

The Wiley logo, consisting of a stylized 'W' inside a circle, followed by the word 'WILEY' in a bold, sans-serif font.

Advanced
Digital Signal
Processing
and Noise
Reduction

Second Edition

SAEED V. VASEGHI

CONTENTS

| | |
|--|-------------|
| PREFACE | xvii |
| FREQUENTLY USED SYMBOLS AND ABBREVIATIONS..... | xxi |
| CHAPTER 1 INTRODUCTION..... | 1 |
| 1.1 Signals and Information | 2 |
| 1.2 Signal Processing Methods | 3 |
| 1.2.1 Non-parametric Signal Processing | 3 |
| 1.2.2 Model-Based Signal Processing | 4 |
| 1.2.3 Bayesian Statistical Signal Processing | 4 |
| 1.2.4 Neural Networks..... | 5 |
| 1.3 Applications of Digital Signal Processing | 5 |
| 1.3.1 Adaptive Noise Cancellation and Noise Reduction | 5 |
| 1.3.2 Blind Channel Equalisation..... | 8 |
| 1.3.3 Signal Classification and Pattern Recognition | 9 |
| 1.3.4 Linear Prediction Modelling of Speech..... | 11 |
| 1.3.5 Digital Coding of Audio Signals | 12 |
| 1.3.6 Detection of Signals in Noise | 14 |
| 1.3.7 Directional Reception of Waves: Beam-forming | 16 |
| 1.3.8 Dolby Noise Reduction | 18 |
| 1.3.9 Radar Signal Processing: Doppler Frequency Shift | 19 |
| 1.4 Sampling and Analog-to-Digital Conversion | 21 |
| 1.4.1 Time-Domain Sampling and Reconstruction of Analog Signals | 22 |
| 1.4.2 Quantisation..... | 25 |
| Bibliography..... | 27 |
| CHAPTER 2 NOISE AND DISTORTION..... | 29 |
| 2.1 Introduction..... | 30 |
| 2.2 White Noise | 31 |
| 2.3 Coloured Noise | 33 |
| 2.4 Impulsive Noise | 34 |
| 2.5 Transient Noise Pulses..... | 35 |
| 2.6 Thermal Noise..... | 36 |

| | |
|---|-----------|
| 2.7 Shot Noise..... | 38 |
| 2.8 Electromagnetic Noise..... | 38 |
| 2.9 Channel Distortions..... | 39 |
| 2.10 Modelling Noise..... | 40 |
| 2.10.1 Additive White Gaussian Noise Model (AWGN)..... | 42 |
| 2.10.2 Hidden Markov Model for Noise..... | 42 |
| Bibliography..... | 43 |
| CHAPTER 3 PROBABILITY MODELS..... | 44 |
| 3.1 Random Signals and Stochastic Processes..... | 45 |
| 3.1.1 Stochastic Processes..... | 47 |
| 3.1.2 The Space or Ensemble of a Random Process..... | 47 |
| 3.2 Probabilistic Models..... | 48 |
| 3.2.1 Probability Mass Function (pmf)..... | 49 |
| 3.2.2 Probability Density Function (pdf)..... | 50 |
| 3.3 Stationary and Non-Stationary Random Processes..... | 53 |
| 3.3.1 Strict-Sense Stationary Processes..... | 55 |
| 3.3.2 Wide-Sense Stationary Processes..... | 56 |
| 3.3.3 Non-Stationary Processes..... | 56 |
| 3.4 Expected Values of a Random Process..... | 57 |
| 3.4.1 The Mean Value..... | 58 |
| 3.4.2 Autocorrelation..... | 58 |
| 3.4.3 Autocovariance..... | 59 |
| 3.4.4 Power Spectral Density..... | 60 |
| 3.4.5 Joint Statistical Averages of Two Random Processes..... | 62 |
| 3.4.6 Cross-Correlation and Cross-Covariance..... | 62 |
| 3.4.7 Cross-Power Spectral Density and Coherence..... | 64 |
| 3.4.8 Ergodic Processes and Time-Averaged Statistics..... | 64 |
| 3.4.9 Mean-Ergodic Processes..... | 65 |
| 3.4.10 Correlation-Ergodic Processes..... | 66 |
| 3.5 Some Useful Classes of Random Processes..... | 68 |
| 3.5.1 Gaussian (Normal) Process..... | 68 |
| 3.5.2 Multivariate Gaussian Process..... | 69 |
| 3.5.3 Mixture Gaussian Process..... | 71 |
| 3.5.4 A Binary-State Gaussian Process..... | 72 |
| 3.5.5 Poisson Process..... | 73 |
| 3.5.6 Shot Noise..... | 75 |
| 3.5.7 Poisson–Gaussian Model for Clutters and Impulsive Noise..... | 77 |
| 3.5.8 Markov Processes..... | 77 |
| 3.5.9 Markov Chain Processes..... | 79 |

3.6 Transformation of a Random Process.....81
 3.6.1 Monotonic Transformation of Random Processes81
 3.6.2 Many-to-One Mapping of Random Signals84
 3.7 Summary.....86
 Bibliography.....87

CHAPTER 4 BAYESIAN ESTIMATION.....89

4.1 Bayesian Estimation Theory: Basic Definitions90
 4.1.1 Dynamic and Probability Models in Estimation.....91
 4.1.2 Parameter Space and Signal Space.....92
 4.1.3 Parameter Estimation and Signal Restoration93
 4.1.4 Performance Measures and Desirable Properties of Estimators94
 4.1.5 Prior and Posterior Spaces and Distributions96
 4.2 Bayesian Estimation.....100
 4.2.1 Maximum A Posteriori Estimation101
 4.2.2 Maximum-Likelihood Estimation102
 4.2.3 Minimum Mean Square Error Estimation105
 4.2.4 Minimum Mean Absolute Value of Error Estimation.....107
 4.2.5 Equivalence of the MAP, ML, MMSE and MAVE for Gaussian Processes With Uniform Distributed Parameters108
 4.2.6 The Influence of the Prior on Estimation Bias and Variance.....109
 4.2.7 The Relative Importance of the Prior and the Observation.....113
 4.3 The Estimate–Maximise (EM) Method117
 4.3.1 Convergence of the EM Algorithm118
 4.4 Cramer–Rao Bound on the Minimum Estimator Variance.....120
 4.4.1 Cramer–Rao Bound for Random Parameters122
 4.4.2 Cramer–Rao Bound for a Vector Parameter.....123
 4.5 Design of Mixture Gaussian Models124
 4.5.1 The EM Algorithm for Estimation of Mixture Gaussian Densities125
 4.6 Bayesian Classification.....127
 4.6.1 Binary Classification129
 4.6.2 Classification Error.....131
 4.6.3 Bayesian Classification of Discrete-Valued Parameters .132
 4.6.4 Maximum A Posteriori Classification.....133
 4.6.5 Maximum-Likelihood (ML) Classification.....133
 4.6.6 Minimum Mean Square Error Classification134
 4.6.7 Bayesian Classification of Finite State Processes134

| | |
|---|------------|
| 4.6.8 Bayesian Estimation of the Most Likely State Sequence..... | 136 |
| 4.7 Modelling the Space of a Random Process..... | 138 |
| 4.7.1 Vector Quantisation of a Random Process..... | 138 |
| 4.7.2 Design of a Vector Quantiser: <i>K</i> -Means Clustering..... | 138 |
| 4.8 Summary..... | 140 |
| Bibliography..... | 141 |
| CHAPTER 5 HIDDEN MARKOV MODELS..... | 143 |
| 5.1 Statistical Models for Non-Stationary Processes..... | 144 |
| 5.2 Hidden Markov Models..... | 146 |
| 5.2.1 A Physical Interpretation of Hidden Markov Models..... | 148 |
| 5.2.2 Hidden Markov Model as a Bayesian Model..... | 149 |
| 5.2.3 Parameters of a Hidden Markov Model..... | 150 |
| 5.2.4 State Observation Models..... | 150 |
| 5.2.5 State Transition Probabilities..... | 152 |
| 5.2.6 State-Time Trellis Diagram..... | 153 |
| 5.3 Training Hidden Markov Models..... | 154 |
| 5.3.1 Forward-Backward Probability Computation..... | 155 |
| 5.3.2 Baum-Welch Model Re-Estimation..... | 157 |
| 5.3.3 Training HMMs with Discrete Density Observation Models..... | 159 |
| 5.3.4 HMMs with Continuous Density Observation Models..... | 160 |
| 5.3.5 HMMs with Mixture Gaussian pdfs..... | 161 |
| 5.4 Decoding of Signals Using Hidden Markov Models..... | 163 |
| 5.4.1 Viterbi Decoding Algorithm..... | 165 |
| 5.5 HMM-Based Estimation of Signals in Noise..... | 167 |
| 5.6 Signal and Noise Model Combination and Decomposition..... | 170 |
| 5.6.1 Hidden Markov Model Combination..... | 170 |
| 5.6.2 Decomposition of State Sequences of Signal and Noise..... | 171 |
| 5.7 HMM-Based Wiener Filters..... | 172 |
| 5.7.1 Modelling Noise Characteristics..... | 174 |
| 5.8 Summary..... | 174 |
| Bibliography..... | 175 |
| CHAPTER 6 WIENER FILTERS..... | 178 |
| 6.1 Wiener Filters: Least Square Error Estimation..... | 179 |
| 6.2 Block-Data Formulation of the Wiener Filter..... | 184 |
| 6.2.1 OR Decomposition of the Least Square Error Equation..... | 185 |

| | |
|--|------------|
| 6.3 Interpretation of Wiener Filters as Projection in Vector Space ... | 187 |
| 6.4 Analysis of the Least Mean Square Error Signal | 189 |
| 6.5 Formulation of Wiener Filters in the Frequency Domain | 191 |
| 6.6 Some Applications of Wiener Filters | 192 |
| 6.6.1 Wiener Filter for Additive Noise Reduction | 193 |
| 6.6.2 Wiener Filter and the Separability of Signal and Noise .. | 195 |
| 6.6.3 The Square-Root Wiener Filter | 196 |
| 6.6.4 Wiener Channel Equaliser | 197 |
| 6.6.5 Time-Alignment of Signals in Multichannel/Multisensor Systems | 198 |
| 6.6.6 Implementation of Wiener Filters | 200 |
| 6.7 The Choice of Wiener Filter Order | 201 |
| 6.8 Summary | 202 |
| Bibliography | 202 |
| CHAPTER 7 ADAPTIVE FILTERS | 205 |
| 7.1 State-Space Kalman Filters | 206 |
| 7.2 Sample-Adaptive Filters | 212 |
| 7.3 Recursive Least Square (RLS) Adaptive Filters | 213 |
| 7.4 The Steepest-Descent Method | 219 |
| 7.5 The LMS Filter | 222 |
| 7.6 Summary | 224 |
| Bibliography | 225 |
| CHAPTER 8 LINEAR PREDICTION MODELS | 227 |
| 8.1 Linear Prediction Coding | 228 |
| 8.1.1 Least Mean Square Error Predictor | 231 |
| 8.1.2 The Inverse Filter: Spectral Whitening | 234 |
| 8.1.3 The Prediction Error Signal | 236 |
| 8.2 Forward, Backward and Lattice Predictors | 236 |
| 8.2.1 Augmented Equations for Forward and Backward Predictors | 239 |
| 8.2.2 Levinson–Durbin Recursive Solution | 239 |
| 8.2.3 Lattice Predictors | 242 |
| 8.2.4 Alternative Formulations of Least Square Error Prediction | 244 |
| 8.2.5 Predictor Model Order Selection | 245 |
| 8.3 Short-Term and Long-Term Predictors | 247 |

| | |
|--|-----|
| 8.4 MAP Estimation of Predictor Coefficients | 249 |
| 8.4.1 Probability Density Function of Predictor Output..... | 249 |
| 8.4.2 Using the Prior pdf of the Predictor Coefficients | 251 |
| 8.5 Sub-Band Linear Prediction Model | 252 |
| 8.6 Signal Restoration Using Linear Prediction Models..... | 254 |
| 8.6.1 Frequency-Domain Signal Restoration Using Prediction Models | 257 |
| 8.6.2 Implementation of Sub-Band Linear Prediction Wiener Filters..... | 259 |
| 8.7 Summary | 261 |
| Bibliography..... | 261 |

CHAPTER 9 POWER SPECTRUM AND CORRELATION

| | |
|---|-----|
| 9.1 Power Spectrum and Correlation | 264 |
| 9.2 Fourier Series: Representation of Periodic Signals | 265 |
| 9.3 Fourier Transform: Representation of Aperiodic Signals..... | 267 |
| 9.3.1 Discrete Fourier Transform (DFT)..... | 269 |
| 9.3.2 Time/Frequency Resolutions, The Uncertainty Principle | 269 |
| 9.3.3 Energy-Spectral Density and Power-Spectral Density | 270 |
| 9.4 Non-Parametric Power Spectrum Estimation | 272 |
| 9.4.1 The Mean and Variance of Periodograms | 272 |
| 9.4.2 Averaging Periodograms (Bartlett Method)..... | 273 |
| 9.4.3 Welch Method: Averaging Periodograms from Overlapped and Windowed Segments..... | 274 |
| 9.4.4 Blackman–Tukey Method | 276 |
| 9.4.5 Power Spectrum Estimation from Autocorrelation of Overlapped Segments | 277 |
| 9.5 Model-Based Power Spectrum Estimation | 278 |
| 9.5.1 Maximum–Entropy Spectral Estimation | 279 |
| 9.5.2 Autoregressive Power Spectrum Estimation | 282 |
| 9.5.3 Moving-Average Power Spectrum Estimation..... | 283 |
| 9.5.4 Autoregressive Moving-Average Power Spectrum Estimation..... | 284 |
| 9.6 High-Resolution Spectral Estimation Based on Subspace Eigen- Analysis | 284 |
| 9.6.1 Pisarenko Harmonic Decomposition..... | 285 |
| 9.6.2 Multiple Signal Classification (MUSIC) Spectral Estimation..... | 288 |
| 9.6.3 Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT)..... | 292 |

| | |
|---|------------|
| 9.7 Summary | 294 |
| Bibliography..... | 294 |
| CHAPTER 10 INTERPOLATION..... | 297 |
| 10.1 Introduction..... | 298 |
| 10.1.1 Interpolation of a Sampled Signal | 298 |
| 10.1.2 Digital Interpolation by a Factor of I | 300 |
| 10.1.3 Interpolation of a Sequence of Lost Samples | 301 |
| 10.1.4 The Factors That Affect Interpolation Accuracy..... | 303 |
| 10.2 Polynomial Interpolation..... | 304 |
| 10.2.1 Lagrange Polynomial Interpolation | 305 |
| 10.2.2 Newton Polynomial Interpolation | 307 |
| 10.2.3 Hermite Polynomial Interpolation | 309 |
| 10.2.4 Cubic Spline Interpolation..... | 310 |
| 10.3 Model-Based Interpolation | 313 |
| 10.3.1 Maximum A Posteriori Interpolation | 315 |
| 10.3.2 Least Square Error Autoregressive Interpolation | 316 |
| 10.3.3 Interpolation Based on a Short-Term Prediction Model | 317 |
| 10.3.4 Interpolation Based on Long-Term and Short-term Correlations | 320 |
| 10.3.5 LSAR Interpolation Error..... | 323 |
| 10.3.6 Interpolation in Frequency–Time Domain | 326 |
| 10.3.7 Interpolation Using Adaptive Code Books..... | 328 |
| 10.3.8 Interpolation Through Signal Substitution | 329 |
| 10.4 Summary | 330 |
| Bibliography..... | 331 |
| CHAPTER 11 SPECTRAL SUBTRACTION..... | 333 |
| 11.1 Spectral Subtraction..... | 334 |
| 11.1.1 Power Spectrum Subtraction | 337 |
| 11.1.2 Magnitude Spectrum Subtraction | 338 |
| 11.1.3 Spectral Subtraction Filter: Relation to Wiener Filters..... | 339 |
| 11.2 Processing Distortions | 340 |
| 11.2.1 Effect of Spectral Subtraction on Signal Distribution..... | 342 |
| 11.2.2 Reducing the Noise Variance | 343 |
| 11.2.3 Filtering Out the Processing Distortions | 344 |
| 11.3 Non-Linear Spectral Subtraction | 345 |
| 11.4 Implementation of Spectral Subtraction | 348 |
| 11.4.1 Application to Speech Restoration and Recognition..... | 351 |

| | |
|---|------------|
| 11.5 Summary | 352 |
| Bibliography..... | 352 |
| CHAPTER 12 IMPULSIVE NOISE | 355 |
| 12.1 Impulsive Noise | 356 |
| 12.1.1 Autocorrelation and Power Spectrum of Impulsive Noise | 359 |
| 12.2 Statistical Models for Impulsive Noise..... | 360 |
| 12.2.1 Bernoulli–Gaussian Model of Impulsive Noise | 360 |
| 12.2.2 Poisson–Gaussian Model of Impulsive Noise..... | 362 |
| 12.2.3 A Binary-State Model of Impulsive Noise | 362 |
| 12.2.4 Signal to Impulsive Noise Ratio..... | 364 |
| 12.3 Median Filters | 365 |
| 12.4 Impulsive Noise Removal Using Linear Prediction Models | 366 |
| 12.4.1 Impulsive Noise Detection | 367 |
| 12.4.2 Analysis of Improvement in Noise Detectability | 369 |
| 12.4.3 Two-Sided Predictor for Impulsive Noise Detection | 372 |
| 12.4.4 Interpolation of Discarded Samples | 372 |
| 12.5 Robust Parameter Estimation..... | 373 |
| 12.6 Restoration of Archived Gramophone Records..... | 375 |
| 12.7 Summary | 376 |
| Bibliography..... | 377 |
| CHAPTER 13 TRANSIENT NOISE PULSES..... | 378 |
| 13.1 Transient Noise Waveforms | 379 |
| 13.2 Transient Noise Pulse Models | 381 |
| 13.2.1 Noise Pulse Templates | 382 |
| 13.2.2 Autoregressive Model of Transient Noise Pulses | 383 |
| 13.2.3 Hidden Markov Model of a Noise Pulse Process..... | 384 |
| 13.3 Detection of Noise Pulses | 385 |
| 13.3.1 Matched Filter for Noise Pulse Detection | 386 |
| 13.3.2 Noise Detection Based on Inverse Filtering | 388 |
| 13.3.3 Noise Detection Based on HMM | 388 |
| 13.4 Removal of Noise Pulse Distortions..... | 389 |
| 13.4.1 Adaptive Subtraction of Noise Pulses | 389 |
| 13.4.2 AR-based Restoration of Signals Distorted by Noise Pulses | 392 |
| 13.5 Summary | 395 |

| | |
|---|------------|
| Bibliography..... | 395 |
| CHAPTER 14 ECHO CANCELLATION | 396 |
| 14.1 Introduction: Acoustic and Hybrid Echoes | 397 |
| 14.2 Telephone Line Hybrid Echo | 398 |
| 14.3 Hybrid Echo Suppression | 400 |
| 14.4 Adaptive Echo Cancellation | 401 |
| 14.4.1 Echo Canceller Adaptation Methods..... | 403 |
| 14.4.2 Convergence of Line Echo Canceller..... | 404 |
| 14.4.3 Echo Cancellation for Digital Data Transmission..... | 405 |
| 14.5 Acoustic Echo | 406 |
| 14.6 Sub-Band Acoustic Echo Cancellation..... | 411 |
| 14.7 Summary | 413 |
| Bibliography..... | 413 |
| CHAPTER 15 CHANNEL EQUALIZATION AND BLIND DECONVOLUTION..... | 416 |
| 15.1 Introduction..... | 417 |
| 15.1.1 The Ideal Inverse Channel Filter | 418 |
| 15.1.2 Equalization Error, Convolutional Noise | 419 |
| 15.1.3 Blind Equalization..... | 420 |
| 15.1.4 Minimum- and Maximum-Phase Channels..... | 423 |
| 15.1.5 Wiener Equalizer | 425 |
| 15.2 Blind Equalization Using Channel Input Power Spectrum..... | 427 |
| 15.2.1 Homomorphic Equalization | 428 |
| 15.2.2 Homomorphic Equalization Using a Bank of High- Pass Filters | 430 |
| 15.3 Equalization Based on Linear Prediction Models..... | 431 |
| 15.3.1 Blind Equalization Through Model Factorisation | 433 |
| 15.4 Bayesian Blind Deconvolution and Equalization | 435 |
| 15.4.1 Conditional Mean Channel Estimation | 436 |
| 15.4.2 Maximum-Likelihood Channel Estimation..... | 436 |
| 15.4.3 Maximum A Posteriori Channel Estimation | 437 |
| 15.4.4 Channel Equalization Based on Hidden Markov Models..... | 438 |
| 15.4.5 MAP Channel Estimate Based on HMMs..... | 441 |
| 15.4.6 Implementations of HMM-Based Deconvolution | 442 |
| 15.5 Blind Equalization for Digital Communication Channels..... | 446 |

| | |
|---|------------|
| 15.5.1 LMS Blind Equalization..... | 448 |
| 15.5.2 Equalization of a Binary Digital Channel..... | 451 |
| 15.6 Equalization Based on Higher-Order Statistics | 453 |
| 15.6.1 Higher-Order Moments, Cumulants and Spectra | 454 |
| 15.6.2 Higher-Order Spectra of Linear Time-Invariant Systems | 457 |
| 15.6.3 Blind Equalization Based on Higher-Order Cepstra | 458 |
| 15.7 Summary | 464 |
| Bibliography..... | 465 |
| INDEX | 467 |