

Cognitive Radio Techniques

Spectrum Sensing, Interference Mitigation, and Localization

Kandeepan Sithamparanathan
Andrea Giorgetti



**ARTECH
HOUSE**

BOSTON | LONDON
artechhouse.com

Contents

	Preface	xxi
1	Introduction to Cognitive Radios	1
1.1	Introduction	1
1.2	Definition of Cognitive Radios	3
1.3	Software-Defined Radios	4
1.4	The Cognitive Cycle	5
1.5	The Radio Scene Analysis	7
1.5.1	Spectrum Occupancy Classification	9
1.5.2	Hidden Terminals	9
1.5.3	Locating Primary Users	10
1.6	Dynamic Spectrum Access and Management	10
1.6.1	Spectrum Underlay and Overlay	11
1.7	Regulatory Aspects	13

1.7.1	The IEEE DySPAN Standards Committee	14
1.7.2	The IEEE 802.22 WRAN Standards	15
1.7.3	The ETSI-RRS Technical Committee	16
1.8	Application Clusters	17
1.8.1	Cellular Mobile Networks	17
1.8.2	Energy Efficiency in Wireless Networks	18
1.8.3	Public Safety Communications	18
1.8.4	Coexistence of UWB Radio Technology	18
1.8.5	Wireless Networks for Smart Grids	19
1.8.6	Vehicular Networks	19
1.8.7	Defense Application Systems	19
	References	20
Part I	Spectrum Sensing in Cognitive Radios	23
2	Fundamentals of Spectrum Sensing and Detection	25
2.1	Introduction	25
2.2	Statistical Detection Techniques	28
2.2.1	Maximum A Posteriori Detection	28
2.2.2	Maximum Likelihood Detection	29
2.2.3	The Neyman-Pearson Detector	29
2.2.4	The Bayesian Risk-Based Detector	30
2.3	Continuous and Discrete Signal Detection	30
2.4	Detection Performance	31
2.4.1	Detection Performance Versus the SNR	33
2.4.2	Detection Performance Versus the Signal Observation Length	33
2.4.3	The ROC Curves	34
2.4.4	Area Under the ROC Curves	34

2.5	Wireless Channel Models	35
2.5.1	Mean Pathloss	35
2.5.2	Shadowing	35
2.5.3	Small Scale Fading	36
2.6	Basic Models for Spectrum Occupancy	37
2.6.1	The Poisson-Exponential Model	38
2.6.2	The Markov Modulated Poisson Process	38
2.6.3	The Poisson-Pareto Burst Process	40
2.7	Stochastic Analysis of Radio Signals	40
2.8	Blind, Partial, and Complete Context Aware Signal Detection	42
2.8.1	Blind Signal Detection	42
2.8.2	Partial-Context Aware Signal Detection	42
2.8.3	Fully Context Aware Detection	42
2.9	Summary	43
	References	43
3	Introduction to Spectrum Sensing Techniques	45
3.1	Introduction	45
3.2	Spectrum Sensing with Energy Detection	46
3.2.1	Energy Detector	46
3.2.2	Energy Detector in Gaussian Channel	47
3.2.3	Energy Detector in Fading Channels	49
3.2.4	Energy Detector in Fading Channels with Shadowing	51

3.3	Energy detection and noise power uncertainty	52
3.3.1	ED Threshold Mismatch	53
3.3.2	SNR Wall	53
3.3.3	Existence of the SNR Wall	55
3.4	Spectrum Sensing with Cyclostationary Feature Detection	56
3.4.1	Cyclostationarity Analysis	57
3.4.2	Cyclostationary Feature-Based Detector	59
3.5	Spectrum Sensing with Matched Filter Detection	60
3.6	Other Spectrum Sensing Techniques	61
3.6.1	Covariance-Based Method	62
3.6.2	Eigenvalue-Based Method	63
3.6.3	Wavelet-Based Edge Detection	63
3.6.4	Spectral Estimation Methods	64
3.7	Summary	65
	References	65
4	Temporal Spectrum Sensing and Performance Analysis	69
4.1	Introduction	69
4.2	Temporal Periodic-Spectrum Sensing	71
4.3	Primary User Spectral Occupancy Model with Poisson Arrival	72
4.3.1	Exponential Random Spectral Occupancy Time	73
4.3.2	Pareto Random Spectral Occupancy Time	73

4.3.3	Classifying Primary User Spectrum Occupancy Levels	74
4.4	Detection Performance of Periodic-Sensing with Poisson Arrival and Deterministic Occupancy Time	75
4.4.1	Spectral Occupancy Probability	75
4.4.2	Probability of Detection	76
4.4.3	False Alarm Probability	78
4.5	Primary User Misdetection Risk Regions	80
4.6	Temporal Periodic-Sensing with Poisson-exponential Occupancy Model	82
4.7	Temporal Periodic-Sensing with Poisson-Pareto Occupancy Model	84
4.8	Temporal Periodic-Sensing Performance Comparison with Deterministic and Random Occupancies	85
4.9	Temporal Periodic-Sensing in Noise	86
4.10	Temporal Periodic-Sensing in Noise with Signal Fading/Shadowing	91
4.11	Optimum Sensing Period	92
4.12	Reality of Spectrum Occupancy Models	93
4.13	Summary	93
	References	94

5	<u>Cooperative Spectrum Sensing</u>	97
5.1	Introduction	97
5.2	Spatio-Temporal Fusion Strategy	99
5.2.1	Synchronized Reporting	100
5.2.2	Nonsynchronized Reporting	100
5.3	Hard Decision Fusion	101
5.3.1	Chair-Varshney Fusion Strategy	102
5.3.2	The M -out-of- N Fusion Strategy	103
5.4	Soft Decision Fusion	106
5.4.1	Optimal Soft Decision Fusion	107
5.4.2	Equal Gain Soft Decision Fusion	108
5.4.3	Maximal Ratio Soft Decision Fusion	109
5.5	Cluster-Based Cooperative Spectrum Sensing	109
5.5.1	Space-Divisional Cluster	110
5.5.2	Frequency-Divisional Cluster	111
5.5.3	Time-Divisional Cluster	111
5.6	Noisy Reporting Channels	113
5.7	Other Issues in Cooperative Sensing	115
5.7.1	Cooperation Overhead and the Reporting Channel	116
5.7.2	Unreliable Reporter and Accreditation	116
5.7.3	Security Issues	116
5.7.4	Knowledge Distribution	117
5.7.5	Spatial Limitation	117
5.8	Summary	117
	References	118

6	Distributed Spectrum Sensing	121
6.1	Introduction	121
6.2	Parallel Topology-Based Distributed Sensing	123
6.3	Sequential Topology-Based Distributed Sensing	125
6.3.1	Detection Performance	127
6.4	Tree Topology-Based Distributed Sensing	127
6.5	Ring-Around Distributed Sensing	128
6.5.1	Message Passing in Ring-Around Sensing	130
6.5.2	Hard Decision Fusion with the OR Rule	130
6.5.3	Equal Ratio Combining Soft Decision-Based Fusion	131
6.6	Summary	132
	References	132
7	Advanced Spectrum Sensing Topics	135
7.1	Introduction	135
7.2	Spectrum Sensing in UWB Radios with Frequency Sweeping	136
7.3	Spectrum Sensing in OFDM Systems	139
7.3.1	The Likelihood Ratio Test	140
7.3.2	Frequency Domain Detection	141
7.4	Combined Localization and Detection of Primary Users	142
7.4.1	Detection Using the Likelihood Function $f_{r H_i}(r H_i)$	143

7.4.2	Detection Using the Output of \mathcal{L}	144
7.5	Sequential Spectrum Sensing	145
7.5.1	The Sequential Probability Ratio Test	145
7.6	Spectrum Sensing with Ordered Statistics	146
7.7	Spectrum Sensing with Reconfigurable Antennas	147
7.7.1	Frequency Reconfigurability	148
7.7.2	Radiation Pattern Reconfigurability	150
7.8	Spectrum Sensing in 3D-Space	150
7.9	Summary	153
	References	154
Part II	Coexistence and Interference Mitigation Techniques	157
8	Fundamentals of Coexistence and Interference Mitigation Techniques	159
8.1	Interference in Cognitive Radio and its Characterization	160
8.1.1	Intentional Interference: From Jamming to Emulation	160
8.1.2	Unintentional Interference	163
8.1.3	Metrics to Quantify Interference and its Effects	163
8.2	Coexistence Scenarios	167
8.2.1	Spatial Configuration of the Systems	169
8.2.2	From Narrowband to Ultrawideband	170
8.2.3	The Coexistence Region	172

8.3	Interference Mitigation Techniques	173
8.3.1	Interference Mitigation in Spread Spectrum CRs	174
8.3.2	Power Control	175
8.3.3	Band Relocation	175
8.3.4	Spectrum Shaping	175
8.3.5	Adaptive Antenna Techniques	176
8.4	Summary and Further Readings	176
	References	176
9	Coexistence Analysis	181
9.1	Coexistence Between Heterogeneous Wireless Systems	182
9.2	Channel Model	183
9.2.1	Block Fading Channel	185
9.3	Interference Modeling	185
9.3.1	Gaussian Approximation	186
9.3.2	Tone Approximation	186
9.3.3	Multitone Approximation	187
9.3.4	Band-Limited Gaussian Process Approximation	188
9.3.5	Pulse Train Model	188
9.3.6	Modeling the Interfering Power	188
9.4	The Effect of Narrowband Interference on a Wideband Communication	189
9.4.1	Single-Carrier WB Communication in the Presence of NB Interference	190
9.4.2	Multicarrier WB Communication in the Presence of NB Interference	203

9.5	The Effect of Wideband Interference on a Narrowband Communication	208
9.5.1	Single-Carrier NB Communication in the Presence of WB Interference	209
9.5.2	Multicarrier NB Communication in the Presence of WB Interference	217
9.6	Summary and Further Readings	217
	References	218
10	<u>Coexistence in Network Scenarios</u>	<u>223</u>
10.1	Coexistence Between Heterogeneous Networks	223
10.1.1	Network Scenario Definition	224
10.2	Statistical Characterization of Network Interference	226
10.2.1	Interference Generated Outside the Guard Zone	229
10.2.2	Interference From the Whole Plane	231
10.3	The Effect of Interference on Performance of Coexisting Networks	236
10.3.1	Transmission Characteristics of the Nodes	236
10.3.2	Narrowband Communication in the Presence of Wideband Network Interference	237
10.3.3	Wideband Communication in the Presence of Narrowband Network Interference	240
10.4	Performance Examples of Heterogeneous Coexisting Networks	243
10.5	Summary and Further Readings	245
	References	246

11	Interference Mitigation Techniques Enabling Coexistence	249
11.1	Cognitive Radio Transmission Techniques Enabling Coexistence	250
11.1.1	Spectrum Interweave: Interference Avoiding Behavior	250
11.1.2	Spectrum Underlay: Interference Controlling Behavior	251
11.1.3	Spectrum Overlay: Interference Mitigating Behavior	252
11.2	The Secondary User Perspective: Performance of CR Transmission Strategies	253
11.2.1	System Model	254
11.2.2	Comparison of the SU Achievable Rates	255
11.3	The Primary User Perspective: Impact of CR Transmission Strategies	256
11.3.1	The Scenario	257
11.3.2	Cognitive Network Interference as a Mis-detection Problem	259
11.3.3	PU Outage due to Mis-detection by a Single SU	260
11.3.4	PU Outage due to Mis-detections in a Cognitive Network	261
11.3.5	A Case Study	262
11.4	Summary and Further Readings	265
	References	266
12	Advanced Interference Mitigation Techniques	269
12.1	Interference Mitigation Techniques in UWB Radios	270

12.1.1	Interference Mitigation in UWB Impulse Radio	271
12.1.2	Interference Mitigation in MB-OFDM UWB Radio	279
12.2	Interference Mitigation in Spatial Domain	283
12.2.1	Example: MIMO Beamforming	284
12.3	Summary and Further Readings	287
	References	287
Part III	Localization and Radio Environment Mapping	291
13	Fundamentals of Ranging and Localization for Cognitive Radio	293
13.1	Ranging Techniques and Enabling Technologies	294
13.1.1	Time-Based Ranging	294
13.1.2	RSS-Based Ranging	296
13.1.3	Other Ranging Techniques	297
13.1.4	Error Sources in Time-Based Ranging	298
13.2	Performance Limits of Time-based Ranging: From Theory to Practice	302
13.2.1	Theoretical Performance Limits	303
13.2.2	Practical Schemes	304
13.3	Cognitive Ranging	306
13.4	Localization Techniques	308
13.4.1	Single-Hop Localization	309
13.4.2	Multihop Localization	311

13.4.3	Anchor-Free Localization	312
13.4.4	Location Tracking	313
13.4.5	Case Study	314
13.5	Summary and Further Readings	316
	References	316
14	Localization of Primary Users	321
14.1	Localization of Noncollaborative Emitters	322
14.1.1	Range-Free Localization of PUs	323
14.1.2	Semirange-Based Localization of PUs	324
14.1.3	RSSI-Based Localization of PUs	325
14.1.4	Other Range-Based Algorithms	329
14.1.5	Tracking of PUs	330
14.1.6	Case Study	331
14.2	Radio Environment Mapping	334
14.2.1	Radio Cartography	336
14.2.2	Database for SU Access Control	338
14.3	Summary and Further Readings	339
	References	339
15	Conclusions and Future Work	343
	Glossary	349
	About the Authors	355
	Index	357