMUNICATION SYSTEMS

Chapter 10 Optimum Combining: A Diversity Technique for Communication Over Fading Channels in the Presence of Interference 437
10.1 Performance of Optimum Combining Receivers 438

10.1.1 Single Interferer, Independent Identically Distributed Fading 438
10.1.2 Multiple Interferers, Independent Identically Distributed Fading 454
10.1.3 Comparison with Results for MRC in the Presence of Interference 466
References 470

Chapter 11 Direct-Sequence Code-Division Multiple Access 473
11.1 Single-Carrier DS-CDMA Systems 474
11.1.1 System and Channel Models 474
11.1.2 Performance Analysis 477
11.2 Multicarrier DS-CDMA Systems 479
11.2.1 System and Channel Models 480
11.2.2 Performance Analysis 483
11.2.3 Numerical Examples 489
References 492

PART 5 FURTHER EXTENSIONS

Chapter 12 Coded Communication Over Fading Channels 497
12.1 Coherent Detection 499
12.1.1 System Model 499
12.1.2 Evaluation of Pairwise Error Probability 502
12.1.3 Transfer Function Bound on Average Bit Error Probability 510
12.1.4 Alternative Formulation of the Transfer Function Bound 513
12.1.5 Example 514
12.2 Differentially Coherent Detection 520
12.2.1 System Model 520
12.2.2 Performance Evaluation 522
12.2.3 Example 524
12.3 Numerical Results: Comparison of the True Upper Bounds and Union–Chernoff Bounds 526
References 530
Appendix 12A: Evaluation of a Moment Generating Function Associated with Differential Detection of M-PSK Sequences 532

Index 535