
*Space–Time Coding
for Broadband Wireless
Communications*

**GEORGIOS B. GIANNAKIS
ZHIQIANG LIU
XIAOLI MA
SHENGLI ZHOU**



**WILEY-
INTERSCIENCE**

A JOHN WILEY & SONS, INC., PUBLICATION

Contents

<i>Preface</i>	<i>xv</i>
<i>Acronyms</i>	<i>xix</i>
<i>1 Motivation and Context</i>	<i>1</i>
1.1 <i>Evolution of Wireless Communication Systems</i>	<i>2</i>
1.2 <i>Wireless Propagation Effects</i>	<i>3</i>
1.3 <i>Parameters and Classification of Wireless Channels</i>	<i>5</i>
1.3.1 <i>Delay Spread and Coherence Bandwidth</i>	<i>6</i>
1.3.2 <i>Doppler Spread and Coherence Time</i>	<i>7</i>
1.4 <i>Providing, Enabling, and Collecting Diversity</i>	<i>11</i>
1.4.1 <i>Diversity Provided by Frequency-Selective Channels</i>	<i>11</i>
1.4.2 <i>Diversity Provided by Time-Selective Channels</i>	<i>13</i>
1.4.3 <i>Diversity Provided by Multi-Antenna Channels</i>	<i>15</i>
1.5 <i>Chapter-by-Chapter Organization</i>	<i>18</i>
<i>2 Fundamentals of ST Wireless Communications</i>	<i>23</i>
2.1 <i>Generic ST System Model</i>	<i>23</i>
2.2 <i>ST Coding viz Channel Coding</i>	<i>27</i>
2.3 <i>Capacity of ST Channels</i>	<i>29</i>
2.3.1 <i>Outage Capacity</i>	<i>30</i>

2.3.2	<i>Ergodic Capacity</i>	34
2.4	<i>Error Performance of ST Coding</i>	39
2.5	<i>Design Criteria for ST Codes</i>	43
2.6	<i>Diversity and Rate: Finite SNR viz Asymptotics</i>	44
2.7	<i>Classification of ST Codes</i>	48
2.8	<i>Closing Comments</i>	50
3	<i>Coherent ST Codes for Flat Fading Channels</i>	51
3.1	<i>Delay Diversity ST Codes</i>	51
3.2	<i>ST Trellis Codes</i>	53
3.2.1	<i>Trellis Representation</i>	53
3.2.2	<i>TSC ST Trellis Codes</i>	55
3.2.3	<i>BBH ST Trellis Codes</i>	56
3.2.4	<i>GFK ST Trellis Codes</i>	58
3.2.5	<i>Viterbi Decoding of ST Trellis Codes</i>	60
3.3	<i>Orthogonal ST Block Codes</i>	61
3.3.1	<i>Encoding of OSTBCs</i>	61
3.3.2	<i>Linear ML Decoding of OSTBCs</i>	63
3.3.3	<i>BER Performance with OSTBCs</i>	65
3.3.4	<i>Channel Capacity with OSTBCs</i>	66
3.4	<i>Quasi-Orthogonal ST Block Codes</i>	68
3.5	<i>ST Linear Complex Field Codes</i>	70
3.5.1	<i>Antenna Switching and Linear Precoding</i>	71
3.5.2	<i>Designing Linear Precoding Matrices</i>	72
3.5.3	<i>Upper Bound on Coding Gain</i>	72
3.5.4	<i>Construction Based on Parameterization</i>	73
3.5.5	<i>Construction Based on Algebraic Tools</i>	74
3.5.6	<i>Decoding ST Linear Complex Field Codes</i>	76
3.5.7	<i>Modulus-Preserving STLCFC</i>	79
3.6	<i>Linking OSTBC, QO-STBC, and STLCFC Designs</i>	82
3.6.1	<i>Embedding MP-STLCFCs into the Alamouti Code</i>	82
3.6.2	<i>Embedding 2×2 MP-STLCFCs into an OSTBC</i>	83
3.6.3	<i>Decoding QO-MP-STLCFC</i>	84
3.7	<i>Closing Comments</i>	85
4	<i>Layered ST Codes</i>	87
4.1	<i>BLAST Designs</i>	88
4.1.1	<i>D-BLAST</i>	88

4.1.2	<i>V-BLAST</i>	91
4.1.3	<i>Rate Performance with BLAST Codes</i>	92
4.2	<i>ST Codes Trading Diversity for Rate</i>	93
4.2.1	<i>Layered ST Codes with Antenna Grouping</i>	93
4.2.2	<i>Layered High-Rate Codes</i>	94
4.3	<i>Full-Diversity Full-Rate ST Codes</i>	94
4.3.1	<i>FDFR Transceiver</i>	95
4.3.2	<i>Algebraic FDFR Code Design</i>	98
4.3.3	<i>Mutual Information Analysis</i>	99
4.3.4	<i>Diversity-Rate-Performance Trade-offs</i>	99
4.4	<i>Numerical Examples</i>	101
4.5	<i>Closing Comments</i>	104
5	<i>Sphere Decoding and (Near-)Optimal MIMO Demodulation</i>	105
5.1	<i>Sphere Decoding Algorithm</i>	106
5.1.1	<i>Selecting a Finite Search Radius</i>	108
5.1.2	<i>Initializing with Unconstrained LS</i>	109
5.1.3	<i>Searching Within the Fixed-Radius Sphere</i>	110
5.2	<i>Average Complexity of The SDA in Practice</i>	113
5.3	<i>SDA Improvements</i>	117
5.3.1	<i>SDA with Detection Ordering and Nulling-Canceling</i>	117
5.3.2	<i>Schnorr-Euchner Variate of the SDA</i>	118
5.3.3	<i>SDA with Increasing Radius Search</i>	119
5.3.4	<i>Simulated Comparisons</i>	120
5.4	<i>Reduced-Complexity IRS-SDA</i>	123
5.5	<i>Soft-Decision Sphere Decoding</i>	125
5.5.1	<i>List Sphere Decoding</i>	126
5.5.2	<i>Soft SDA Using Hard SDAs</i>	127
5.6	<i>Closing Comments</i>	129
6	<i>Noncoherent and Differential ST Codes for Flat Fading Channels</i>	133
6.1	<i>Noncoherent ST Codes</i>	133
6.1.1	<i>Search-Based Designs</i>	135
6.1.2	<i>Training-Based Designs</i>	138
6.2	<i>Differential ST Codes</i>	139
6.2.1	<i>Scalar Differential Codes</i>	140
6.2.2	<i>Differential Unitary ST Codes</i>	141

6.2.3	<i>Differential Alamouti Codes</i>	144
6.2.4	<i>Differential OSTBCs</i>	147
6.2.5	<i>Cayley Differential Unitary ST Codes</i>	148
6.3	<i>Closing Comments</i>	150
7	<i>ST Codes for Frequency-Selective Fading Channels: Single-Carrier Systems</i>	151
7.1	<i>System Model and Performance Limits</i>	152
7.1.1	<i>Flat Fading Equivalence and Diversity</i>	153
7.1.2	<i>Rate Outage Probability</i>	154
7.2	<i>ST Trellis Codes</i>	156
7.2.1	<i>Generalized Delay Diversity</i>	156
7.2.2	<i>Search-Based STTC Construction</i>	158
7.3	<i>ST Block Codes</i>	161
7.3.1	<i>Block Coding with Two Transmit-Antennas</i>	161
7.3.2	<i>Receiver Processing</i>	164
7.3.3	<i>ML Decoding Based on the Viterbi Algorithm</i>	167
7.3.4	<i>Turbo Equalization</i>	168
7.3.5	<i>Multi-Antenna Extensions</i>	169
7.3.6	<i>OSTBC Properties</i>	172
7.3.7	<i>Numerical Examples</i>	174
7.4	<i>Closing Comments</i>	177
8	<i>ST Codes for Frequency-Selective Channels: Multi-Carrier Systems</i>	179
8.1	<i>General MIMO OFDM Framework</i>	180
8.1.1	<i>OFDM Basics</i>	180
8.1.2	<i>MIMO OFDM</i>	183
8.1.3	<i>STF Framework</i>	184
8.2	<i>ST and SF Coded MIMO OFDM</i>	188
8.3	<i>STF Coded OFDM</i>	189
8.3.1	<i>Subcarrier Grouping</i>	189
8.3.2	<i>GSTF Block Codes</i>	190
8.3.3	<i>GSTF Trellis Codes</i>	192
8.3.4	<i>Numerical Examples</i>	195
8.4	<i>Digital-Phase Sweeping and Block Circular Delay</i>	197
8.5	<i>Full-Diversity Full-Rate MIMO OFDM</i>	201
8.5.1	<i>Encoders and Decoders</i>	201
8.5.2	<i>Diversity and Rate Analysis</i>	203

8.5.3	<i>Numerical Examples</i>	205
8.6	<i>Closing Comments</i>	206
9	<i>ST Codes for Time-Varying Channels</i>	209
9.1	<i>Time-Varying Channels</i>	210
9.1.1	<i>Channel Models</i>	211
9.1.2	<i>Time-Frequency Duality</i>	214
9.1.3	<i>Doppler Diversity</i>	215
9.2	<i>Space-Time-Doppler Block Codes</i>	216
9.2.1	<i>Duality-Based STDO Codes</i>	219
9.2.2	<i>Phase Sweeping Design</i>	222
9.3	<i>Space-Time-Doppler FDFR Codes</i>	227
9.4	<i>Space-Time-Doppler Trellis Codes</i>	227
9.4.1	<i>Design Criterion</i>	228
9.4.2	<i>Smart-Greedy Codes</i>	229
9.5	<i>Numerical Examples</i>	229
9.6	<i>Space-Time-Doppler Differential Codes</i>	231
9.6.1	<i>Inner Codec</i>	233
9.6.2	<i>Outer Differential Codec</i>	234
9.7	<i>ST Codes for Doubly Selective Channels</i>	235
9.7.1	<i>Numerical Examples</i>	237
9.8	<i>Closing Comments</i>	239
10	<i>Joint Galois- and Linear Complex-Field ST Codes</i>	241
10.1	<i>GF-LCF ST Codes</i>	242
10.1.1	<i>Separate Versus Joint GF-LCF ST Coding</i>	243
10.1.2	<i>Performance Analysis</i>	245
10.1.3	<i>Turbo Decoding</i>	248
10.2	<i>GF-LCF Layered ST Codes</i>	251
10.2.1	<i>GF-LCF ST FDFR Codes: QPSK Signaling</i>	251
10.2.2	<i>GF-LCF ST FDFR Codes: QAM Signaling</i>	253
10.2.3	<i>Performance Analysis</i>	256
10.2.4	<i>GF-LCF FDFR Versus GF-Coded V-BLAST</i>	259
10.2.5	<i>Numerical Examples</i>	260
10.3	<i>GF-LCF Coded MIMO OFDM</i>	263
10.3.1	<i>Joint GF-LCF Coding and Decoding</i>	263
10.3.2	<i>Numerical Examples</i>	265
10.4	<i>Closing Comments</i>	265

11	<i>MIMO Channel Estimation and Synchronization</i>	269
11.1	<i>Preamble-Based Channel Estimation</i>	270
11.2	<i>Optimal Training-Based Channel Estimation</i>	271
11.2.1	<i>ZP-Based Block Transmissions</i>	274
11.2.2	<i>CP-Based Block Transmissions</i>	283
11.2.3	<i>Special Cases</i>	288
11.2.4	<i>Numerical Examples</i>	290
11.3	<i>(Semi-)Blind Channel Estimation</i>	293
11.4	<i>Joint Symbol Detection and Channel Estimation</i>	294
11.4.1	<i>Decision-Directed Methods</i>	294
11.4.2	<i>Kalman Filtering-Based Methods</i>	295
11.5	<i>Carrier Synchronization</i>	299
11.5.1	<i>Hopping Pilot-Based CFO Estimation</i>	300
11.5.2	<i>Blind CFO Estimation</i>	305
11.5.3	<i>Numerical Examples</i>	307
11.6	<i>Closing Comments</i>	310
12	<i>ST Codes with Partial Channel Knowledge: Statistical CSI</i>	313
12.1	<i>Partial CSI Models</i>	315
12.1.1	<i>Statistical CSI</i>	315
12.2	<i>ST Spreading</i>	319
12.2.1	<i>Average Error Performance</i>	321
12.2.2	<i>Optimization Based on Average SER Bound</i>	323
12.2.3	<i>Mean Feedback</i>	324
12.2.4	<i>Covariance Feedback</i>	328
12.2.5	<i>Beamforming Interpretation</i>	330
12.3	<i>Combining OSTBC with Beamforming</i>	331
12.3.1	<i>Two-Dimensional Coder-Beamformer</i>	333
12.4	<i>Numerical Examples</i>	335
12.4.1	<i>Performance with Mean Feedback</i>	335
12.4.2	<i>Performance with Covariance Feedback</i>	339
12.5	<i>Adaptive Modulation for Rate Improvement</i>	344
12.5.1	<i>Numerical Examples</i>	347
12.6	<i>Optimizing Average Capacity</i>	350
12.7	<i>Closing Comments</i>	351
13	<i>ST Codes with Partial Channel Knowledge: Finite-Rate CSI</i>	353
13.1	<i>General Problem Formulation</i>	354

13.2	<i>Finite-Rate Beamforming</i>	356
13.2.1	<i>Beamformer Selection</i>	357
13.2.2	<i>Beamformer Codebook Design</i>	357
13.2.3	<i>Quantifying the Power Loss</i>	362
13.2.4	<i>Numerical Examples</i>	364
13.3	<i>Finite-Rate Precoded Spatial Multiplexing</i>	366
13.3.1	<i>Precoder Selection Criteria</i>	367
13.3.2	<i>Codebook Construction: Infinite Rate</i>	369
13.3.3	<i>Codebook Construction: Finite Rate</i>	371
13.3.4	<i>Numerical Examples</i>	374
13.4	<i>Finite-Rate Precoded OSTBC</i>	380
13.4.1	<i>Precoder Selection Criterion</i>	381
13.4.2	<i>Codebook Construction: Infinite Rate</i>	381
13.4.3	<i>Codebook Construction: Finite Rate</i>	382
13.4.4	<i>Numerical Examples</i>	382
13.5	<i>Capacity Optimization with Finite-Rate Feedback</i>	383
13.5.1	<i>Selection Criterion</i>	383
13.5.2	<i>Codebook Design</i>	384
13.6	<i>Combining Adaptive Modulation with Beamforming</i>	385
13.6.1	<i>Mode Selection</i>	386
13.6.2	<i>Codebook Design</i>	386
13.7	<i>Finite-Rate Feedback in MIMO OFDM</i>	387
13.8	<i>Closing Comments</i>	388
14	<i>ST Codes in the Presence of Interference</i>	391
14.1	<i>ST Spreading</i>	392
14.1.1	<i>Maximizing the Average SINR</i>	393
14.1.2	<i>Minimizing the Average Error Bound</i>	394
14.2	<i>Combining STS with OSTBC</i>	396
14.2.1	<i>Low-Complexity Receivers</i>	399
14.3	<i>Optimal Training with Interference</i>	399
14.3.1	<i>LS Channel Estimation</i>	400
14.3.2	<i>LMMSE Channel Estimation</i>	401
14.4	<i>Numerical Examples</i>	401
14.5	<i>Closing Comments</i>	408
15	<i>ST Codes for Orthogonal Multiple Access</i>	409
15.1	<i>System Model</i>	410

15.1.1	<i>Synchronous Downlink</i>	410
15.1.2	<i>Quasi-synchronous Uplink</i>	411
15.2	<i>Single-Carrier Systems: OSTBC-CIBS-CDMA</i>	413
15.2.1	<i>CIBS-CDMA for User Separation</i>	413
15.2.2	<i>OSTBC Encoding and Decoding</i>	417
15.2.3	<i>Attractive Features of OSTBC-CIBS-CDMA</i>	418
15.2.4	<i>Numerical Examples</i>	421
15.3	<i>Multi-Carrier Systems: STF-OFDMA</i>	425
15.3.1	<i>OFDMA for User Separation</i>	425
15.3.2	<i>STF Block Codes</i>	426
15.3.3	<i>Attractive Features of STF-OFDMA</i>	426
15.3.4	<i>Numerical Examples</i>	428
15.4	<i>Closing Comments</i>	431
	<i>References</i>	433
	<i>Index</i>	461