

Contents

Preface

xvii

Acknowledgments

xxi

1	Introduction	1
1.1	Linear Filters	1
1.2	Adaptive Filters	2
1.3	Adaptive Filter Structures	3
1.4	Adaptation Approaches	7
1.4.1	<i>Approach Based on Wiener Filter Theory</i>	7
1.4.2	<i>Method of Least-Squares</i>	8
1.5	Real and Complex Forms of Adaptive Filters	9
1.6	Applications	9
1.6.1	<i>Modeling</i>	9
1.6.2	<i>Inverse Modeling</i>	11
1.6.3	<i>Linear Prediction</i>	15
1.6.4	<i>Interference Cancellation</i>	20
2	Discrete-Time Signals and Systems	28
2.1	Sequences and z -Transform	28
2.2	Parseval's Relation	32
2.3	System Function	33
2.4	Stochastic Processes	35
2.4.1	<i>Stochastic Averages</i>	35
2.4.2	<i>z-Transform Representations</i>	37
2.4.3	<i>The Power Spectral Density</i>	38
2.4.4	<i>Response of Linear Systems to Stochastic Processes</i>	41
2.4.5	<i>Ergodicity and Time Averages</i>	44
	Problems	44
3	Wiener Filters	48
3.1	Mean-Squared Error Criterion	48
3.2	Wiener Filter – Transversal, Real-Valued Case	50

3.3	Principle of Orthogonality	55
3.4	Normalized Performance Function	57
3.5	Extension to Complex-Valued Case	58
3.6	Unconstrained Wiener Filters	61
3.6.1	<i>Performance Function</i>	61
3.6.2	<i>Optimum Transfer Function</i>	64
3.6.3	<i>Modeling</i>	66
3.6.4	<i>Inverse Modeling</i>	69
3.6.5	<i>Noise Cancellation</i>	74
3.7	Summary and Discussion	79
	Problems	80
4	Eigenanalysis and Performance Surface	90
4.1	Eigenvalues and Eigenvectors	90
4.2	Properties of Eigenvalues and Eigenvectors	91
4.3	Performance Surface	104
	Problems	112
5	Search Methods	119
5.1	Method of Steepest Descent	120
5.2	Learning Curve	126
5.3	Effect of Eigenvalue Spread	130
5.4	Newton's Method	131
5.5	An Alternative Interpretation of Newton's Algorithm	133
	Problems	135
6	LMS Algorithm	139
6.1	Derivation of LMS Algorithm	139
6.2	Average Tap-Weight Behavior of the LMS Algorithm	141
6.3	MSE Behavior of the LMS Algorithm	144
6.3.1	<i>Learning Curve</i>	146
6.3.2	<i>Weight-Error Correlation Matrix</i>	149
6.3.3	<i>Excess MSE and Misadjustment</i>	151
6.3.4	<i>Stability</i>	153
6.3.5	<i>The Effect of Initial Values of Tap Weights on the Transient Behavior of the LMS Algorithm</i>	155
6.4	Computer Simulations	156
6.4.1	<i>System Modeling</i>	156
6.4.2	<i>Channel Equalization</i>	158
6.4.3	<i>Adaptive Line Enhancement</i>	163
6.4.4	<i>Beamforming</i>	165
6.5	Simplified LMS Algorithms	167
6.6	Normalized LMS Algorithm	170
6.7	Affine Projection LMS Algorithm	173
6.8	Variable Step-Size LMS Algorithm	177

6.9	LMS Algorithm for Complex-Valued Signals	179
6.10	Beamforming (Revisited)	182
6.11	Linearly Constrained LMS Algorithm	186
6.11.1	<i>Statement of the Problem and Its Optimal Solution</i>	186
6.11.2	<i>Update Equations</i>	187
6.11.3	<i>Extension to the Complex-Valued Case</i>	188
	Problems	190
	Appendix 6A: Derivation of Eq. (6.39)	205
7	Transform Domain Adaptive Filters	207
7.1	Overview of Transform Domain Adaptive Filters	208
7.2	Band-Partitioning Property of Orthogonal Transforms	210
7.3	Orthogonalization Property of Orthogonal Transforms	211
7.4	Transform Domain LMS Algorithm	213
7.5	Ideal LMS-Newton Algorithm and Its Relationship with TDLMS	215
7.6	Selection of the Transform \mathcal{T}	216
7.6.1	<i>A Geometrical Interpretation</i>	216
7.6.2	<i>A Useful Performance Index</i>	220
7.6.3	<i>Improvement Factor and Comparisons</i>	221
7.6.4	<i>Filtering View</i>	224
7.7	Transforms	229
7.8	Sliding Transforms	230
7.8.1	<i>Frequency Sampling Filters</i>	230
7.8.2	<i>Recursive Realization of Sliding Transforms</i>	231
7.8.3	<i>Nonrecursive Realization of Sliding Transforms</i>	234
7.8.4	<i>Comparison of Recursive and Nonrecursive Sliding Transforms</i>	238
7.9	Summary and Discussion	242
	Problems	243
8	Block Implementation of Adaptive Filters	251
8.1	Block LMS Algorithm	252
8.2	Mathematical Background	255
8.2.1	<i>Linear Convolution Using the Discrete Fourier Transform</i>	255
8.2.2	<i>Circular Matrices</i>	257
8.2.3	<i>Window Matrices and Matrix Formulation of the Overlap-Save Method</i>	258
8.3	The FBLMS Algorithm	260
8.3.1	<i>Constrained and Unconstrained FBLMS Algorithms</i>	261
8.3.2	<i>Convergence Behavior of the FBLMS Algorithm</i>	262
8.3.3	<i>Step-Normalization</i>	263
8.3.4	<i>Summary of the FBLMS Algorithm</i>	264
8.3.5	<i>FBLMS Misadjustment Equations</i>	266
8.3.6	<i>Selection of the Block Length</i>	266
8.4	The Partitioned FBLMS Algorithm	267
8.4.1	<i>Analysis of the PFBLMS Algorithm</i>	269
8.4.2	<i>PFBLMS Algorithm with $M > L$</i>	271

8.4.3	<i>PFBLMS Misadjustment Equations</i>	274
8.4.4	<i>Computational Complexity and Memory Requirement</i>	274
8.4.5	<i>Modified Constrained PFBLMS Algorithm</i>	276
8.5	Computer Simulations	276
	Problems	279
	Appendix 8A: Derivation of a Misadjustment Equation for the BLMS Algorithm	285
	Appendix 8B: Derivation of Misadjustment Equations for the FBLMS Algorithms	288
9	Subband Adaptive Filters	294
9.1	DFT Filter Banks	295
9.1.1	<i>Weighted Overlap–Add Method for Realization of DFT Analysis Filter Banks</i>	296
9.1.2	<i>Weighted Overlap–Add Method for Realization of DFT Synthesis Filter Banks</i>	297
9.2	Complementary Filter Banks	299
9.3	Subband Adaptive Filter Structures	303
9.4	Selection of Analysis and Synthesis Filters	304
9.5	Computational Complexity	307
9.6	Decimation Factor and Aliasing	308
9.7	Low-Delay Analysis and Synthesis Filter Banks	310
9.7.1	<i>Design Method</i>	310
9.7.2	<i>Filters Properties</i>	312
9.8	A Design Procedure for Subband Adaptive Filters	313
9.9	An Example	316
9.10	Comparison with FBLMS Algorithm	318
	Problems	319
10	IIR Adaptive Filters	322
10.1	Output Error Method	323
10.2	Equation Error Method	327
10.3	Case Study I: IIR Adaptive Line Enhancement	332
10.3.1	<i>IIR ALE Filter, $W(z)$</i>	333
10.3.2	<i>Performance Functions</i>	334
10.3.3	<i>Simultaneous Adaptation of s and w</i>	335
10.3.4	<i>Robust Adaptation of w</i>	337
10.3.5	<i>Simulation Results</i>	337
10.4	Case Study II: Equalizer Design for Magnetic Recording Channels	343
10.4.1	<i>Channel Discretization</i>	344
10.4.2	<i>Design Steps</i>	345
10.4.3	<i>FIR Equalizer Design</i>	345
10.4.4	<i>Conversion from FIR into IIR Equalizer</i>	347
10.4.5	<i>Conversion from z Domain into s Domain</i>	348

10.4.6	<i>Numerical Results</i>	348
10.5	Concluding Remarks	349
	Problems	352
11	Lattice Filters	355
11.1	Forward Linear Prediction	355
11.2	Backward Linear Prediction	357
11.3	Relationship Between Forward and Backward Predictors	359
11.4	Prediction-Error Filters	359
11.5	Properties of Prediction Errors	360
11.6	Derivation of Lattice Structure	362
11.7	Lattice as an Orthogonalization Transform	367
11.8	Lattice Joint Process Estimator	369
11.9	System Functions	370
11.10	Conversions	370
	<i>11.10.1 Conversion Between Lattice and Transversal Predictors</i>	371
	<i>11.10.2 Levinson–Durbin Algorithm</i>	372
	<i>11.10.3 Extension of Levinson–Durbin Algorithm</i>	374
11.11	All-Pole Lattice Structure	376
11.12	Pole-Zero Lattice Structure	376
11.13	Adaptive Lattice Filter	378
	<i>11.13.1 Discussion and Simulations</i>	380
11.14	Autoregressive Modeling of Random Processes	383
11.15	Adaptive Algorithms Based on Autoregressive Modeling	385
	<i>11.15.1 Algorithms</i>	386
	<i>11.15.2 Performance Analysis</i>	390
	<i>11.15.3 Simulation Results and Discussion</i>	394
	Problems	400
	Appendix 11A: Evaluation of $E[\mathbf{u}_a(n)\mathbf{x}^T(n)\mathbf{K}(n)\mathbf{x}(n)\mathbf{u}_a^T(n)]$	407
	Appendix 11B: Evaluation of the parameter γ	408
12	Method of Least-Squares	410
12.1	Formulation of Least-Squares Estimation for a Linear Combiner	411
12.2	Principle of Orthogonality	412
12.3	Projection Operator	415
12.4	Standard Recursive Least-Squares Algorithm	416
	<i>12.4.1 RLS Recursions</i>	416
	<i>12.4.2 Initialization of the RLS Algorithm</i>	418
	<i>12.4.3 Summary of the Standard RLS Algorithm</i>	419
12.5	Convergence Behavior of the RLS Algorithm	421
	<i>12.5.1 Average Tap-Weight Behavior of the RLS Algorithm</i>	422
	<i>12.5.2 Weight-Error Correlation Matrix</i>	422
	<i>12.5.3 Learning Curve</i>	423

12.5.4	<i>Excess MSE and Misadjustment</i>	426
12.5.5	<i>Initial Transient Behavior of the RLS Algorithm</i>	427
	Problems	430
13	Fast RLS Algorithms	433
13.1	Least-Squares Forward Prediction	434
13.2	Least-Squares Backward Prediction	435
13.3	Least-Squares Lattice	437
13.4	RLSL Algorithm	440
13.4.1	<i>Notations and Preliminaries</i>	440
13.4.2	<i>Update Recursion for the Least-Squares Error Sums</i>	443
13.4.3	<i>Conversion Factor</i>	444
13.4.4	<i>Update Equation for Conversion Factor</i>	446
13.4.5	<i>Update Equation for Cross-Correlations</i>	447
13.4.6	<i>RLSL Algorithm Using A Posteriori Errors</i>	450
13.4.7	<i>RLSL Algorithm with Error Feedback</i>	450
13.5	FTRLs Algorithm	453
13.5.1	<i>Derivation of the FTRLs Algorithm</i>	454
13.5.2	<i>Summary of the FTRLs Algorithm</i>	458
13.5.3	<i>Stabilized FTRLs Algorithm</i>	458
	Problems	460
14	Tracking	463
14.1	Formulation of the Tracking Problem	463
14.2	Generalized Formulation of LMS Algorithm	464
14.3	MSE Analysis of the Generalized LMS Algorithm	465
14.4	Optimum Step-Size Parameters	469
14.5	Comparisons of Conventional Algorithms	471
14.6	Comparisons Based on Optimum Step-Size Parameters	475
14.7	VSLMS: An Algorithm with Optimum Tracking Behavior	477
14.7.1	<i>Derivation of VSLMS Algorithm</i>	477
14.7.2	<i>Variations and Extensions</i>	478
14.7.3	<i>Normalization of the Parameter ρ</i>	480
14.7.4	<i>Computer Simulations</i>	480
14.8	RLS Algorithm with Variable Forgetting Factor	485
14.9	Summary	486
	Problems	488
15	Echo Cancellation	492
15.1	The Problem Statement	492
15.2	Structures and Adaptive Algorithms	495
15.2.1	<i>Normalized LMS (NLMS) Algorithm</i>	496
15.2.2	<i>Affine Projection LMS (APLMS) Algorithm</i>	499
15.2.3	<i>Frequency Domain Block LMS Algorithm</i>	501
15.2.4	<i>Subband LMS Algorithm</i>	502

15.2.5	<i>LMS-Newton Algorithm</i>	502
15.2.6	<i>Numerical Results</i>	505
15.3	Double-Talk Detection	512
15.3.1	<i>Coherence Function</i>	512
15.3.2	<i>Double-Talk Detection Using the Coherence Function</i>	513
15.3.3	<i>Numerical Evaluation of the Coherence Function</i>	513
15.3.4	<i>Power-Based Double-Talk Detectors</i>	517
15.3.5	<i>Numerical Results</i>	518
15.4	Howling Suppression	521
15.4.1	<i>Howling Suppression Through Notch Filtering</i>	521
15.4.2	<i>Howling Suppression by Spectral Shift</i>	521
15.5	Stereophonic Acoustic Echo Cancellation	524
15.5.1	<i>The Fundamental Problem</i>	526
15.5.2	<i>Reducing Coherence Between $x_1(n)$ and $x_2(n)$</i>	528
15.5.3	<i>The LMS-Newton Algorithm for Stereophonic Systems</i>	532
	Appendix 15A: Multitaper method	542
	Appendix 15B: Derivation of the Two-Channel Levinson–Durbin Algorithm	549
16	Active Noise Control	551
16.1	Broadband Feedforward Single-Channel ANC	553
16.1.1	<i>System Block Diagram in the Absence of the Secondary Path $S_1(z)$</i>	554
16.1.2	<i>Filtered-X LMS Algorithm</i>	555
16.1.3	<i>Convergence Analysis</i>	555
16.1.4	<i>Adding the Secondary Path $S_1(z)$</i>	557
16.2	Narrowband Feedforward Single-Channel ANC	559
16.2.1	<i>Waveform Synthesis Method</i>	560
16.2.2	<i>Adaptive Notch Filters</i>	569
16.3	Feedback Single-Channel ANC	573
16.4	Multichannel ANC Systems	577
16.4.1	<i>MIMO Blocks/Transfer Functions</i>	578
16.4.2	<i>Derivation of the LMS Algorithm for MIMO Adaptive Filters</i>	579
	Appendix 16A: Derivation of Eq. (16.46)	582
	Appendix 16B: Derivation of Eq. (16.53)	583
17	Synchronization and Equalization in Data Transmission Systems	584
17.1	Continuous Time Channel Model	585
17.2	Discrete Time Channel Model and Equalizer Structures	589
17.2.1	<i>Symbol-Spaced Equalizer</i>	590
17.2.2	<i>Fractionally Spaced Equalizer</i>	591
17.2.3	<i>Decision Feedback Equalizer</i>	592
17.3	Timing Recovery	593
17.3.1	<i>Cost Function</i>	593
17.3.2	<i>The Optimum Timing Phase</i>	595

17.3.3	<i>Improving the Cost Function</i>	598
17.3.4	<i>Algorithms</i>	600
17.3.5	<i>Early-Late Gate Timing Recovery</i>	600
17.3.6	<i>Gradient-Based Algorithm</i>	604
17.4	Equalizers Design and Performance Analysis	606
17.4.1	<i>Wiener–Hopf Equation for Symbol-Spaced Equalizers</i>	606
17.4.2	<i>Numerical Examples</i>	613
17.5	Adaptation Algorithms	617
17.6	Cyclic Equalization	618
17.6.1	<i>Symbol-Spaced Cyclic Equalizer</i>	618
17.6.2	<i>Fractionally Spaced Cyclic Equalizer</i>	625
17.6.3	<i>Alignment of $s(n)$ and $x(n)$</i>	627
17.6.4	<i>Carrier and Timing Phase Acquisition and Tracking</i>	627
17.7	Joint Timing Recovery, Carrier Recovery, and Channel Equalization	628
17.8	Maximum Likelihood Detection	629
17.9	Soft Equalization	631
17.9.1	<i>Soft MMSE Equalizer</i>	633
17.9.2	<i>Statistical Soft Equalizer</i>	635
17.9.3	<i>Iterative Channel Estimation and Data Detection</i>	641
17.10	Single-Input Multiple-Output Equalization	643
17.11	Frequency Domain Equalization	645
17.11.1	<i>Packet Structure</i>	646
17.11.2	<i>Frequency Domain Equalizer</i>	647
17.11.3	<i>Packet Structure for Fast Tracking</i>	648
17.11.4	<i>Summary</i>	649
17.12	Blind Equalization	649
17.12.1	<i>Examples of Kurtosis</i>	651
17.12.2	<i>Cost Function</i>	652
17.12.3	<i>Blind Adaptation Algorithm</i>	654
	Problems	654
18	Sensor Array Processing	659
18.1	Narrowband Sensor Arrays	660
18.1.1	<i>Array Topology and Parameters</i>	660
18.1.2	<i>Signal subspace, noise subspace, and spectral factorization</i>	662
18.1.3	<i>Direction of Arrival Estimation</i>	665
18.1.4	<i>Beamforming Methods</i>	670
18.2	Broadband Sensor Arrays	678
18.2.1	<i>Steering</i>	679
18.2.2	<i>Beamforming Methods</i>	680
18.3	Robust Beamforming	683
18.3.1	<i>Soft-Constraint Minimization</i>	686
18.3.2	<i>Diagonal Loading Method</i>	688
18.3.3	<i>Methods Based on Sample Matrix Inversion</i>	690
	Problems	692

19	Code Division Multiple Access Systems	695
19.1	CDMA Signal Model	695
19.1.1	<i>Chip-Spaced Users-Synchronous Model</i>	696
19.1.2	<i>Chip-Spaced Users-Asynchronous Model</i>	698
19.1.3	<i>Fractionally Spaced Model</i>	699
19.2	Linear Detectors	699
19.2.1	<i>Conventional Detector: The Matched Filter Detector</i>	700
19.2.2	<i>Decorrelator Detector</i>	700
19.2.3	<i>Minimum Mean-Squared Error (Optimal) Detector</i>	701
19.2.4	<i>Minimum Output Energy (Blind) Detector</i>	703
19.2.5	<i>Soft Detectors</i>	707
19.3	Adaptation Methods	707
19.3.1	<i>Conventional Detector</i>	707
19.3.2	<i>Decorrelator Detector</i>	707
19.3.3	<i>MMSE Detector</i>	708
19.3.4	<i>MOE Detector</i>	708
19.3.5	<i>Soft Detectors</i>	709
	Problems	709
20	OFDM and MIMO Communications	711
20.1	OFDM Communication Systems	711
20.1.1	<i>The Principle of OFDM</i>	711
20.1.2	<i>Packet Structure</i>	714
20.1.3	<i>Carrier Acquisition</i>	716
20.1.4	<i>Timing Acquisition</i>	717
20.1.5	<i>Channel Estimation and Frequency Domain Equalization</i>	717
20.1.6	<i>Estimation of R_{hh} and R_{vv}</i>	720
20.1.7	<i>Carrier-Tracking Methods</i>	721
20.1.8	<i>Channel-Tracking Methods</i>	730
20.2	MIMO Communication Systems	730
20.2.1	<i>MIMO Channel Model</i>	732
20.2.2	<i>Transmission Techniques for Space-Diversity Gain</i>	732
20.2.3	<i>Transmission Techniques and MIMO Detectors for Space-Multiplexing Gain</i>	737
20.2.4	<i>Channel Estimation Methods</i>	741
20.3	MIMO-OFDM	743
	Problems	743
	References	746
	Index	761