

# Contents

<b>Preface</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Communication Systems . . . . .	1
1.2 Information Theory . . . . .	3
1.2.1 Entropy . . . . .	3
1.2.2 Channel Capacity . . . . .	4
1.2.3 Binary Symmetric Channel . . . . .	5
1.2.4 AWGN Channel . . . . .	6
1.3 A Simple Channel Code . . . . .	8
<b>2 Algebraic Coding Theory</b>	<b>13</b>
2.1 Fundamentals of Block Codes . . . . .	14
2.1.1 Code Parameters . . . . .	16
2.1.2 Maximum Likelihood Decoding . . . . .	19
2.1.3 Binary Symmetric Channel . . . . .	23
2.1.4 Error Detection and Error Correction . . . . .	25
2.2 Linear Block Codes . . . . .	27
2.2.1 Definition of Linear Block Codes . . . . .	27
2.2.2 Generator Matrix . . . . .	27
2.2.3 Parity-Check Matrix . . . . .	30
2.2.4 Syndrome and Cosets . . . . .	31
2.2.5 Dual Code . . . . .	36
2.2.6 Bounds for Linear Block Codes . . . . .	37
2.2.7 Code Constructions . . . . .	41
2.2.8 Examples of Linear Block Codes . . . . .	46
2.3 Cyclic Codes . . . . .	62
2.3.1 Definition of Cyclic Codes . . . . .	62
2.3.2 Generator Polynomial . . . . .	63
2.3.3 Parity-Check Polynomial . . . . .	67
2.3.4 Dual Codes . . . . .	70
2.3.5 Linear Feedback Shift Registers . . . . .	71
2.3.6 BCH Codes . . . . .	74
2.3.7 Reed–Solomon Codes . . . . .	81

2.3.8	Algebraic Decoding Algorithm . . . . .	84
2.4	Summary . . . . .	93
<b>3</b>	<b>Convolutional Codes</b>	<b>97</b>
3.1	Encoding of Convolutional Codes . . . . .	98
3.1.1	Convolutional Encoder . . . . .	98
3.1.2	Generator Matrix in the Time Domain . . . . .	101
3.1.3	State Diagram of a Convolutional Encoder . . . . .	103
3.1.4	Code Termination . . . . .	104
3.1.5	Puncturing . . . . .	106
3.1.6	Generator Matrix in the $D$ -Domain . . . . .	108
3.1.7	Encoder Properties . . . . .	110
3.2	Trellis Diagram and the Viterbi Algorithm . . . . .	112
3.2.1	Minimum Distance Decoding . . . . .	113
3.2.2	Trellises . . . . .	115
3.2.3	Viterbi Algorithm . . . . .	116
3.3	Distance Properties and Error Bounds . . . . .	121
3.3.1	Free Distance . . . . .	121
3.3.2	Active Distances . . . . .	122
3.3.3	Weight Enumerators for Terminated Codes . . . . .	126
3.3.4	Path Enumerators . . . . .	129
3.3.5	Pairwise Error Probability . . . . .	131
3.3.6	Viterbi Bound . . . . .	134
3.4	Soft-input Decoding . . . . .	136
3.4.1	Euclidean Metric . . . . .	136
3.4.2	Support of Punctured Codes . . . . .	137
3.4.3	Implementation Issues . . . . .	138
3.5	Soft-output Decoding . . . . .	140
3.5.1	Derivation of APP Decoding . . . . .	141
3.5.2	APP Decoding in the Log Domain . . . . .	145
3.6	Convolutional Coding in Mobile Communications . . . . .	147
3.6.1	Coding of Speech Data . . . . .	147
3.6.2	Hybrid ARQ . . . . .	150
3.6.3	EGPRS Modulation and Coding . . . . .	152
3.6.4	Retransmission Mechanism . . . . .	155
3.6.5	Link Adaptation . . . . .	156
3.6.6	Incremental Redundancy . . . . .	157
3.7	Summary . . . . .	160
<b>4</b>	<b>Turbo Codes</b>	<b>163</b>
4.1	LDPC Codes . . . . .	165
4.1.1	Codes Based on Sparse Graphs . . . . .	165
4.1.2	Decoding for the Binary Erasure Channel . . . . .	168
4.1.3	Log-Likelihood Algebra . . . . .	169
4.1.4	Belief Propagation . . . . .	174
4.2	A First Encounter with Code Concatenation . . . . .	177
4.2.1	Product Codes . . . . .	177

4.2.2	Iterative Decoding of Product Codes . . . . .	180
4.3	Concatenated Convolutional Codes . . . . .	182
4.3.1	Parallel Concatenation . . . . .	182
4.3.2	The UMTS Turbo Code . . . . .	183
4.3.3	Serial Concatenation . . . . .	184
4.3.4	Partial Concatenation . . . . .	185
4.3.5	Turbo Decoding . . . . .	186
4.4	EXIT Charts . . . . .	188
4.4.1	Calculating an EXIT Chart . . . . .	189
4.4.2	Interpretation . . . . .	191
4.5	Weight Distribution . . . . .	196
4.5.1	Partial Weights . . . . .	196
4.5.2	Expected Weight Distribution . . . . .	197
4.6	Woven Convolutional Codes . . . . .	198
4.6.1	Encoding Schemes . . . . .	200
4.6.2	Distance Properties of Woven Codes . . . . .	202
4.6.3	Woven Turbo Codes . . . . .	205
4.6.4	Interleaver Design . . . . .	208
4.7	Summary . . . . .	212
<b>5</b>	<b>Space–Time Codes</b>	<b>215</b>
5.1	Introduction . . . . .	215
5.1.1	Digital Modulation Schemes . . . . .	216
5.1.2	Diversity . . . . .	223
5.2	Spatial Channels . . . . .	229
5.2.1	Basic Description . . . . .	229
5.2.2	Spatial Channel Models . . . . .	234
5.2.3	Channel Estimation . . . . .	239
5.3	Performance Measures . . . . .	241
5.3.1	Channel Capacity . . . . .	241
5.3.2	Outage Probability and Outage Capacity . . . . .	250
5.3.3	Ergodic Error Probability . . . . .	252
5.4	Orthogonal Space–Time Block Codes . . . . .	257
5.4.1	Alamouti’s Scheme . . . . .	257
5.4.2	Extension to More than Two Transmit Antennas . . . . .	260
5.4.3	Simulation Results . . . . .	263
5.5	Spatial Multiplexing . . . . .	265
5.5.1	General Concept . . . . .	265
5.5.2	Iterative APP Preprocessing and Per-layer Decoding . . . . .	267
5.5.3	Linear Multilayer Detection . . . . .	272
5.5.4	Original BLAST Detection . . . . .	275
5.5.5	QL Decomposition and Interference Cancellation . . . . .	278
5.5.6	Performance of Multi-Layer Detection Schemes . . . . .	287
5.5.7	Unified Description by Linear Dispersion Codes . . . . .	291
5.6	Summary . . . . .	294

<b>A Algebraic Structures</b>	<b>295</b>
A.1 Groups, Rings and Finite Fields . . . . .	295
A.1.1 Groups . . . . .	295
A.1.2 Rings . . . . .	296
A.1.3 Finite Fields . . . . .	298
A.2 Vector Spaces . . . . .	299
A.3 Polynomials and Extension Fields . . . . .	300
A.4 Discrete Fourier Transform . . . . .	305
<b>B Linear Algebra</b>	<b>311</b>
<b>C Acronyms</b>	<b>319</b>
<b>Bibliography</b>	<b>325</b>
<b>Index</b>	<b>335</b>