Coding for
MIMO Communication Systems

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Contents

About the Authors **xi**

Preface **xiii**

List of Figures **xv**

List of Tables **xxiii**

Notation **xxv**

Abbreviations **xxvii**

1 Overview **1**

1.1 Need for MIMO Systems . . . 1
1.2 MIMO Communications in Wireless Standards . . . 3
1.3 Organization of the Book . . . 3
1.4 Other Topics in MIMO Systems . . . 5

2 Fading Channels and Diversity Techniques **7**

2.1 Wireless Channels . . . 7
  2.1.1 Path Loss, Shadowing and Small-Scale Fading . . . 9
  2.1.2 Fading Channel Models . . . 10
2.2 Error/Outage Probabilities over Fading Channels . . . 17
  2.2.1 Outage Probability for Rayleigh Fading Channels . . . 17
  2.2.2 Average Error Probabilities over Rayleigh Fading Channels . . . 18
  2.2.3 Extensions to Other Fading Channels . . . 19
  2.2.4 Performance over Frequency Selective Fading Channels . . . 19
2.3 Diversity Techniques . . . 20
  2.3.1 Types of Diversity . . . 21
  2.3.2 System Model for Lth Order Diversity . . . 22
  2.3.3 Maximal Ratio Combining (MRC) . . . 23
  2.3.4 Suboptimal Combining Algorithms . . . 26
  2.3.5 Selection Combining . . . 27
  2.3.6 Examples . . . 28

2.4 Channel Coding as a Means of Time Diversity 28
2.4.1 Block Coding over a Fully Interleaved Channel 30
2.4.2 Convolutional Coding 34
2.5 Multiple Antennas in Wireless Communications 35
2.5.1 Receive Diversity 35
2.5.2 Smart Antennas and Beamforming 35
2.5.3 Space-Time Coding – Basic Ideas 37
2.6 Chapter Summary and Further Reading 38
Problems 39

3 Capacity and Information Rates of MIMO Channels 43
3.1 Capacity and Information Rates of Noisy Channels 43
3.2 Capacity and Information Rates of AWGN and Fading Channels 45
3.2.1 AWGN Channels 45
3.2.2 Fading Channels 46
3.3 Capacity of MIMO Channels 50
3.3.1 Deterministic MIMO Channels 51
3.3.2 Ergodic MIMO Channels 56
3.3.3 Non-Ergodic MIMO Channels and Outage Capacity 60
3.3.4 Transmit CSI for MIMO Fading Channels 62
3.4 Constrained Signaling for MIMO Communications 64
3.5 Discussion: Why Use MIMO Systems? 65
3.6 Chapter Summary and Further Reading 67
Problems 68

4 Space-Time Block Codes 71
4.1 Transmit Diversity with Two Antennas: The Alamouti Scheme 71
4.1.1 Transmission Scheme 72
4.1.2 Optimal Receiver for the Alamouti Scheme 72
4.1.3 Performance Analysis of the Alamouti Scheme 76
4.1.4 Examples 77
4.2 Orthogonal Space-Time Block Codes 79
4.2.1 Linear Orthogonal Designs 80
4.2.2 Decoding of Linear Orthogonal Designs 82
4.2.3 Performance Analysis of Space-Time Block Codes 84
4.2.4 Examples 86
4.3 Quasi-Orthogonal Space-Time Block Codes 87
4.4 Linear Dispersion Codes 88
4.5 Chapter Summary and Further Reading 90
Problems 90

5 Space-Time Trellis Codes 93
5.1 A Simple Space-Time Trellis Code 93
5.2 General Space-Time Trellis Codes 94
5.2.1 Notation and Preliminaries 95
5.2.2 Decoding of Space-Time Trellis Codes 96
5.3 Basic Space-Time Code Design Principles 97

5.3.1 Pairwise Error Probability 97
5.3.2 Space-Time Code Design Principles 99
5.3.3 Examples of Good Space-Time Codes 101
5.3.4 Space-Time Trellis Codes for Fast Fading Channels 104
5.4 Representation of Space-Time Trellis Codes for PSK Constellations . . . 107
5.4.1 Generator Matrix Representation 107
5.4.2 Improved Space-Time Code Design 108
5.5 Performance Analysis for Space-Time Trellis Codes 109
5.5.1 Union Bound for Space-Time Trellis Codes 110
5.5.2 Useful Performance Bounds for Space-Time Trellis Codes 113
5.5.3 Examples 118
5.6 Comparison of Space-Time Block and Trellis Codes 120
5.7 Chapter Summary and Further Reading 121
Problems 122

6 Layered Space-Time Codes 123
6.1 Basic Bell Laboratories Layered Space-Time (BLAST) Architectures . . . 124
6.1.1 VBLAST/HBLAST/SCBLAST 124
6.1.2 Detection Algorithms for Basic BLAST Architectures 125
6.1.3 Examples 131
6.2 Diagonal BLAST (DBLAST) 135
6.2.1 Detection Algorithms for DBLAST 136
6.2.2 Examples 140
6.3 Multilayered Space-Time Codes 142
6.3.1 Encoder Structure 142
6.3.2 Group Interference Cancellation Detection 143
6.3.3 Example 145
6.4 Threaded Space-Time Codes 146
6.4.1 Layering Approach 147
6.4.2 Threaded Space-Time Code Design 148
6.4.3 Example 150
6.4.4 Detection of Threaded Space-Time Codes 151
6.5 Other Detection Algorithms for Spatial Multiplexing Systems 151
6.5.1 Greedy Detection 152
6.5.2 Belief Propagation Detection 152
6.5.3 Turbo-BLAST Detection 153
6.5.4 Reduced Complexity ZF/MMSE Detection 153
6.5.5 Sphere Decoding 153
6.6 Diversity/Multiplexing Gain Trade-off 154
6.7 Chapter Summary and Further Reading 158
Problems 158

7 Concatenated Codes and Iterative Decoding 161
7.1 Development of Concatenated Codes 161
7.2 Concatenated Codes for AWGN Channels 163
7.2.1 Encoder Structures 163
7.2.2 Iterative Decoder Structures 165

7.2.3 The SOVA Decoder 176
7.2.4 Performance with Maximum Likelihood Decoding 181
7.2.5 Examples 183
7.3 Concatenated Codes for MIMO Channels 186
7.3.1 Concatenated Space-Time Turbo Coding Scheme 187
7.3.2 Turbo Space-Time Trellis Coding Scheme 188
7.3.3 Turbo Space-Time Coding Scheme 189
7.4 Turbo-Coded Modulation for MIMO Channels 190
7.4.1 Encoder Structure 190
7.4.2 Decoder Structure 191
7.4.3 Examples 194
7.5 Concatenated Space-Time Block Coding 195
7.5.1 Encoder Structure 196
7.5.2 Decoder Structure 196
7.5.3 Performance Analysis 197
7.5.4 Examples 201
7.6 Chapter Summary and Further Reading 204
Problems 204

8 Unitary and Differential Space-Time Codes 207
8.1 Capacity of Noncoherent MIMO Channels 208
8.1.1 Channel Capacity 209
8.1.2 Capacity Achieving Signals 211
8.2 Unitary Space-Time Codes 211
8.2.1 USTC Encoder 211
8.2.2 ML Detection of USTCs 212
8.2.3 Performance Analysis 213
8.2.4 Construction of Unitary Space-Time Signals 214
8.2.5 Examples 221
8.3 Differential Space-Time Codes 221
8.3.1 Differential Space-Time Coding for Single Antenna Systems . . . 221
8.3.2 Differential Space-Time Coding for MIMO Systems 224
8.4 Turbo-Coded Unitary Space-Time Codes 228
8.4.1 Encoder Structure 229
8.4.2 Noncoherent Iterative Decoder 229
8.4.3 Example 232
8.5 Trellis-Coded Unitary Space-Time Codes 233
8.6 Turbo-Coded Differential Space-Time Codes 235
8.6.1 Encoder Structure 235
8.6.2 Iterative Detectors 236
8.7 Chapter Summary and Further Reading 237
Problems 238

9 Space-Time Coding for Frequency Selective Fading Channels 239
9.1 MIMO Frequency Selective Channels 239
9.2 Capacity and Information Rates of MIMO Frequency Selective Fading Channels 240

9.2.1 Information Rates with Gaussian Inputs 240
9.2.2 Achievable Information Rates with Practical Constellations 241
9.2.3 Examples 245
9.3 Space-Time Coding for MIMO FS Channels 247
9.3.1 Interpretation of MIMO FS Channels Using Virtual Antennas . . 247
9.3.2 A Simple Full Diversity Code for MIMO FS Channels 249
9.3.3 Space-Time Trellis Codes for MIMO FS Channels 250
9.3.4 Concatenated Coding for MIMO FS Channels 253
9.3.5 Spatial Multiplexing for MIMO FS Channels 257
9.4 Channel Detection for MIMO FS Channels 257
9.4.1 Linear Equalization for MIMO FS Channels 258
9.4.2 Decision Feedback Equalization for MIMO FS Channels 258
9.4.3 Soft-Input Soft-Output Channel Detection 258
9.4.4 Other Reduced Complexity Approaches 259
9.5 MIMO OFDM Systems 260
9.5.1 MIMO-OFDM Channel Model 261
9.5.2 Space-Frequency Coding 262
9.5.3 Challenges in MIMO-OFDM 263
9.6 Chapter Summary and Further Reading 263
Problems 264

10 Practical Issues in MIMO Communications 267
10.1 Channel State Information Estimation 267
10.1.1 CSI Estimation Using Pilot Tones 268
10.1.2 What to Do with CSI? 271
10.1.3 Space-Time Coding Examples with Estimated CSI 272
10.2 Spatial Channel Correlation for MIMO Systems 273
10.2.1 Measurements and Modeling of Spatial Correlation 275
10.2.2 Spatial Channel Correlation Models 276
10.2.3 Channel Capacity with Spatial Correlation 277
10.2.4 Space-Time Code Performance with Spatial Correlation 279
10.3 Temporal Channel Correlation 281
10.4 MIMO Communication System Design Issues 283
10.5 Chapter Summary and Further Reading 284
Problems 285

11 Antenna Selection for MIMO Systems 287
11.1 Capacity-based Antenna Selection 287
11.1.1 System Model 288
11.1.2 Optimal Selection 289
11.1.3 Simplified (Suboptimal) Selection 290
11.1.4 Examples 290
11.2 Energy-based Antenna Selection 292
11.3 Antenna Selection for Space-Time Trellis Codes 293
11.3.1 Quasi-Static Fading Channels 293
11.3.2 Block Fading Channels 295

11.3.3 Fast Fading Channels 298
11.3.4 Examples 299
11.4 Antenna Selection for Space-Time Block Codes 302
11.4.1 Receive Antenna Selection 302
11.4.2 Transmit Antenna Selection 304
11.4.3 Examples 304
11.5 Antenna Selection for Combined Channel Coding and Orthogonal STBCs 306
11.5.1 Performance Analysis 306
11.5.2 Examples 307
11.6 Antenna Selection for Frequency Selective Channels 310
11.7 Antenna Selection with Nonidealities 311
11.7.1 Impact of Spatial Correlation 311
11.7.2 Example 312
11.7.3 Impact of Channel Estimation Error 312
11.8 Chapter Summary and Further Reading 313
Problems 314

Bibliography **317**

Index **333**

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Preface

Employing multiple transmit and receive antennas, namely using multi-input multi-output (MIMO) systems, has proven to be a major breakthrough in providing reliable wireless communication links. Since their invention in the mid-1990s, transmit diversity, achieved through space-time coding, and spatial multiplexing schemes have been the focus of much research in the area of wireless communications. Although many significant advancements have been made recently in MIMO communications, there is still much ongoing research in this area. Parallel to that, communication companies have already started looking into integrating MIMO systems in their current and future wireless communication systems. In fact, several standards for future wireless communication applications have already adopted MIMO systems as an option.

This book is intended to provide a comprehensive coverage of coding techniques for MIMO communication systems. The contents of this book have evolved over the past several years as a result of our own research in MIMO communications, and the tutorials and short courses we have given at several conferences (including IEEE International Conference on Communications (ICC), Global Telecommunications Conference (GLOBECOM), Vehicular Technology Conference (VTC), and Wireless Communications and Networking Conference (WCNC)). The feedback we have received motivated us to write this book in order to address the fundamentals of MIMO communications in an accessible manner.

At this time, several books have been published on MIMO systems. However, there are a number of factors that differentiate this book from the existing ones. First, we try to stay away from including very complicated derivations, mathematical expressions, and very specific systems. Instead, we focus more on the fundamental issues pertaining to MIMO systems. We use language that is easy to comprehend for a wide audience interested in this topic, including starting graduate or senior undergraduate students majoring in electrical engineering with some limited training in digital communications and probability theory. For certain topics, we present more details with some derivations in an effort to accommodate the needs of a more specific group of researchers or advanced graduate students. However, the book is organized in such a way that these subjects are easy to spot, and thus, these should not overwhelm the rest of the audience. Another major factor that differentiates this book from other books is the breadth of coverage of topics. For instance, in addition to our coverage of basic MIMO communication algorithms, such as space-time block codes, space-time trellis codes, unitary and differential signaling and spatial multiplexing schemes, we include a detailed coverage of turbo codes and iterative decoding for MIMO systems, antenna selection algorithms, practical issues such as spatial correlation and channel estimation, as well as MIMO systems for frequency selective fading channels. Finally, we provide numerous examples – some elementary, some more advanced – on various topics covered, and a large number of references on MIMO communications at the end of each chapter.

Audience

The primary audience of this book is senior undergraduate students, graduate students, practitioners and researchers who are interested in learning more about MIMO systems, or perhaps would like to get into this area of research. For the audience to get the full benefits of the book, it is recommended that they have some background in digital communications, linear algebra and probability theory.

Although this book is intended primarily for researchers and practitioners, it can also be adopted as a textbook for a graduate level, or an advanced undergraduate level, course on "Wireless MIMO Communications." The language, organization, and flow of the material should make this easy. The material could be covered in a one-semester course. In order to facilitate its use as a textbook, the book is also complemented with a set of problems at the end of each chapter which serve the purpose of making the main topics covered in each chapter more clear, and shedding some light on certain aspects that are not provided in detail in the text.

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List of Figures

2.1 Illustration of the wireless propagation mechanisms. 8
2.2 Effect of path loss and shadowing on the received signal power. 10
2.3 Received power when small-scale fading is also taken into account. . . 10
2.4 A typical scattering function. 13
2.5 Frequency flat versus frequency selective fading (in the frequency domain). 13
2.6 Illustration of frequency selective fading in the time domain. 14
2.7 Error rates of BPSK modulation over Rayleigh and Rician fading channels. 19
2.8 Error rates of BPSK modulation over several frequency selective fading channels. 20
2.9 Illustration of time and frequency diversity techniques. 21
2.10 Spatial diversity scheme. 22
2.11 Channel model for an Lth order diversity scheme. 23
2.12 Outage probability of MRC and SC over a Rayleigh fading channel (assuming minimum acceptable signal-to-noise ratio is 0 dB). 29
2.13 Average error probability of binary DPSK with MRC and SC over a Rayleigh fading channel. 29
2.14 Coding over a wireless channel. 30
2.15 An example of a convolutional code with generators $(21, 37)_{octal}$. . . . 34
2.16 A simple ad-hoc network illustration. 36
2.17 Illustration of beamforming being used for improving signal-to-noise ratio and reducing interference. 36
2.18 Multiple antennas being used for beamforming. 38
2.19 Multiple antennas being used for space-time coding or spatial multiplexing. 38
2.20 Figure for Problem 2.4. 40
3.1 Generic block diagram for a channel coded communication system. . . 44
3.2 Capacity and information rates for several modulation schemes over AWGN channels. 46
3.3 Capacity and information rates for several modulation schemes over ergodic Rayleigh fading channels. 48
3.4 Outage capacity and information rates for quasi-static Rayleigh fading channels. 49
3.5 Generic block diagram for a channel coded MIMO communication system. 50
3.6 Capacity of the channel $\boldsymbol{H}_1$. 55
3.7 Capacity of the channel $\boldsymbol{H}_2$. 56
3.8 Ergodic capacity of MIMO Rayleigh fading channels with $N_t = 1$. . . . 59
3.9 Ergodic capacity of MIMO Rayleigh fading channels with $N_r = 1$. . . . 59

3.10 Ergodic capacity of MIMO Rayleigh fading channels with equal number of transmit and receive antennas. 60

3.11 Outage probability of MIMO Rayleigh fading channels for several scenarios. 62

3.12 Outage capacity of MIMO Rayleigh fading channels as a function of the number of antennas for 1% outage probability. 63

3.13 Outage capacity of MIMO Rayleigh fading channels as a function of the number of antennas for 10% outage probability. 63

3.14 Capacity and information rates for an ergodic Rayleigh fading MIMO system with two transmit and two receive antennas. 65

3.15 Capacity and information rates for an ergodic Rayleigh fading MIMO system with four transmit and four receive antennas. 66

3.16 Outage information rates for $P_{out} = 10\%$ for quasi-static Rayleigh fading as a function of $N_t = N_r = n$). 66

3.17 Outage information rates for $P_{out} = 1\%$ for quasi-static Rayleigh fading as a function of $N_t = N_r = n$). 67

4.1 The Alamouti scheme. 72

4.2 Bit error rate performance of the Alamouti scheme with BPSK modulation (simulation and bound). 78

4.3 Symbol error rate performance of the Alamouti scheme with 8-PSK modulation (simulation and bound). 78

4.4 Bit error rate of $\boldsymbol{X}_1$ with BPSK modulation. 86

4.5 Symbol error rate of $\boldsymbol{X}_2$ with QPSK modulation. 87

5.1 A four-state space-time trellis code example. 94

5.2 Eight-state and 16-state space-time trellis codes using 4-PSK modulation (2 bits per channel use). 102

5.3 Eight-state space-time trellis code using 8-PSK modulation (3 bits per channel use). 102

5.4 Outage probability and frame error rates of several space-time trellis codes with QPSK (quasi-static fading, two transmit and one receive antennas). 103

5.5 Outage probability and frame error rates of several space-time trellis codes with QPSK (quasi-static fading, two transmit and two receive antennas). 104

5.6 Bit error rates for the four-state code in quasi-static fading (two transmit and two receive antennas). 105

5.7 Bit error rate results for four-, eight- and 16-state space-time trellis codes over fully interleaved Rayleigh fading channels (two transmit and one receive antennas). 106

5.8 Frame error rate bound and simulation results for fast fading (two transmit and one receive antennas). 112

5.9 Simple versus compound error events. 114

5.10 Two-state space-time trellis code with BPSK modulation and its extended state diagram for bound computation. 117

5.11 Four-state space-time trellis code with 4-PSK modulation (by Yan and Blum). 118

5.12 Frame error rate bound and simulation results for quasi-static fading with a frame length of 130 (two transmit and two receive antennas). 119
5.13 Frame error rate bound and simulation results for quasi-static fading with a frame length of 130 (two transmit and three receive antennas). 119
5.14 Frame error rate comparison of the Alamouti scheme with several space-time trellis codes (two transmit and one receive antennas, 2 bits per channel use). 120
5.15 Frame error rate comparison of the Alamouti scheme with several space-time trellis codes (two transmit and two receive antennas, 2 bits per channel use). 121
6.1 VBLAST encoder structure (Π_i denotes the interleaver corresponding to the ith layer). 124
6.2 HBLAST encoder structure. 125
6.3 SCBLAST encoder structure. 125
6.4 VBLAST bit error rate performance with various detection criteria for $N_t = N_r = 4$ with uncoded BPSK. 132
6.5 VBLAST bit error rate performance for $N_t = N_r = 4$ for the four layers using the ZF-IC criterion (for uncoded BPSK). 133
6.6 VBLAST bit error rate performance for $N_t = N_r = 4$ using the ZF-IC criterion with and without sorting (for uncoded BPSK). 133
6.7 HBLAST bit error rate performance with various detection criteria for $N_t = N_r = 4$ and BPSK signaling. 134
6.8 SCBLAST bit error rate performance with various detection criteria for $N_t = N_r = 4$ and BPSK signaling. 134
6.9 DBLAST encoder structure. 135
6.10 Illustration of the DBLAST transmission. 135
6.11 DBLAST bit error rate performance with various detection criteria for $N_t = N_r = 4$ and uncoded BPSK. 141
6.12 DBLAST bit error rate performance with various detection criteria for $N_t = N_r = 4$ and uncoded BPSK. 141
6.13 MLSTC encoder structure. 142
6.14 MLSTC bit error rate performance for a 4 × 4 MIMO system employing orthogonal STBCs as component codes with two transmit antennas per group. 146
6.15 Layering in threaded space-time coding. 147
6.16 Iterative multiuser detector for threaded space-time coded MIMO systems. 151
6.17 Illustration of sphere decoding. 154
6.18 Diversity/multiplexing trade-off for the Alamouti scheme and the optimal trade-off curve ($N_r = 2$, coherence time ≥ 3). 156
6.19 Diversity/multiplexing trade-off for the VBLAST scheme (with and without sorting in the detection process) and the optimal trade-off curve. . . 157
7.1 PCCC encoder structure. 163
7.2 A typical SCCC encoder structure. 164
7.3 Rate 1/3 PCCC encoder structure. 170
7.4 PCCC iterative decoder structure. 171

7.5 Rate 1/4 SCCC encoder structure. 173

7.6 SCCC iterative decoder structure. 174

7.7 Illustration of obtaining the SOVA output for bit b_k. 178

7.8 Structure of the MSOVA. 179

7.9 Bit error rate performance of the PCCC system for different code rates and number of decoder iterations over an AWGN channel. The interleaver length used is $N = 4096$. The iterative decoder employs two identical log-APP algorithms. 183

7.10 Bit error rate performance of the PCCC system for different code rates and different number of decoder iterations over an AWGN channel. The interleaver length used is $N = 4096$. The iterative decoder employs two identical SOVA algorithms. A decoding depth of $\delta = 50$ is used. . . . 184

7.11 Bit error rate performance comparison of the SOVA, MSOVA, APP and MAPP decoders in AWGN for the SCCC scheme using a convolutional code with generator polynomials $(5, 7)_{octal}$, a differential encoder for the inner code, overall rate 1/2, and $N = 512$ with eight iterations. 185

7.12 Bit error rate performance comparison of the SOVA, MSOVA, APP and MAPP decoders in AWGN for the PCCC scheme using 16-state RSC encoders, overall rate 4/5, $N = 512$, and eight iterations. 186

7.13 Parallel concatenated space-time turbo code encoder (for two transmit antennas). 188

7.14 Encoder structure for the serial concatenated space-time turbo code. . . 188

7.15 Encoder structure for the serial concatenation of an outer channel code and an inner recursive space-time code. 189

7.16 Encoder structure for the turbo-TCM scheme (Π denotes a symbol interleaver). 189

7.17 Encoder structure for the turbo-coded modulation scheme. 190

7.18 Iterative decoder structure for the turbo-coded modulation scheme. . . . 192

7.19 Bit error rate performance comparison between the TuCM and STTC schemes for $N_t = 2$, $N_r = 1$ with block lengths 1300 and 5200. 194

7.20 Frame error rate performance comparison between iterative demodulation/decoding and iterative decoding only. 195

7.21 Encoder structure for the coded STBC scheme. (Π_1 denotes a bit interleaver whereas Π_2 denotes a symbol interleaver.) 196

7.22 Decoder structure for the coded STBC scheme. 196

7.23 Bit error rate performance for the convolutional coded STBC scheme on an ideally interleaved channel with BPSK modulation for $N_t = 2$ and $N_r = 1, 2, 3$. 202

7.24 Bit error rate performance of the convolutional coded STBC over block fading channels without interleaving. 202

7.25 Bit error performance of a rate 2/3, 4-state TCM coded STBC system on an ideally interleaved channel for $N_t = 2$, $N_r = 1, 2, 3$. 203

7.26 Bit error rate performance comparison between the convolutional coded STBC and uncoded STBC systems with 8-PSK modulation for $N_t = 2$ and $N_r = 1, 3$. Both soft and hard decision decoding are considered. . . 203

8.1 Capacity comparisons of an $N_t = N_r = 8$ MIMO channel for the coherent and noncoherent cases with $T = 16$ and 40. 210
8.2 USTC encoder. 211
8.3 Correlation of the signals defined by (8.20) as a function of $\left|k' - k\right|$ for $T = 6$ and $L = 64$ resulting from picking the first six columns of the 64×64 DFT matrix. 216
8.4 Correlation of the signals defined by (8.20) as a function of $\left|k' - k\right|$ for $T = 6$ and $L = 64$ generated according to (8.23) (with $\boldsymbol{\Omega}$ generated by random selection). 217
8.5 Correlation of the signals defined by (8.20) as a function of $\left|k' - k\right|$ for the $N_t = 3$ case with $T = 6$ and $L = 64$. These signals resulted from picking the first six columns of the 64×64 DFT matrix. 219
8.6 Correlation of the signals defined by (8.20) as a function of $\left|k' - k\right|$ for the $N_t = 3$ case with $T = 6$ and $L = 64$. These signals are generated according to (8.23) (with $\boldsymbol{\Omega}$ generated by random selection). 219
8.7 Bit error rate performance of a USTC with parameters $L = 64$ and $T = 6$ for $N_t = 1, 2, 3$ and $N_r = 1$. 220
8.8 Bit error rate performance comparison between the coherent and noncoherent receivers for a USTC with $L = 64$ and $T = 6$ for $N_r = 1$. . . . 220
8.9 DPSK modulator. 221
8.10 Bit error rate performance comparison between coherent and differential detection for the differential BPSK scheme with $N_t = N_r = 1$. 223
8.11 Bit error rate performance for the DSTC example for the overlap case using coherent and noncoherent detection. 228
8.12 Bit error rate performance for the DSTC example for the non-overlap case using coherent and noncoherent detection. 229
8.13 TC-USTC encoder. 230
8.14 Noncoherent iterative TC-USTC decoder. 230
8.15 Performance of the TC-USTC scheme with various interleaver sizes. . . 232
8.16 Block diagram of the trellis-coded unitary signaling scheme. 233
8.17 Bit error rate performance comparison between TCM coded and uncoded unitary space-time systems with $N_t = 2$ and $N_r = 1$. The signal constellation size for the coded system is $L = 16$ and it is $L = 8$ for the uncoded system, thus achieving a spectral efficiency of $3/8$ bits per channel use. 234
8.18 TC-DSTC encoder. 235
8.19 Differential TC-DSTC detector. 236
8.20 Near-differential TC-DSTC detector. 237
9.1 Information rates with BPSK over ergodic MIMO FS channels with two transmit and two receive antennas. 245
9.2 Gaussian input outage capacity and outage information rates with BPSK modulation for quasi-static MIMO FS channels with two transmit and two receive antennas (10% outage level). 246
9.3 Ergodic BPSK information rates for MIMO FS channels (with two equal average power taps) as a function of $N_t = N_r = n$. 246
9.4 Virtual antenna interpretation of transmission over MIMO FS channels (with $N_t = 2$ and $L = 3$). 249

9.5 Block diagram of space-time trellis coding over a MIMO FS channel. . 251

9.6 Combined code and channel trellis for $(5, 7)_{octal}$ convolutional code over a two-input two-tap FS channel. 252

9.7 Bit error rates of two convolutional codes with BPSK over quasi-static MIMO FS channels (with two transmit and one receive antennas). . . . 253

9.8 Bit error rates of two convolutional codes with BPSK over quasi-static MIMO FS channels (with two transmit antennas and two receive antennas). 254

9.9 Block diagram of the concatenated coding approach. 255

9.10 Bit error rates of $(5, 7)_{octal}$ convolutional code with BPSK concatenated with a three-tap quasi-static MIMO FS channel (with two transmit antennas). 256

9.11 Bit error rates of $(5, 7)_{octal}$ convolutional code with QPSK modulation concatenated with a three-tap quasi-static MIMO FS channel (with two transmit antennas). 256

9.12 Block diagram of a MIMO-DFE. 259

9.13 Illustration of multi-carrier communications in the frequency domain. . 260

9.14 Block diagram of a MIMO-OFDM system. 261

10.1 Effects of CSI estimation on the performance of the Alamouti scheme using QPSK. 272

10.2 Effects of CSI estimation on the performance of an orthogonal space-time block code with BPSK ($N_t = 4$). 273

10.3 Effects of CSI estimation on the performance of an STTC ($N_t = 2$ and $N_r = 1$). 274

10.4 Effects of CSI estimation on the performance of an STTC ($N_t = N_r = 2$). 274

10.5 Ergodic capacity for a two transmit antenna system with spatial channel correlation. For $N_r = 1$, $r = 0, 0.8, 0.95$, and for $N_r = 2$, $r = 0$, 0.5, 0.8, 0.95 are used. 280

10.6 Ergodic capacity of pinhole channel as a function of number of antennas ($N_t = N_r = n$). 280

10.7 Symbol error rate of the Alamouti scheme with channel correlation (for one and two receive antennas). 281

10.8 Space-time trellis code performance with channel correlation (two transmit and one receive antennas). 282

10.9 Space-time trellis code performance with channel correlation (two transmit and two receive antennas). 282

11.1 Generic MIMO system model with antenna selection. 288

11.2 The cumulative distribution function of the capacity for a MIMO channel with $N_t = 3$, $N_r = 5$, and $L_r = 1, 2, 3, 4$ at a signal-to-noise ratio of 20 dB. Exhaustive search is performed to find the best L_r antennas. 291

11.3 The cumulative distribution function of the capacity for a MIMO channel with $N_t = 3$, $N_r = 1, 3, 5$, and $L_r = 1, 3$ at a signal-to-noise ratio of 20 dB. Exhaustive search, where applicable, is performed to find the best L_r antennas. 291

11.4 The cumulative distribution function of the capacity for an $N_t = 3$, $N_r = 5$ MIMO channel at a signal-to-noise ratio of 20 dB with receive antenna selection where selection is performed using the energy-based and capacity-based selection criteria. 293
11.5 Frame error rate performance of the four-state, QPSK STTC presented in Chapter 5 over quasi-static fading for $N_t = 2,\ N_r = 1, 2, 3$ with receive antenna selection where $L_r = 1, 2, 3$. 300
11.6 Frame error rate performance of the STTC considered in Figure 11.5 over fast fading for $N_t = 2,\ N_r = 1, 2, 3$ with receive antenna selection where $L_r = 1, 2, 3$. 301
11.7 Frame error rate performance for the four-state, QPSK STTC in quasi-static fading for $N_t = 2, 4, 6,\ N_r = 1$ with $L_t = 2$. 301
11.8 Bit error rate performance for the Alamouti scheme with receive antenna selection for the cases with $N_r = 3$ and $L_r = 1, 2, 3$. 305
11.9 Bit error rate performance for the Almouti scheme with receive antenna selection for the cases with $N_r = 2, 3$ and $L_r = 1, 2, 3$ along with their exact theoretical results given by (11.36). 305
11.10 Bit error rate performance of the Alamouti scheme with transmit antenna selection for the cases $N_t = 2, 4, 6,\ N_r = 1$ and $L_t = 2$. 306
11.11 Bit error rate performance comparison between various antenna selection scenarios along with their upper bounds (for the convolutional code). . 308
11.12 Bit error rate performance comparison between various antenna selection scenarios along with their upper bounds (for the TCM case). 309
11.13 Bit error rate performance comparison between simulations and the upper bounds for the cases with $N_t = 2$, $N_r = 3$, $L_r = 1$, 3 (for the TCM case). 309
11.14 Frame error rate performance for a coded system with receive antenna selection over frequency selective fading. 310
11.15 Frame error rate performance with receive antenna selection over spatially correlated Rayleigh fading. 313

List of Tables

6.1 The ZF-IC algorithm for the VBLAST/HBLAST/SCBLAST schemes . . 128
6.2 The MMSE-IC algorithm for the VBLAST/HBLAST/SCBLAST schemes 131
6.3 The ZF-IC detection algorithm for the DBLAST scheme 139
6.4 The MMSE-IC detection algorithm for the DBLAST scheme 140
7.1 Values of c and d for various PCCCs and SCCCs for the MSOVA algorithm. 180
11.1 Values of the constant $f(N_t, N_r, L_r)$ for specific values of N_t. 299
11.2 Diversity order of STTCs with antenna selection for various Rayleigh fading channel models 299

Notation

$\approx$	approximately equal to
$\triangleq$	defined as equal to
$\gg$	much greater than
$\ll$	much less than
$\cdot$	multiplication operator
$\arg\max\limits_{x}\left[f(x)\right]$	the value of x that maximizes the function $f(x)$
$\arg\min\limits_{x}\left[f(x)\right]$	the value of x that minimizes the function $f(x)$
$\exp(x)$	exponential of x (i.e., e^x)
$\mathrm{Im}\{x\}$	the imaginary part of x
$\mathrm{Re}\{x\}$	the real part of x
$Q(x)$	Gaussian Q-function $\left(\frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt\right)$
$\mathbb{R}$	the field of all real numbers
$X \sim p_X(x)$	the random variable X has p.d.f. $p_X(x)$
$E\left[X\right]$	the expected value of random variable X
$H(X)$	the entropy of random variable X
$H(Y\|X)$	the conditional entropy of random variable Y given random variable X
$I(X;Y)$	the mutual information between random variables X and Y
$\|x\|$	the absolute value of the complex number x
$\angle x$	the angle of the complex number x
x^*	the conjugate of a scalar or vector quantity
$\boldsymbol{x}$	the vector $\boldsymbol{x}$
$\\|\boldsymbol{x}\\|$	the norm of vector $\boldsymbol{x}$
$\boldsymbol{x}^T$	the transpose of vector $\boldsymbol{x}$
$\boldsymbol{x}^H$	the Hermitian (conjugate transpose) of vector $\boldsymbol{x}$
$\boldsymbol{A}$	the matrix $\boldsymbol{A}$
$\boldsymbol{A}^T$	the transpose of matrix $\boldsymbol{A}$
$\boldsymbol{A}^H$	the Hermitian (conjugate transpose) of matrix $\boldsymbol{A}$
$\boldsymbol{A}^*$	the conjugate of matrix $\boldsymbol{A}$
$\boldsymbol{A}^{-1}$	the inverse of matrix $\boldsymbol{A}$
$\\|\boldsymbol{A}\\|$	the Frobenius norm of the matrix $\boldsymbol{A}$ (i.e., sum of absolute value squares of all the entries of $\boldsymbol{A}$)
$\det(\boldsymbol{A})$	the determinant of matrix $\boldsymbol{A}$
$\mathrm{trace}(\boldsymbol{A})$	the trace of matrix $\boldsymbol{A}$

$\boldsymbol{I}_N$	the $N \times N$ identity matrix
$\mathbf{0}_N$	the $N \times N$ all zero matrix
$\mathbf{0}_{M \times N}$	the $M \times N$ all zero matrix
$diag\,\{a_1, a_2, \ldots, a_N\}$	the diagonal matrix with elements $a_1, a_2, \ldots, a_N$ on the main diagonal
N_t	number of transmit antennas
N_r	number of receive antennas
$h_{i,j}$	channel coefficient between the ith transmit and jth receive antennas
$h^{(l)}(k)$	ISI channel coefficient for the lth tap at time k
$h_{i,j}^{(l)}(k)$	channel coefficient from the ith antenna to the jth antenna at time k for the lth channel tap
$\boldsymbol{H}$	MIMO channel matrix
$\boldsymbol{X}$	transmitted signal
$\boldsymbol{Y}$	received signal
$\boldsymbol{N}$	AWGN noise
ρ	average signal-to-noise ratio at each receive antenna
L	number of intersymbol interference taps
L_r	number of selected antennas at the receiver side
L_t	number of selected antennas at the transmitter side
R_c	code rate
P_b	bit error probability
P_e	probability of error
T	coherence time in number of symbols
N	frame length at each transmit antenna
$\log_x \det[\boldsymbol{A}]$	the log, base x, of the determinant of matrix $\boldsymbol{A}$
$\mathrm{sinc}(x)$	the sinc function $(\sin(\pi x)/\pi x)$
$X \sim \mathcal{CN}(0, 1)$	the random variable X is circularly symmetric complex Gaussian with zero mean and variance $1/2$ in each dimension
W	bandwidth of a signal
$C(f;t)$	time-varying frequency response of a wireless channel
$c(\tau;t)$	impulse response of a wireless channel
T_m	multipath spread
B_D	Doppler spread
B_C	coherence bandwidth
$(\Delta t)_c$	coherence time (in seconds)
$S(\tau;\lambda)$	scattering function

Abbreviations

APP	a posteriori probability
AWGN	additive white Gaussian noise
BP	belief propagation
BICM	bit interleaved coded modulation
BLAST	Bell Laboratories layered space-time
BPSK	binary phase shift keying
BSC	binary symmetric channel
c.d.f.	cumulative distribution function
CSI	channel state information
DBLAST	diagonal Bell Laboratories layered space-time
DFE	decision feedback equalization
DFT	discrete Fourier transform
DPSK	differential phase shift keying
DSTC	differential space-time code
EGC	equal gain combining
EM	expectation maximization
FFT	fast Fourier transform
FS	frequency selective
FSK	frequency shift keying
HBLAST	horizontal Bell Laboratories layered space-time
HDD	hard decision decoding
IFFT	inverse fast Fourier transform
IIR	infinite impulse response
ISI	intersymbol interference
LAPP	log a posteriori probability
LDPC	low density parity check
LLR	log likelihood ratio
LOS	line of sight
LS	least squares
LSTC	layered space-time code
MAP	maximum a posteriori
MAPP	modified a posteriori probability
MIMO	multiple-input multiple-output
MISO	multiple-output single-input
ML	maximum likelihood
MLSD	maximum likelihood sequence detector

MLSTC	multilayered space-time code
MMSE	minimum mean-squared error
MMSE-IC	minimum mean-squared error with interference cancellation
M-PSK	M-ary phase shift keying
MRC	maximum ratio combining
MSOVA	modified soft output Viterbi algorithm
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PAM	pulse amplitude modulation
PCCC	parallel concatenated convolutional code
PEP	pairwise error probability
p.d.f.	probability density function
PSK	phase shift keying
QAM	quadrature amplitude modulation
RF	radio frequency
RSC	recursive systematic convolutional
SC	selection combining
SCBLAST	single code Bell Laboratories layered space-time
SCCC	serial concatenated convolutional code
SDD	soft decision decoding
SISO	soft-input soft-output
SOVA	soft-output Viterbi algorithm
SSC	switch and stay combining
STBC	space-time block code
STC	space-time code
STCM	space-time coded modulation
STTC	space-time trellis code
SVD	singular value decomposition
TC-DSTC	turbo coded differential space-time code
TC-USTC	turbo-coded unitary space-time code
TCM	trellis-coded modulation
TDMA	time-division multiple access
TSTC	threaded space-time code
TuCM	turbo-coded modulation
USTC	unitary space-time code
VA	Viterbi algorithm
VBLAST	vertical Bell Laboratories layered space-time
ZF	zero forcing
ZF-IC	zero forcing with interference cancelation