CONTENTS

PREFACE xv

PART I INTRODUCTION TO COGNITIVE RADIOS 1

1 Introduction 3

1.1 Introduction, 3
1.2 Signal Processing and Cognitive Radios, 4
1.3 Software-Defined Radios, 6
  1.3.1 Software-Defined Radio Platforms, 14
  1.3.2 Software-Defined Radio Systems, 15
1.4 From Software-Defined Radios to Cognitive Radios, 19
  1.4.1 The Spectrum Scarcity Problem, 19
  1.4.2 Emergence of CRs, 21
1.5 What this Book is About, 22
1.6 Summary, 26

2 The Cognitive Radio 27

2.1 Introduction, 27
2.2 A Functional Model of a Cognitive Radio, 30
  2.2.1 Spectrum Knowledge Acquisition (Spectrum Awareness), 30
  2.2.2 Communications Decision-Making, 33
  2.2.3 Learning in Cognitive Radios, 33
CONTENTS

2.3 The Cognitive Radio Architecture, 35
  2.3.1 Spectrum Sensing Region of a Cognitive Engine, 36
  2.3.2 Radio Reconfiguration Region of a Cognitive Engine, 36
  2.3.3 Learning Region of a Cognitive Engine, 37
  2.3.4 Memory Region of a Cognitive Engine, 37
2.4 The Ideal Cognitive Radio, 38
2.5 Signal Processing Challenges in Cognitive Radios, 39
2.6 Summary, 40

3 Cognitive Radios and Dynamic Spectrum Sharing 42
  3.1 Introduction, 42
  3.2 Interference and Spectrum Opportunities, 46
  3.3 Dynamic Spectrum Access, 50
  3.4 Dynamic Spectrum Leasing, 54
  3.5 Challenges in DSS Cognitive Radios, 55
  3.6 Cognitive Radios and Future of Wireless Communications, 60
  3.7 Summary, 61

PART II THEORETICAL FOUNDATIONS 65

4 Introduction to Detection Theory 67
  4.1 Introduction, 67
  4.2 Optimality Criteria: Bayesian versus Non-Bayesian, 71
    4.2.1 The Bayesian Approach, 72
    4.2.2 A Non-Bayesian Approach: Neyman–Pearson Optimality Criterion, 73
  4.3 Parametric Signal Detection Theory, 75
    4.3.1 Bayesian Optimal Detection, 76
    4.3.2 Neyman–Pearson Optimal Detection, 82
    4.3.3 Another Non-Bayesian Alternative: The Generalized Likelihood Ratio Test, 99
    4.3.4 Parametric Signal Detection in Additive Noise, 103
  4.4 Nonparametric Signal Detection Theory, 122
    4.4.1 Signal Detection in Additive Zero-Median Noise: The Sign Test, 124
    4.4.2 Signal Detection in Additive Symmetric Noise: The Rank Test, 125
    4.4.3 Signal Detection in Additive Zero Median, Zero Mean, Finite-Variance Noise: The t-Test, 126
  4.5 Summary, 127
CONTENTS

5 Introduction to Estimation Theory 132

5.1 Introduction, 132
5.2 Random Parameter Estimation: Bayesian Estimation, 134
  5.2.1 Minimum Mean-Squared Error Estimation, 134
  5.2.2 MMSE Estimation of Vector Parameters, 135
  5.2.3 Linear Minimum Mean-Squared Error Estimation, 138
  5.2.4 Maximum A Posteriori Probability Estimation, 139
5.3 Nonrandom Parameter Estimation, 140
  5.3.1 Theory of Minimum Variance Unbiased Estimation, 142
  5.3.2 Best Linear Unbiased Estimator, 147
  5.3.3 Maximum Likelihood Estimation, 152
  5.3.4 Performance Bounds: Cramer-Rao Lower Bound, 154
5.4 Summary, 158

6 Power Spectrum Estimation 164

6.1 Introduction, 164
6.2 PSD Estimation of a Stationary Discrete-Time Signal, 168
  6.2.1 Correlogram Method, 168
  6.2.2 Periodogram Method, 170
  6.2.3 Performance of the Periodogram PSD Estimate, 172
6.3 Blackman–Tukey Estimator of the Power Spectrum, 177
6.4 Other PSD Estimators Based on Modified Periodograms, 181
  6.4.1 Bartlett PSD Estimator, 181
  6.4.2 Welch PSD Estimator, 183
6.5 PSD Estimation of Nonstationary Discrete-Time Signals, 186
  6.5.1 Temporally Windowed Observations, 188
  6.5.2 Temporal and Spectral Smoothing of PSD Estimates of Nonstationary Discrete-Time Signals, 189
  6.5.3 DFT-Based PSD Computation, 191
6.6 Spectral Correlation of Cyclostationary Signals, 192
  6.6.1 Spectral Correlation and Spectral Autocoherence, 196
  6.6.2 Time-Averaged Spectral Correlation, 197
  6.6.3 Estimation of Spectral Correlation, 198
6.7 Summary, 200

7 Markov Decision Processes 207

7.1 Introduction, 207
7.2 Markov Decision Processes, 209
7.3 Finite-Horizon MDPs, 212
  7.3.1 Definitions, 212
  7.3.2 Optimal Policies for MDPs, 216
CONTENTS

7.4 Infinite-Horizon MDPs, 222
  7.4.1 Stationary Optimal Policies for Infinite-Horizon MDPs, 224
  7.4.2 Bellman-Optimality Equations, 227

7.5 Partially Observable Markov Decision Processes, 232
  7.5.1 Definitions, 233
  7.5.2 Policy Evaluation for a Finite-Horizon POMDP, 238
  7.5.3 Optimality Equations for a Finite-Horizon POMDP, 241
  7.5.4 Optimal Policy Computation for a Finite-Horizon POMDP, 242
  7.5.5 Infinite-Horizon POMDPs, 257

7.6 Summary, 259

8 Bayesian Nonparametric Classification 269
  8.1 Introduction, 269
  8.2 K-Means Classification Algorithm, 274
  8.3 X-Means Classification Algorithm, 276
  8.4 Dirichlet Process Mixture Model, 278
    8.4.1 Dirichlet Process, 278
    8.4.2 Construction of the Dirichlet Process, 279
    8.4.3 DPMM, 282
  8.5 Bayesian Nonparametric Classification Based on the DPMM and
    the Gibbs Sampling, 283
    8.5.1 DPMM-Based Classification of Scalar Observations, 287
    8.5.2 DPMM-Based Classification of Multidimensional Gaussian
      Observations, 298
    8.5.3 DPMM-Based Classification of Possibly Non-Gaussian
      Multidimensional Observations, 308
  8.6 Summary, 315

PART III  SIGNAL PROCESSING IN COGNITIVE RADIOS 321

9 Wideband Spectrum Sensing 323
  9.1 Introduction, 323
  9.2 Wideband Spectrum Sensing Problem, 325
  9.3 Wideband Spectrum Scanning Problem, 326
  9.4 Spectrum Segmentation and Subbanding, 328
  9.5 Wideband Spectrum Sensing Receiver, 330
    9.5.1 Homodyne Receiver Configuration, 332
    9.5.2 Super Heterodyne Digital Receiver Configuration, 334
    9.5.3 A/D Conversion and the Discrete-Time Received Signal
      Model, 335
  9.6 Subband Selection Problem in Wideband Spectrum Sensing, 336
    9.6.1 Subband Dynamics, 338
CONTENTS

9.6.2 A POMDP Model for Subband Selection, 340
9.6.3 An Optimal Subband Selection Policy for Spectrum Sensing, 347
9.6.4 A Reduced-Complexity Optimal Sensing Decision-Making Algorithm with Independent Channels, 350
9.6.5 A Reduced Complexity Optimal Sensing Decision-Making Algorithm with Independent Subbands, 354
9.6.6 Optimal Myopic Sensing Decision Policies, 354
9.7 A Reduced Complexity Optimal Subband Selection Framework with an Alternative Reward Function, 355
9.7.1 A New Model for Subband Dynamics, 357
9.7.2 A Simplified Reward Function and a Reduced-Complexity Optimal Policy, 359
9.7.3 A Reduced Complexity Optimal Policy for Independent Subbands, 362
9.7.4 Optimal Myopic Policies with Reduced Dimensional Subband State Vectors, 363
9.8 Machine-Learning Aided Subband Selection Policies, 364
9.8.1 Q-Learning, 365
9.8.2 Q-Learning in a POMDP: A Q-Learning Algorithm for Subband Selection, 368
9.9 Summary, 372

10 Spectral Activity Detection in Wideband Cognitive Radios 377
10.1 Introduction, 377
10.2 Optimal Wideband Spectral Activity Detection, 379
10.3 Wideband Spectral Activity Detection, 386
10.4 Wavelet Transform-Based Wideband Spectral Activity Detection, 392
  10.4.1 Wavelet Transform, 394
  10.4.2 Edge Detection with Wavelet Transform, 395
  10.4.3 Spectral Activity Detection Based on Edge Detection, 397
10.5 Wideband Spectral Activity Detection in Non-Gaussian Noise, 398
  10.5.1 Arbitrary but Known Noise Distribution, 399
  10.5.2 Robust Spectral Activity Detection, 406
10.6 Wideband Spectral Activity Detection with Compressive Sampling, 413
  10.6.1 Compressive Sampling, 415
  10.6.2 Compressive Sensing of Wideband Spectrum, 419
10.7 Summary, 421

11 Signal Classification in Wideband Cognitive Radios 429
11.1 Introduction, 429
11.2 Signal Classification Problem in a Wideband Cognitive Radio, 431
11.3 Feature Extraction for Signal Classification, 435
CONTENTS

11.3.1 Carrier/Center Frequency, 435
11.3.2 Cyclostationary Features, 436
11.3.3 Modulation Type and Order Features, 441
11.4 A Signal Classification Architecture for a Wideband Cognitive Radio, 445
11.5 Bayesian Nonparametric Signal Classification, 447
11.6 Sequential Bayesian Nonparametric Signal Classification, 462
11.7 Summary, 469

12 Primary Signal Detection in DSA Cognitive Networks 472
12.1 Introduction, 472
12.2 Spectrum Sensing Problem in Dynamic Spectrum Sharing CR Networks, 475
12.3 Autonomous Spectrum Sensing for Dynamic Spectrum Sharing, 479
   12.3.1 Secondary User Sensing Observations, 480
   12.3.2 Channel-State (Idle/Busy) Decisions, 481
12.4 Limitations of Autonomous Spectrum Sensing, 489
12.5 Cooperative Spectrum Sensing for Dynamic Spectrum Sharing, 492
12.6 Cooperative Channel-State Detection, 495
   12.6.1 Local Processing and Sensing Reports from Secondary Users, 498
   12.6.2 Final Channel-State Decisions at the SSDC: Decision Fusion, 502
12.7 Summary, 516

13 Spectrum Decision-Making in DSA Cognitive Networks 519
13.1 Introduction, 519
13.2 Primary Channel Dynamic Model, 520
13.3 Sensing Decisions in DSS Networks with Autonomous Cognitive Radios, 522
   13.3.1 Optimal Sensing Policy Determination, 525
   13.3.2 Optimal Myopic Sensing Policy Determination, 530
13.4 Sensing Decisions in Cooperative DSS Networks, 533
   13.4.1 Optimal SSDC Decisions for Independent Channel Dynamics, 537
   13.4.2 Optimal Myopic Sensing Decisions at the SSDC with Independent Channel Dynamics, 541
13.5 Summary, 550

14 Dynamic Spectrum Leasing in Cognitive Radio Networks 553
14.1 Introduction, 553
14.2 DSL with Direct Rewards to Primary Users, 555
   14.2.1 Interference at the Primary Receiver, 560
CONTENTS

14.2.2 A Game Model for Dynamic Spectrum Leasing, 565
14.2.3 Nash Equilibria in Noncooperative Games, 570
14.2.4 Existence of a Nash Equilibrium in the DSL Game, 573
14.3 DSL Based on Asymmetric Cooperation with Primary Users, 587
14.3.1 A Primary–Secondary Coexistence Model, 588
14.3.2 Asymmetric Cooperative Communications-Based DSL between Primary Users and a Centralized Secondary Network, 591
14.3.3 Asymmetric Cooperative Communications-Based DSL between Primary Users and Autonomous Cognitive Secondary Users, 604
14.4 Summary, 609

15 Cooperative Cognitive Communications 613

15.1 Introduction, 613
15.2 Cooperative Spectrum Sensing, 619
15.3 Cooperative Spectrum Sensing and Channel-Access Decisions, 621
15.4 Cooperative Communications Strategies in Cognitive Radio Networks, 624
15.5 Asymmetric Cooperative Relaying in DSA Cognitive Radios, 627
15.5.1 Secondary User Optimal Power Allocation for Asymmetric Cooperative Relaying, 629
15.5.2 Centralized Assignment of Cognitive Radios for Cooperation with Primary Users: An Ideal Approach, 635
15.5.3 Centralized Assignment of Cognitive Radios for Cooperation with Primary Users: A Realistic Approach, 640
15.6 Summary, 644

16 Machine Learning in Cognitive Radios 647

16.1 Introduction, 647
16.2 Artificial Neural Networks, 650
16.2.1 Learning Algorithms for LTUs, 651
16.2.2 Layered Neural Networks, 655
16.2.3 Learning in Layered Feed-Forward Networks: Back-Propagation Algorithm, 656
16.2.4 Neural Networks in Cognitive Radios, 662
16.3 Support Vector Machines, 664
16.3.1 Statistical Learning Theory, 665
16.3.2 Structural Risk Minimization with Support Vector Machines, 669
16.3.3 Linear Support Vector Machines, 670
16.3.4 Nonlinear Support Vector Machines, 674
16.3.5 Kernel Function Implementation of Support Vector Machines, 677
CONTENTS

16.3.6 SVMs in Cognitive Radios, 679
16.4 Reinforcement Learning, 681
  16.4.1 Temporal Difference Learning, 683
  16.4.2 Q-Learning in a POMDP: Replicated Q-Learning, 684
  16.4.3 Reinforcement Learning in Cognitive Radios, 686
16.5 Multiagent Learning, 688
  16.5.1 Game-Theoretic Multiagent Learning, 691
  16.5.2 Cooperative Multiagent Learning, 694
  16.5.3 Multiagent Learning in Cognitive Radio Networks, 696
16.6 Summary, 698

Appendix A Nyquist Sampling Theorem 704
Appendix B A Collection of Useful Probability Distributions 711
  B.1 Univariate Distributions, 711
  B.2 Multivariate Distributions, 713

Appendix C Conjugate Priors 716

REFERENCES 721
INDEX 740