



universal personal communications

Mohinder Jankiraman

space-time codes and **MIMO** systems

$$= \frac{E_{ss}}{M} I_{M_T} C = \sum_i \log_2 ($$



CD-ROM
INCLUDED

Contents

Preface	<i>xiii</i>
Acknowledgments	<i>xv</i>
CHAPTER 1	
Introduction	1
1.1 The Crowded Spectrum	1
1.2 Need for High Data Rates	1
1.3 Multiple-Input Multiple-Output Systems	6
1.4 Internet Protocol	8
1.4.1 Routing Operations	8
1.4.2 The Transmission Control Protocol	8
1.5 Wireless Internet Protocol	11
References	12
CHAPTER 2	
The MIMO Wireless Channel	15
2.1 Introduction	15
2.2 Preliminaries	15
2.2.1 Multiantenna Systems	15
2.2.2 Array Gain	15
2.2.3 Diversity Gain	16
2.2.4 Data Pipes	18
2.2.5 Spatial Multiplexing	19
2.2.6 Additional Terms	19
2.3 MIMO System Model	20
2.4 MIMO System Capacity	22
2.5 Channel Unknown to the Transmitter	23
2.6 Channel Known to the Transmitter	24
2.6.1 Water-Pouring Principle	24
2.6.2 Capacity When Channel Is Known to the Transmitter	26
2.7 Deterministic Channels	27
2.7.1 SIMO Channel Capacity	27
2.7.2 MISO Channel Capacity	28

2.8	Random Channels	29
2.8.1	Ergodic Capacity	30
2.8.2	Outage Capacity	31
2.9	Influence of Fading Correlation on MIMO Capacity	32
2.10	Influence of LOS on MIMO Capacity	35
2.11	Influence of XPD on MIMO Capacity	38
2.12	Keyhole Effect: Degenerate Channels	39
2.13	Capacity of Frequency Selective MIMO Channels	42
2.13.1	Channel Unknown to the Transmitter	43
2.13.2	Channel Known to the Transmitter	44
	References	45

CHAPTER 3

	Channel Propagation, Fading, and Link Budget Analysis	47
3.1	Introduction	47
3.2	Radio Wave Propagation	47
3.2.1	Reflection	47
3.2.2	Diffraction	48
3.2.3	Scattering	48
3.3	Large-Scale Fading or Macroscopic Fading	50
3.3.1	Free-Space Propagation Model	50
3.3.2	Outdoor Propagation Models	53
3.4	Small-Scale Fading	57
3.4.1	Microscopic Fading	58
3.5	Microscopic Fading Measurements	65
3.5.1	Direct Pulse Measurements	66
3.5.2	Spread-Spectrum Sliding Correlator Channel Sounding	66
3.5.3	Frequency Domain Channel Sounding	68
3.6	Antenna Diversity	69
3.6.1	Diversity Combining Methods	69
3.6.2	MIMO Channels	73
	References	73

CHAPTER 4

	Space-Time Block Coding	75
4.1	Introduction	75
4.2	Delay Diversity Scheme	75
4.3	Alamouti Space-Time Code	76
4.3.1	Maximum Likelihood Decoding	78
4.3.2	Maximum Ratio Combining	78
4.3.3	Transmit Diversity	79
4.3.4	Summary of Alamouti's Scheme	80
4.4	Space-Time Block Codes	80
4.4.1	STBC for Real Signal Constellations	82
4.4.2	STBC for Complex Signal Constellations	84

4.5	Decoding of STBC	86
4.6	Simulation Results	88
4.7	Imperfect Channel Estimation: A Performance Analysis	92
4.7.1	Least Squares Estimation	93
4.7.2	Minimum Mean Squares Estimation	94
4.7.3	Channel Estimation Algorithm Using the FFT Method	95
4.8	Effect of Antenna Correlation on Performance	97
4.9	Dominant Eigenmode Transmission	98
4.10	Capacity of OSTBC Channels	100
4.11	Simulation Exercises	101
	References	101

CHAPTER 5

	Space-Time Trellis Codes	103
5.1	Introduction	103
5.2	Space-Time Coded Systems	103
5.3	Space-Time Code Word Design Criteria	105
5.4	Design of Space-Time Trellis Codes on Slow Fading Channels	107
5.4.1	Error Probability on Slow Fading Channels	107
5.4.2	Design Criteria for Slow Rayleigh Fading STTCs	109
5.4.3	Encoding/Decoding of STTCs for Quasi-Static Flat Fading Channels	113
5.4.4	Code Construction for Quasi-Static Flat Fading Channels	116
5.4.5	Example Using 4-PSK	117
5.5	Design of Space-Time Trellis Codes on Fast Fading Channels	121
5.5.1	Error Probability on Fast Fading Channels	121
5.6	Performance Analysis in a Slow Fading Channel	126
5.7	Performance Analysis in a Fast Fading Channel	128
5.8	The Effect of Imperfect Channel Estimation on Code Performance	128
5.9	Effect of Antenna Correlation on Performance	130
5.10	Delay Diversity as an STTC	130
5.11	Comparison of STBC and STTC	131
5.12	Simulation Exercises	134
	References	135

CHAPTER 6

	Layered Space-Time Codes	137
6.1	Introduction	137
6.2	LST Transmitters: Types of Encoding	137
6.2.1	Horizontal Encoding	137
6.2.2	Vertical Encoding	144
6.3	Layered Space-Time Coding: Design Criteria	148
6.3.1	Performance Analysis of an HLST System	149
6.3.2	Performance Analysis of a DLST System	152
6.3.3	Code Design Criteria	154

6.4	LST Receivers	157
6.4.1	ML Receiver	157
6.4.2	Zero-Forcing Receiver	157
6.4.3	MMSE Receiver	158
6.4.4	Successive Cancellation Receiver	158
6.4.5	Zero Forcing V-BLAST Receiver	159
6.4.6	MMSE V-BLAST Receiver	159
6.4.7	Simulation Results	160
6.4.8	Receivers for HLST and DLST Systems	161
6.5	Iterative Receivers	161
6.6	The Effect of Imperfect Channel Estimation on Code Performance	162
6.7	Effect of Antenna Correlation on Performance	162
6.8	Diversity Performance of SM Receivers	162
6.9	Summary	163
6.10	Simulation Exercises	164
	References	164

CHAPTER 7

	Orthogonal Frequency Division Multiplexing	165
7.1	Introduction	165
7.2	Basic Principles	165
7.2.1	Data Transmission over Multipath Channels	165
7.2.2	Single Carrier Approach	165
7.2.3	Multicarrier Approach	167
7.3	OFDM	167
7.4	OFDM Generation	168
7.5	Synchronization Issues	171
7.5.1	Symbol Time and Frequency Carrier Offset Derivation	171
7.6	Survey of Synchronization Techniques	178
7.6.1	Symbol Synchronization	178
7.7	Frequency Offset Estimation	189
7.8	Carrier Synchronization	190
7.8.1	Pilots	191
7.8.2	Cyclic Prefix	191
7.9	Sampling-Frequency Synchronization	191
7.10	Performance Analysis of Synchronization Techniques	192
7.10.1	Symbol Synchronization	192
7.11	ML Estimation of Timing and Frequency Offset	193
7.11.1	The Correlation Algorithm Using the Guard Interval	194
7.12	Carrier Synchronization	195
7.12.1	Pilots	195
7.13	Sampling-Frequency Synchronization	198
7.14	Observations	198
7.15	Suggested Solution to the Synchronization Problem	199
7.16	Channel Estimation	200
7.17	Peak to Average Power Ratio	200
7.17.1	Schemes for Reduction of PAPR	201

7.18 Application to Packet Transmission Systems	206
7.19 Conclusions	206
7.20 Simulation Exercises	207
References	207

CHAPTER 8

IEEE 802.11a Packet Transmission System	209
8.1 Introduction	209
8.2 Background	210
8.3 Wireless LAN Topology	210
8.4 IEEE 802.11 Standard Family	211
8.4.1 802.11	211
8.4.2 802.11b	211
8.4.3 802.11a	212
8.4.4 Others	212
8.5 WLAN Protocol Layer Architecture	212
8.6 Medium Access Control	213
8.6.1 IEEE 802.11 MAC Layer	213
8.7 Physical Layer	215
8.7.1 Frequency Hopping Spread Spectrum	216
8.7.2 Direct Sequence Spread Spectrum	216
8.7.3 Orthogonal Frequency Division Multiplexing and 5-GHz WLAN Physical Layer	217
8.8 Synchronization and Packet Detection Algorithms	224
8.8.1 Packet Detection	224
8.8.2 Symbol Timing	226
8.8.3 Sampling Clock Frequency Error	227
8.8.4 Carrier Frequency Synchronization	229
8.8.5 Carrier Phase Tracking	232
8.9 Channel Estimation	233
References	234

CHAPTER 9

Space-Time Coding for Broadband Channel	237
9.1 Introduction	237
9.2 Performance of Space-Time Coding on Frequency-Selective Fading Channels	237
9.3 Space-Time Coding in Wideband OFDM Systems	239
9.4 Capacity of MIMO-OFDM Systems	240
9.4.1 Assumptions	242
9.4.2 Mutual Information	244
9.4.3 Ergodic Capacity and Outage Capacity	246
9.4.4 Influence of Channel and System Parameters on Capacity	247
9.4.5 Simulations	251
9.4.6 Summary	254

9.5	Performance Analysis of MIMO-OFDM Systems	254
9.5.1	Analysis	260
9.6	CDMA-OFDM-MIMO	260
9.6.1	Introduction	260
9.6.2	Overall System Concept	262
9.6.3	Comparison with MC-CDMA	267
9.6.4	Interfacing with MIMO	272
9.7	Simulation Exercises	272
	References	272

CHAPTER 10

	The Way Ahead	275
10.1	Introduction	275
10.2	MIMO Multiuser	275
10.2.1	Capacity in the Uplink	276
10.3	Linear Dispersion Coding	280
10.3.1	Hassibi and Hochwald Method	281
10.3.2	Method of Heath and Paulraj	288
10.4	Conclusion	292
	References	292

APPENDIX A

	Wideband Simulator: Description and Explanatory Notes	295
A.1	Introduction	295
A.2	Files Listing	295
A.3	SISO Mode	297
A.4	SIMO Mode	300
A.5	MISO/MIMO Mode	301
A.6	V-BLAST Mode	302
	Reference	303

APPENDIX B

	Narrowband Simulator	305
B.1	Introduction	305
B.2	Description	305
	List of Acronyms	307
	List of Symbols	311
	About the Author	313
	Index	315