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Spectrum Map and its Applications in Cognitive Radio Networks

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical Engineering and Computer Science in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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Major Professor: Mainak Chatterjee

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ABSTRACT

Recent measurements on radio spectrum usage have revealed the abundance of underutilized bands of spectrum that belong to licensed users. This necessitated the paradigm shift from static to dynamic spectrum access. Cognitive radio based secondary networks that utilize such unused spectrum holes in the licensed band, have been proposed as a possible solution to the spectrum crisis. The idea is to detect times when a particular licensed band is unused and use it for transmission without causing interference to the licensed user. We argue that prior knowledge about occupancy of such bands and the corresponding achievable performance metrics can potentially help secondary networks to devise effective strategies to improve utilization.

In this work, we use Shepard's method of interpolation to create a spectrum map that provides a spatial distribution of spectrum usage over a region of interest. It is achieved by intelligently fusing the spectrum usage reports shared by the secondary nodes at various locations. The obtained spectrum map is a continuous and differentiable 2-dimension distribution function in space. With the spectrum usage distribution known, we show how different radio spectrum and network performance metrics like channel capacity, secondary network throughput, spectral efficiency, and bit error rate can be estimated. We show the applicability of the spectrum map in solving the intra-cell channel allocation problem in centralized cognitive radio networks, such as IEEE 802.22. We propose a channel allocation scheme where the base station allocates interference free channels to the consumer premise equipments (CPE) using the spectrum map that it creates by fusing the spectrum usage information shared by some CPEs. The most suitable CPEs for information sharing are chosen on a dynamic basis using an iterative clustering algorithm. Next, we present a contention based media access control (MAC) protocol for distributed cognitive radio network. The unlicensed secondary users contend among themselves over a common control channel. Winners of the contention get to access the available channels ensuring high utilization and minimum collision with primary incumbent. Last, we propose a multi-channel, multi-hop routing protocol with secondary transmission power control. The spectrum map, created and maintained by a set of sensors, acts as the basis of finding the best route for every source destination pair. The proposed routing protocol ensures primary receiver protection and maximizes achievable link capacity.

Through simulation experiments we show the correctness of the prediction model and how it can be used by secondary networks for strategic positioning of secondary transmitterreceiver pairs and selecting the best candidate channels. The simulation model mimics realistic distribution of TV stations for urban and non-urban areas. Results validate the nature and accuracy of estimation, prediction of performance metrics, and efficiency of the allocation process in an IEEE 802.22 network. Results for the proposed MAC protocol show high channel utilization with primary quality of service degradation within a tolerable limit. Performance evaluation of the proposed routing scheme reveals that it ensures primary receiver protection through secondary power control and maximizes route capacity.

To my father, my idol Mr. Samarjit Debroy, my mom, my God Mrs. Mahua Debroy, and my grandparents Late Mr. Tamonash Debroy, late Mrs. Shova Rani Debroy, Mr. Paresh Lal Sarkar, and Mrs. Chitra Sarkar. For you I am here.

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TABLE OF CONTENTS

LIST OF FIGURES
LIST OF TABLES
CHAPTER 1: INTRODUCTION
1.1 Contributions
1.2 Organization of the Dissertation
CHAPTER 2: RELATED WORK
2.1 Radio Spectrum Measurements
2.2 Resource Allocation in IEEE 802.22 Networks
2.3 MAC Protocols for Cognitive Radio Networks
2.4 Routing in Cognitive Radio Networks
CHAPTER 3: SPECTRUM MAP

3.1	Specti	rum Sensing and Cooperative Sharing 1	6
	3.1.1	Cooperative sharing of sensed data 1	7
3.2	Chara	cterizing Spectrum Usage Distribution	8
	3.2.1	Distance of data points	0
	3.2.2	Direction of data points	1
	3.2.3	Hypothesis analysis 2	4
3.3	Estim	ating Performance Metrics 2	5
	3.3.1	Channel capacity	7
	3.3.2	Secondary network throughput	7
	3.3.3	Spectral efficiency	8
	3.3.4	Bit error rate	9
3.4	Simula	ated Spectrum Map and Performance Metrics	0
3.5	Summ	nary	3
CHAP	ΓER 4:	CHANNEL ALLOCATION IN IEEE 802.22 NETWORKS	8

4.1	IEEE 802.22 Wireless Regional Area Networks	39
4.2	System Model	41
	4.2.1 State definitions	42
	4.2.2 Delegation of CPEs	43
	4.2.3 Sharing raw spectrum data	48
	4.2.4 Intelligent beacon broadcast	50
4.3	Performance Metrics based Channel Allocation	52
	4.3.1 Allocation process	52
4.4	Summary	54
CHAPT	FER 5: CONTENTION BASED MAC PROTOCOL	56
5.1	System Model and Assumptions	56
5.2	The Proposed MAC Protocol	58
	5.2.1 The frame structure	58
	5.2.2 The contention process	59

	5.2.3	Data channel grabbing and transmissions	60
	5.2.4	Mode of operation	61
	5.2.5	Design optimizations	62
5.3	Analy	sis of the Proposed MAC Protocol	63
	5.3.1	The primary ON-OFF model	64
	5.3.2	RTS success probability	66
	5.3.3	Idle channel grabbing	66
	5.3.4	Blocking probability	67
	5.3.5	Secondary usage	68
	5.3.6	PU QoS degradation	70
5.4	Differe	ential QoS through multiple slots reservation	73
	5.4.1	Multiple data-slots	73
	5.4.2	Differential QoS	75
	5.4.3	Idle channel utilization	77

5.5	Summary	
CHAP	TER 6: MULTI-CHANNEL, MULTI-HOP ROUTING IN COGNITIVE RA	DIO
NETW	ORKS	
6.1	Challenges in Cognitive Routing	
6.2	System Model	82
	6.2.1 Primary network	82
	6.2.2 Secondary network	83
6.3	Proposed Routing Scheme	84
	6.3.1 Route discovery	85
	6.3.2 Route maintenance	91
6.4	Mathematical Modeling	92
	6.4.1 Edge node probability	
	6.4.2 Connectivity condition	
6.5	Summary	98

CHAPT	ΓER 7:	SIMULATION MODEL AND RESULTS
7.1	IEEE	802.22 Channel Allocation $\ldots \ldots 100$
	7.1.1	Nature and accuracy of estimation
	7.1.2	Channel allocation
7.2	Conte	ntion based MAC Protocol 109
7.3	Spectr	um Map based Multihop Routing
CHAPT	ΓER 8:	CONCLUSIONS 132
LIST O)F REF	ERENCES $\dots \dots \dots$

LIST OF FIGURES

Figure 1.1	Static radio frequency allocation in the United States	8
Figure 3.1	Different orientations of data points influencing estimation at $(\boldsymbol{x}_t, \boldsymbol{y}_t)$	21
Figure 3.2	Power spectral density of a channel with 40 sensing locations $\ldots \ldots$	31
Figure 3.3	Power spectral density of a channel with 60 sensing locations $\ldots \ldots$	32
Figure 3.4	Power spectral density of a channel with 80 sensing locations $\ldots \ldots$	33
Figure 3.5	Spatial distribution of estimated noise	34
Figure 3.6	Spatial distribution of channel capacity	34
Figure 3.7	Spatial distribution of bit error rate	35
Figure 3.8	Channel capacity for different channels in the spectrum band \ldots .	35
Figure 3.9	System throughput	36
Figure 3.10	Per-user throughput	36
Figure 3.11	Spectrum occupancy vectors for two different scenarios	37
Figure 4.1	Architecture of an IEEE 802.22 network	39
Figure 4.2	State transition diagram of a CPE	41
Figure 4.3	One cluster with a single representation point	44

Figure 4.4	Two cluster with two representation points	45
Figure 4.5	Four clusters with four representation points	46
Figure 4.6	IEEE 802.22 network with base station and different types of CPEs $\ . \ .$	48
Figure 5.1	MAC frame structure	59
Figure 5.2	Consecutive data and contention slots	69
Figure 5.3	A scenario with multiple data-slots reservation	76
Figure 6.1	Routing among SUs in the presence of primary transmitters and receivers	80
Figure 6.2	A region of interest with primary transmitters, primary receivers, sensors, ed	dge,
non-edge, a	and uncovered secondary nodes	85
Figure 6.3	Safe zone around secondary node i for channel n	88
Figure 6.4	Inter-domain routing through selective flooding	90
Figure 6.5	Inter-domain routing through selective flooding	91
Figure 6.6	Flowchart for route discovery	93
Figure 6.7	Deterministic grid deployment of sensors with the overlapping regions $\ .$	94
Figure 6.8	Deployment to undirected grid mapping	96
Figure 7.1	Simulation environment	101
Figure 7.2	Estimated signal strength of a channel	103
Figure 7.3	Actual received signal strength of same channel	103
Figure 7.4	Error in estimation	104

Figure 7.5	Estimated signal strength of a channel	104
Figure 7.6	Actual received signal strength of same channel	105
Figure 7.7	Error in estimation	105
Figure 7.8	Instances of false positives in estimation for different values of probability	y of
getting free	channels in the spectrum	106
Figure 7.9	Accuracy of estimation with varying number of delegation CPEs for interpo	ola-
tion		106
Figure 7.10	Number of channel allocated from total available channels $\ldots \ldots \ldots$	107
Figure 7.11	Utilization of available channels for different probabilities of white space	108
Figure 7.12	Number of allocated CPEs for different number of channels in the spectrum	108
Figure 7.13	Number of channels allocated with varying number of idle CPEs \ldots	109
Figure 7.14	RTS success probability.	110
Figure 7.15	Idle channel grabbing characteristics, with $N_T = 30$ and $\lambda_s = 3$	110
Figure 7.16	Idle channel grabbing characteristics with $N_T = 30$ and $N_S = 100$	111
Figure 7.17	Idle channel grabbing characteristics with $N_T = 30$ and $p_{idle} = 0.5$	112
Figure 7.18	Average blocking probability with $N_T = 30, N_S = 200, p_{idle} = 0.5$	113
Figure 7.19	Average blocking probability with $N_T = 30, \lambda = 1$	114
Figure 7.20	Idle channel utilization with $N_T = 30$ and $\lambda_s = 3$	114
Figure 7.21	Idle channel utilization with $N_T = 30$ and $N_S = 100$	115

Figure 7.34 Reachability of the secondary nodes without power control for different scenarios 125

Figure 7.35 Reachability of the secondary network with power control for different scenarios 127

Figure 7.36	Percentage of non-existent channels for using power-control in routing .	128
Figure 7.37	Routing without power control between Node 158 and Node 42 \ldots .	128
Figure 7.38	Routing with power control between Node 158 and Node 42 \ldots .	129
Figure 7.39	Average route capacity with sensor radius	129
Figure 7.40	Bottleneck capacity with sensor radius	130
Figure 7.41	Maximum occurrences of channel switches with hop count in routes	131

LIST OF TABLES

Table 5.1	Notations used for MAC analysis	65
Table 5.2	PU arrivals and corresponding channel grabbing and secondary usage	69
Table 6.1	Notations used for routing analysis	94

CHAPTER 1: INTRODUCTION

Radio spectrum allocation and management have traditionally followed a 'command-andcontrol' approach where chunks of spectrum are allocated for specific services under restrictive licenses. The restrictions specify the technologies to be used and the services to be provided, thereby constraining the ability to make use of new technologies and the ability to redistribute the spectrum to higher valued users. Over the past years, traditional approaches to spectrum management have been challenged by new insights into the actual use of spectrum. In most countries, all frequencies have been completely allocated to specific uses and spectrum appears to be a scarce resource within the current regulatory framework. In Fig. 1.1, we show the radio spectrum allocation chart of the United States. There have been experimental studies that reveal that spectrum utilization is time and space dependent and that most parts of radio spectrum are highly underutilized [1, 2, 3]

These limitations have motivated a paradigm shift from static spectrum allocation towards a notion of dynamic spectrum management where secondary networks/users (nonlicense holders) can 'borrow' idle spectrum from those who primary networks/users (license holders) without causing harmful interference to the latter. Cognitive radio networks (CRNs) that utilize such unused spectrum holes within the licensed band have been proposed as a possible solution to the spectrum crisis. The idea is to detect times when a particular licensed band is unused and use it for transmission without causing interference to the licensed user. Secondary users equipped with cognitive radio enabled devices will facilitate such dynamic spectrum access (DSA) where the cognitive radios continuously monitor the presence of primary users and opportunistically access the unused or under-utilized licensed bands [4]. However, the most important regulatory aspect of these networks is that the secondary nodes must not interfere with primary transmissions. Thus, when secondary nodes detect transmissions from primaries, they are mandated to relinquish those interfering channels immediately and switch to other non-interfering channels.

Due to the temporal and spatial fleetingness of spectrum occupancy, such reactive nature of secondary networks is insufficient for desired utilization of under-used licensed spectrum. We argue that a prior knowledge of the possible transmission activities of the primaries can allow the secondary nodes to effectively access the available resource and predict the expected radio and network performances for quality of service (QoS) provisioning. Such prior knowledge would also help in finding better routes to a destination in a secondary network where route quality are ever changing with primary activity. Thus, there is a need to proactively estimate the spectrum usage at any *arbitrary* location and predict the nature of spectrum utilization in the region of interest. The recent ruling by FCC [5] also necessitates the need for secondary networks to create, manage and refer to spectrum usage databases for secondary access opening new discussions on design, implementation techniques, and capabilities of such spectrum usage databases.

One such secondary network is the IEEE 802.22 Wireless Regional Area Network (WRAN). Channel allocation to Consumer Premise Equipments (CPEs) is performed by the base station, which is assumed to have an accurate estimation of spectrum usage of all CPEs in its range. We argue that efficient channel allocation and sustenance of high data rates with low interference in IEEE 802.22 networks largely rests upon the base station's ability to accurately estimate spectrum usage and allocate unused bandwidth to the CPEs. Therefore, estimating primary activity will allow the base station to allocate better (in terms of achievable QoS) channels to candidate CPEs and at the same time assign best candidate channels among CPEs for greater utilization and re-use. Such spectrum maps can also potentially be used for channel contention in a distributed ad-hoc environment. Using the spectrum map, the secondaries with no sensing ability can contend for free channels among themselves and devise an effective MAC scheme to better utilize available channel and minimize potential collision with primary incumbent. Moreover, prior estimation of spectrum usage can also be an effective tool for intelligent routing in a secondary network where nodes have limited or no sensing ability. A prior knowledge on primary activity and achievable capacity on the free channels can be used to device a multi-channel multi-hop routing that maximizes network throughput, and better utilizes free channels through power control.

1.1 Contributions

In this work, we create a *Spectrum Map* by defining a spatial distribution function for spectrum utilization. This map works as a reference database to predict the spectrum usage at any arbitrary location. We argue that such prediction can be achieved by fusing the information gathered by the various stationary secondary nodes operating at different locations. Therefore, we use a collection of such nodes at different locations that monitor the spectrum usage in a distributed manner and share their findings with others. Through cooperatively fusing the raw spectrum usage data from these nodes, we show how an interpolation function can be used to construct a continuous and differentiable distribution function which governs the estimation of the spectrum utilization at any location. In order to achieve accurate estimation, we use an *iterative clustering* technique using tree structured vector quantization (TSVQ) to find the ideal locations for these monitoring nodes.

We evaluate our proposition by measuring the accuracy of estimation and also characterizing the nature of *spectrum map*. We emulate an environment using the real-world spectrum data of RWTH Mobnets [6] and replicating their transmission pattern. We observe that on an average, the estimation technique yields very few false positives and false negatives. We also derive bounds on the optimal number of monitoring secondary nodes to be consulted in order to reach a desired level of estimation accuracy. We use this prior knowledge of spectrum utilization to predict radio and network performance. We demonstrate how performance metrics like the channel capacity, system throughput, spectrum efficiency, and bit error rates, can be estimated for a secondary transmitter-receiver pair at any secondary network location. We also simulate the nature of these performance metrics.

We then apply our spectrum usage estimation technique to propose an on-demand channel allocation scheme for IEEE 802.22 networks where the base stations allocate free channels to CPEs. We argue that the lack of knowledge about the channel usage scenario at the CPE locations is the primary difficulty in efficient channel assignment. We use an *iterative clustering* technique using TSVQ to find the ideal locations for these *delegate CPEs*. The base station then intelligently combines or fuses data from the delegates to create the spectrum map. Usage of spectrum map is manyfold: the map enables the base station to create binary decision vectors that denote the occupancy/availability of *all* the channels at *any* location (including the CPE locations) within its range. Secondly, it is also used to communicate with a candidate CPE and increase the probability of synchronization between the CPE and the base station. Finally, achievable QoS/performance metrics are estimated for the available channels and the candidate channel is allocated to a CPE maximizing network throughput.

We evaluate the proposed allocation scheme using simulation experiments. We construct a simulation environment emulating the location distribution of digital TV transmitters in US [6], [7] and duplicating their transmission patterns. We deploy the IEEE 802.22 networks at different locations that cover both dense and sparse populations of primaries emulating urban and rural areas. We compare the accuracy of spectrum usage estimation by using the results with actual received signal strength values. We show how the proposed channel allocation scheme ensures free channel utilization. We also show that in a potentially extreme and highly improbable scenario with *all* the CPEs in a cell requesting channels at the same time, the proposed scheme successfully allocates channels to the CPEs. Finally the results show close to perfect allocation and free channel utilization even in worst case scenario with no intra-cell spatial reuse.

Next, we utilize the spectrum map to design an efficient multi-channel MAC protocol for distributed ad-hoc cognitive radio networks. We design a system where the secondary nodes contend over a common control channel for data channel access. Winning the contention prompts the secondary nodes to gain access to the usable data channels. We analyze and simulate the performance of the proposed MAC protocol in terms of probabilities of blocked channels access attempt, idle channel grabbing, idle channel utilization, as well as PU quality of service (QoS) degradation. We compare our scheme with two competitive multi-channel MAC protocols [8] and [9] which are better performing than the other MAC schemes in literature. We compare the performance in terms of average channel utilization, system throughput, and primary degradation caused by misdetection.

We extend the application of spectrum map design a cross layer multi-channel multihop routing algorithm for distributed cognitive radio networks. The protocol ensures data packet routing among low cost sensing incapable secondary nodes through a few sensing enabled nodes capable of building spectrum map. This spectrum map works as a basis of finding best routes among nodes and also governs secondary transmission power to protect primary receivers and ensure better channel utilization and reuse among secondary nodes. We propose a *selective flooding* technique to spread the route requests in the network without causing network wide flooding overhead. We define and analyze the connectivity condition among such secondary nodes in presence of primary users. We perform extensive simulation experiments to examine the performance of the routing protocol in terms of connectivity among the nodes, reachability of each node from all other nodes, achievable bottleneck capacity of routes, average hop count, primary receiver protection, and free channel reuse through power control. We also compare our results with optimal cognitive routing.

1.2 Organization of the Dissertation

The dissertation is organized as follows. Chapter 2 presents the related work that are relevant to this thesis. In Chapter 3, the creation of spectrum map is explained along with the discussion on predicting channel performance metrics. Chapter 4 discusses the proposed intra-cell channel allocation scheme using the spectrum map. Chapter 5 discusses how spectrum map can be used to design an efficient contention based MAC protocol. In Chapter 6, we propose a spectrum map driven multi-channel multi-hop routing scheme in a distributed cognitive radio network with power control. In Chapter 7, the simulation model and results are presented. Conclusions are drawn in Chapter 8.



Figure 1.1 Static radio frequency allocation in the United States

CHAPTER 2: RELATED WORK

In this chapter, we discuss some important related work. We categorize the discussion in works on i) radio spectrum measurements, ii) resource allocation in WRANS, iii) cognitive MAC protocols, and iv) different routing schemes in CRNs.

2.1 Radio Spectrum Measurements

Prior work in modeling the spectrum usage involves deriving the distribution of spectrum utilization in a primary network using both theoretical models and real-world data logs [6, 7, 10, 11, 12]. One of the earliest work in spectrum measurements was reported by NSF [11] where it was concluded that less than 1% of the spectrum opportunities, both in frequency and time, were utilized at the place of measurement. Authors in [10] measured the spectrum usage at different locations in Tokyo city and created 3-dimensional plots that showed the temporal distribution of frequency usage near the monitored points. In [7], authors observed that the location distribution of primary TV transmitters in USA and Europe closely follow Poisson model. A frequency distribution model to emulate the nature of noise from a primary transmitter on different channels was presented in [6]. Most notable recent measurement was carried out by Harrold et. al [12] where three years of continuous measurement observations for the city of Chicago were presented. Though the above mentioned techniques allow us to predict the spectrum usage at known locations, there is still little understanding on how to build a mathematical function to capture the spatial distribution for the spectrum utilization. In [13] authors modeled the temporal behavior of spectral activity as a continuous time semi-Markov process. Some notable work has also been done on geolocation databases. Authors in [14] highlighted the benefits of geolocation database technology and Murty et. al in [15] went closest to implementing a database driven secondary network for TV white space (TVWS). However design principles and implementation specifics on predicting spectrum usage at *any arbitrary location* for any generic secondary network remain a challenge.

2.2 Resource Allocation in IEEE 802.22 Networks

As far as IEEE 802.22 networks are concerned, most of the existing work is focused on selfcoexistence of IEEE 802.22 networks, signal detection, and spectrum sensing. The problem of co-existence where multiple base stations co-cooperatively share the available spectrum so that they can co-exist was discussed in [16]. Through a minority game theoretic approach, the spectrum band switching was modeled as a mixed strategy Nash Equilibrium. Authors in [17], designed a resource-transaction algorithm for inter-base station coexistence in IEEE 802.22 networks. They used a game theoretic approach to demonstrate how the proposed algorithm ensures all players' participation without resource loss and also guarantees revenue maximization of the resource provider. In [18], the authors proposed a multi-player noncooperative repeated potential game with each WRAN as a player maximizing the spatial reuse and minimizing the interference.

Some notable work has been done on primary incumbent spectrum sensing and signal detection in TV spectrum using various techniques. Different signature based spectrum sensing methods are described and compared in [19]. Using simulation experiments, the authors show how these types of algorithms perform better in detecting actual incumbent signals from noise using the probability of detecting a false alarm as a parameter. A WRAN and wireless microphone coexistence model to increase spatial reuse of TV spectrum and protect small scale incumbents has been proposed in [20]. In [21], a study on the TV spectrum in North America is conducted and the authors propose a unified signature-based spectrum sensing algorithm designed for the primary licensed signals. In [22], a mechanism for a robust distributed cooperative sensing is discussed by harnessing diversity of sensors. The authors proposed an *attack tolerant* distributed sensing protocol which takes the geographical proximity to group a collection of sensor nodes to form a cluster. In [23], the authors suggest key techniques for efficient in-band sensing in IEEE 802.22 networks, utilizing a clustered sensor network and subsequently proposing an in-band sensing algorithm that optimizes sensing period and sensing time to meet the detectability requirements while minimizing sensing overhead.

With regard to channel allocation in IEEE 802.22 networks, a distributed assignment scheme has been proposed for an IEEE 802.22 mesh topology in [24]. Although the method tries to propose how a mesh network of all the CPEs and base station can be formed inside a cell, the paper does not discuss problems like channel assignment to CPEs and how links are established between the base station and the CPEs in the absence of any dedicated control channel. In [25], the authors proposed a dynamic spectrum access technique using a game theoretic model for spectrum bidding and pricing. Investigations on control channel assignment in generic cognitive radio networks can be found in [26]. Authors in [15] were the first to create a database driven framework for TV white space networking; however, to the best of our knowledge, no work has been done that investigates channel allocation within an IEEE 802.22 network that enhances performance.

2.3 MAC Protocols for Cognitive Radio Networks

The absence of any central entity or a repository containing up-to-date information about usable channels necessitates the need for a contention based MAC protocol where there cannot be any presumption on any node-to-node coordination. Though there have been MAC protocols developed for single channel [27] and multi channels [28, 29] for distributed ad hoc and sensor networks, they are not directly applicable to the cognitive radio networks because of two reasons: i) the set of available channels for communication is always changing in time because of dynamic primary activity, and ii) the set of available channels for every node could be different based on their spatial location. The cognitive radios either can simply choose to transmit data packets on some channel hoping that there would not be any collision, or they can choose to go through a contention phase where the nodes first agree on what channel each must use. There have been some MAC protocols that have been proposed for cognitive radio networks (CRNs). In [30], authors proposed a broad classification of the MAC protocols. They divided MAC protocols into different genres which include MAC protocol for ad hoc CRNs and centralized CRNs. In [31], a MAC protocol for ad hoc CRNs was defined, which studied the effects of random sensing policy and negotiated sensing policy on the throughput of secondary users. However, how the co-ordination is maintained among the secondaries regarding channel sensing is not discussed. In [8], the authors designed an opportunistic multi-channel MAC for QoS provisioning. Different control channel implementations for multi-channel MAC protocols in CRNs are studied and their performances are analyzed in [32]. None of these work, to the best of our knowledge, have not considered exclusive sensing devices that work independently. Separating sensing from secondary contention and transmission is expected to result in better access of the channels while they are unused, thus increasing the idle channel utilization.

2.4 Routing in Cognitive Radio Networks

Cognitive routing protocols are broadly categorized into two main classes depending on the assumptions taken on the issue of spectrum-awareness: full spectrum knowledge and local spectrum knowledge. In the former case, a spectrum occupancy map is available to the network nodes, or to a central control entity, which could be represented by the centrally maintained spectrum databases. On the other hand, routing schemes based on local spectrum knowledge include all those solutions where information on spectrum availability is locally gathered at each SU through distributed protocols.

Some examples of routing protocols with full spectrum knowledge are [33, 34, 35, 36]. The authors in [33] propose a comprehensive framework to jointly address channel assignment and routing in semi-static multi-hop CRNs. In that work, the PU dynamics are assumed to be low enough such that the channel assignment and the routing among SUs can be statically designed. A graph structured based approach is proposed in [34], where a colored graph is used to represent the network topology. Route and spectrum selection in networks with single transceiver half duplex cognitive radios are addressed in [35]. The proposed solution decouples routing and channel (spectrum) assignment. In [36], the focus is on the problem of designing efficient spectrum sharing techniques for multi-hop CRNs. It introduces a Mixed Integer Non-Linear Programming (MINLP) formulation whose objective is to maximize the spectrum reuse factor throughout the network, or equivalently, to minimize the overall bandwidth usage throughout the network.

Notable work on routing protocols with limited/local spectrum knowledge include [37, 38, 39, 40, 41, 42, 43]. The distributed algorithm presented in [37] addresses the scheduling, power control, and routing problems simultaneously. Authors in [38], introduced a metric for multi-hop CRN which is aware of both the switching delay between frequency bands and back-off delay within a given frequency band. In [39], a distributed resource management strategy to support video streaming in multi-hop cognitive radio networks has been presented. The Spectrum Aware Mesh Routing (SAMER) proposed in [40] is a routing protocol
that accounts for long term and short term spectral availability. SAMER seeks to utilize available spectrum blocks by routing data traffic over paths with higher spectrum availability, without ignoring instantaneous spectral conditions. Link stability is considered in [41] where link stability is associated to the overall path connectivity via a mathematical model based on the Laplacian spectrum of graphs. In [42], a route stability oriented routing analysis and protocol are presented where a novel definition of route stability is introduced based on the concept of route maintenance cost. In [43], SEARCH routing protocol is designed for mobile multi-hop CRNs based on geographic forwarding principles. The proposed protocol makes routing and channel selection decisions while avoiding regions of PU activity.

CHAPTER 3: SPECTRUM MAP

This chapter discusses the creation of the *Spectrum Map* by defining a spatial distribution function for spectrum utilization. We also demonstrate how the map is used to predict radio and network performance metrics like channel capacity, system throughput, spectrum efficiency, and bit error rates for a secondary transmitter-receiver pair at any location.

3.1 Spectrum Sensing and Cooperative Sharing

We consider a collection of secondary cognitive nodes that are randomly deployed at different locations in a region of interest. These nodes continuously sense the transmissions by primary nodes and record the noise from primary transmitters for every channel for the entire spectrum band under consideration. We do not focus on any particular sensing technique since there are several techniques that could possibly be used. These include cyclostationary feature detection [44], matched filter detection [45], eigen value based detection [46], wavelet approach [47], energy detectors (with low bandwidth control channel) [48] to name a few. The simplest form of these detectors can be thought of being energy detectors which have proved to be simple, efficient, and cost-effective. Although any stand-alone sensing technique can be used to detect the presence of primary nodes on a channel, we are more interested in fusing the power spectral density at any location.

3.1.1 Cooperative sharing of sensed data

Cooperative sharing of sensed spectrum data between secondary transmitters employed in our model is functionally different from conventional *Cooperative Spectrum Sensing* [49, 50]. Cooperative spectrum sensing is a technique where multiple secondary nodes share their findings (binary decision vectors indicating occupancy of primary nodes on each channel) in a cooperative manner to better detect the presence of primary transmitters and reduce false positives. However, our approach of collaborative sharing is different– we allow the sensing nodes to share raw spectrum data (i.e., power spectral density) instead of just the decision (binary) vectors. Sharing of such raw spectrum data although increases the broadcasting payload, the eventual fusion of all such data minimizes individual detection error and increases interpolation efficiency. Such sharing of raw data needs high bandwidth control channels and falls under the all possible detectors cooperative regime [51]. Now depending on the network architecture, there can be two ways to share the sensed data: centralized or distributed. It is to be noted that, in both approaches, the sensing mechanism is distributed; however, the collection and fusion of data are different.

Centralized cooperation: In a centralized cooperative system, the secondary nodes periodically share the sensed spectral information with a central node which acts as a central

repository where the data get processed. The nodes are required to share their sensed data in a periodic manner irrespective of the need.

Distributed cooperation In a distributed cooperative system, every cognitive node shares its sensed data with all or selected secondary nodes within a certain radius using some control channels. The target secondary node uses the shared spectrum data to create the spectrum map of its vicinity (neighboring region). In distributed sharing, sharing takes place only when one of the sensing nodes initiates sharing.

3.2 Characterizing Spectrum Usage Distribution

The basis for modeling a spatial distribution of spectrum usage is to estimate the activity on every channel. Such estimation of spectrum usage at any arbitrary point from a given set of points is non-trivial. In essence, we seek to define a continuously differentiable twodimensional interpolation function which passes through all the given irregularly-spaced data points¹. It can be noted that the estimation method is identical for both distributed and centralized sharing system.

Let us consider that we have $|\Delta|$ cognitive radio enabled secondary nodes monitoring the spectrum usage and let the co-ordinates of the *i*th secondary node be δ_i be (x_i, y_i) . Also, this node records some data value of z_i . The data value can correspond to one of the many radio parameters like SNR, duty cycle, or detected energy for a particular channel that the

 $^{^{1}}$ We use the monitoring secondary nodes as the data gathering points, hence we also refer to them as 'data points'.

node is sensing. Now, given $|\Delta|$ such triplets (x_i, y_i, z_i) , we seek to find a two dimensional interpolation function f(x, y) = z that will be continuously differentiable, passing through all the data points i.e., $f(x_i, y_i) = z_i$, and should conform to real life values. Such an interpolation function will allow us to evaluate the spectrum usage (i.e., the data value) at any arbitrary target location say (x_t, y_t)

We start with a basic approach to interpolate values using weighed averages. Let e_q^i be the value of the detected energy at δ_i for channel ch_q . If d_i^t is the Euclidean distance between δ_i and (x_t, y_t) , then the estimated received energy in channel ch_q can be interpolated as:

$$\phi_q^t = \frac{\sum_{i=1}^{|\Delta|} (d_i^t)^{-k} e_q^i}{\sum_{i=1}^{|\Delta|} (d_i^t)^{-k}}$$
(3.1)

Here k is the power of the distance weighing factor.

Although this technique of finding expected received energy at an arbitrary point is easy to compute, it overlooks some key aspects: the distance between the data points and the secondary receiver, and the relative positions of the known data points with respect to that receiver. In this regard, we make use of the Shepard's [52] method of interpolation for irregularly spaced data points in a two dimensional region.

3.2.1 Distance of data points

Let r be the radius of circle drawn centering (x_t, y_t) and the farthest of the data points being at the edge of the circle. The value of r depends upon choice of (x_t, y_t) and the number of monitoring secondary nodes. Let us define the set $R^t = \{\delta_1, \delta_2, \dots, \delta_n\}$ such that $0 \le d_1^t \le d_2^t \le \dots \le d_n^t$ which gives the data points in an ascending order of their distances from (x_t, y_t) . As the data points have varying distances from (x_t, y_t) , they ought to have a weighing function that reflects the effect of distance of a data point. Such a weighing function dependent on the search radius is given by [52]:

$$p_i^t = \begin{cases} \frac{1}{d_i^t} & if \ 0 < d_i^t \le \frac{r}{3} \\ \frac{27}{4r} (\frac{d_i^t}{r} - 1)^2 & if \ \frac{r}{3} < d_i^t \le r \end{cases}$$

The above function is defined to be continuously differentiable over all $d_i^t > 0$. It can easily be argued that more data points will yield a better estimation; however, they will also increase the computational complexity.

Considering the effect of distance of the data points, the estimated received energy value can be modified as:

$$\phi_q^t = \frac{\sum_{\delta_i \in R^t} (p_i^t)^2 e_q^i}{\sum_{\delta_i \in R^t} (p_i^t)^2}$$
(3.2)



Figure 3.1 Different orientations of data points influencing estimation at (x_t, y_t)

However, this interpolation function does not reflect the effect of direction of those data points i.e., the relative angle they make with each other. Next, we consider the direction of data points.

3.2.2 Direction of data points

First, let us demonstrate the effect of direction of data points with the help of an example. In Fig. 3.1, we see two different orientations of data points 1, 2 and 3 with respect to point (x_t, y_t) . In both cases, the distances of the points from (x_t, y_t) are d_1 , d_2 and d_3 respectively. In the first orientation, all the points are on the same side of (x_t, y_t) whereas in the second orientation they are on different directions with respect to (x_t, y_t) . The disparate spatial orientations in these two cases yield different effects on (x_t, y_t) . Thus, we consider *all* the possible set of angles that each data point makes with all other data points. The directional weighting term for each selected data point δ_i near (x_t, y_t) is given as

$$a_i^t = \frac{\sum_{\delta_j \in R^t} (p_j^t) [1 - \cos \angle \delta_i \ t \ \delta_j]}{\sum_{\delta_j \in R^t} (p_j^t)} \forall j \neq i$$

Now, considering the effect of number, distances, and directions of data points on (x_t, y_t) , we define the weighing factor as $w_i^t = (p_i^t)^2(1 + a_i^t)$. It is to be noted that in the directional weighing term a_i^t , the distance weighting factor p_j^t is included in the numerator and the denominator because points near (x_t, y_t) should be more important in shadowing than distant points [52]. Thus, the final interpolated received energy for channel ch_q considering the distance and direction factors is:

$$\phi_q^t = \frac{\sum_{\delta_i \in R^t} w_i^t e_q^i}{\sum_{\delta_i \in R^t} w_i^t}$$
(3.3)

Note, this is the estimated channel usage of a *particular* channel ch_q . To get the values for the entire spectrum range, Φ^t , we simply repeat the computations for all the channels (let there be N channels in the spectrum) concerned. The process of computing Φ^t is shown in Algorithm 1. The interpolation technique meets all the requirements (i.e., defined at every point and is continuously differentiable) for computing the spectrum usage scenario at the target location (x_t, y_t) . With the usage for the entire spectrum known, we can find the set of free channels at (x_t, y_t) for which we needs to apply hypothesis analysis on every channel. Algorithm 1 Interpolation Algorithm

1: Find radius r2: Find the set of data points $R^t = \{\delta_i | 0 \le d_1^t \le \dots \le d_n^t\}$ 3: for all channels q in the spectrum do for all data points i in the set R^t do 4: if $0 \le d_i^t \ge \frac{r}{3}$ then $p_i^t \Leftarrow \frac{1}{d_i^t}$ 5: 6: else $\{\frac{r}{3} \leq d_i^t \leq r\}$ $p_i^t \Leftarrow \frac{27}{r}(\frac{d_i^t}{r} - 1)^2$ end if 7:8: 9: for all data points k where $i \neq k$ do 10: Find p_k^t 11: $angle_{ik}^{t} \leftarrow (x - x_i)(x - x_k) + (y - y_i)(y - y_k)$ $s_{ik}^{t} \leftarrow num_{ik}^{t} + p_k(1 - angle_{ik}^{t})$ $t_{ik}^{t} \leftarrow den_{ik}^{t} + p_k^{t}$ 12:13:14:end for 15: $\begin{aligned} a_i^t &\Leftarrow \frac{s_{ik}^t}{t_{ik}^t} \\ w_i^t &\Leftarrow (p_i^t)^2 (1+a_i^t) \end{aligned}$ 16:17: $\begin{array}{l} num_i^t \leftarrow w_i^t e_q^i + num_i^t \\ num_i^t \leftarrow w_i^t e_q^i + num_i^t \\ den_i^t \leftarrow w_i^t + den_i^t \end{array}$ 18:19:end for 20: $\phi_q^t \Leftarrow \frac{num_i^t}{den_i^t}$ 21: 22: end for

The complexity of algorithm 1 is $O(m^2N)$ where N is the number of channels and m is the number of data points (monitoring secondary nodes) involved in the interpolation. Since the number of monitoring secondary nodes is a constant, the average case complexity is O(N).

3.2.3 Hypothesis analysis

Once the estimates of channel usage for all the channels are known, we apply the energy detection hypothesis principle to decide the channel occupancy from the interpolated values (detected energy) and find the set of free channels, ψ^t at (x_t, y_t) . The cognitive node measures the energy of the received signal and integrates it over an the observation interval. The output from the integrator is compared with a threshold value which depends on the noise floor [48] to determine the presence or absence of the primary user. It is important to mention that the decision about occupancy of a channel is determined by comparing a decision vector Y against a fixed threshold λ . This results in the generation of two hypothesis respectively for free and occupied channels:

$$H_0 : y(g) = \omega(g) \tag{3.4}$$

$$H_1 : y(g) = hs(g) + \omega(g)$$
 (3.5)

where s(g) is the detected primary signal, $\omega(g)$ is the Additive White Gaussian Noise (AWGN), and h is the amplitude gain in the channel. The decision metric for the energy detector is:

$$Y = \sum_{g=0}^{V} |y(g)|^2$$
(3.6)

where V is the size of the observation vector.

In this system, the set of free channels $\psi^t = \{m\} \forall u_m = 0$, where u_m is the decision vector, $\forall u_m \in V$, and can only acquire binary values 1 and 0 which reflect occupancy of the channel with the latter denoting a free channel. Thus,

$$u_m = \begin{cases} 0 & if \ H_0 \ is \ selected \\ 1 & if \ H_1 \ is \ selected \end{cases}$$

3.3 Estimating Performance Metrics

With the spectrum usage distribution known, we are in a position to demonstrate how this distribution function can be used to predict the performance of a secondary transmitterreceiver pair and also the secondary network as a whole. We assume a network where K secondary nodes are exposed to M primary users. A secondary receiver is interfered by potentially all transmitters on all possible channels. The interference experienced by a secondary receiver at (x_t, y_t) is due to the primary transmitters as well as other receivers using the same channel. Let us suppose that the interference experienced by a receiver located at (x_t, y_t) from all primary transmitters is φ_q^t .

The received signal power at (x_t, y_t) is given by $P|h_q^t|^2$, where P is the transmit power of the corresponding secondary transmitter and h_q^t is the channel gain between the secondary transmitter-receiver pair. The channel gain between the two separated by a distance D_t is given by $h_q^t = \frac{A}{D_t^{\alpha/2}}$; where A is a frequency dependent constant and α is the path loss exponent.

Let I_q^t is the interference the receiver at (x_t, y_t) experiences from another secondary communication in the cell using same channel ch_q . Then

$$I_q^t = \sum_{\forall j \in \kappa^q} P |h_q^j|^2 \tag{3.7}$$

where κ^q is the set of all other secondary pairs using channel ch_q .

With the above parameters defined, we show how the we can calculate the various performance metrics. We discuss four such metrics e.g., channel capacity, spectral efficiency, network throughput, and bit error rate.

3.3.1 Channel capacity

We use Shannon-Hartley's capacity model for a band-limited channel with additive white Gaussian noise (AWGN) [53]. Thus, the channel capacity C_q^t for channel ch_q is given as

$$C_{q}^{t} = B \, \log_2(1 + \frac{P|h_{q}^{t}|^2}{\varphi_{q}^{t} + I_{q}^{t}}) \tag{3.8}$$

where B is the channel bandwidth. Note that the channel capacity is dependent on the channel used by the transmitter-receiver pair as the interference experienced from primary transmitters and other secondary communication are different on different channels.

3.3.2 Secondary network throughput

Secondary network throughput depends on the number of secondary pairs in a network using the same channel. If the secondary transmitter transmits with power P to receiver at (x_t, y_t) , then the transmission rate considering all other secondary communication is given by

$$\pi_{q}^{t} = \log(1 + \frac{P|h_{q}^{t}|^{2}}{I_{q}^{t} + \varphi_{q}^{t} + \sigma^{2}})$$
(3.9)

where the received signals are corrupted by zero-mean additive white Gaussian noise of power σ^2 .

To obtain the network throughput for the channel ch_q , we sum the transmission rates of all the secondary pairs using ch_q as [54]:

$$\Pi_q = \sum_{\forall j \in \kappa^q} \pi_q^t = \sum_{\forall j \in \kappa^q} \log(1 + \frac{P|h_q^t|^2}{I_q^t + \varphi_q^t + \sigma^2})$$
(3.10)

3.3.3 Spectral efficiency

Spectral efficiency provides an indication of how efficiently a bandwidth-limited frequency spectrum is used. Spectral efficiency measured in bits/sec/Hz can be represented in two ways: link spectral efficiency and system spectral efficiency. The former is defined as the net bit-rate that can be achieved by a link per channel bandwidth (Hz). Similarly, system spectral efficiency is defined as the maximum throughput, summed over all nodes, divided by the channel bandwidth. It gives the number of secondary nodes that can be *simultaneously* supported by the available spectrum in a geographic area. Thus, link spectral efficiency for ch_q between the secondary transmitter and receiver is

$$\xi_q^t = \frac{1}{B} log(1 + \frac{P|h_q^t|^2}{I_q^t + \varphi_q^t} + \sigma^2)$$
(3.11)

Similarly, the system spectral efficiency is obtained as

$$\Xi_q = \sum_{\forall j \in \kappa^q} \xi_q^t = \frac{1}{B} \sum_{\forall j \in \kappa^q} \log(1 + \frac{P|h_q^t|^2}{I_q^t + \varphi_q^t} + \sigma^2)$$
(3.12)

The nature of spectral efficiency is similar to that of channel capacity as the two parameters are proportional to each other.

3.3.4 Bit error rate

In order to estimate the bit error rate (BER) for a secondary communication using ch_q , we must know what modulation and coding schemes are being used. For example, if DPSK is employed, then BER is given by [55]

$$BER_q^{DPSK} = \frac{1}{2}e^{-\frac{E_b}{\eta}} \tag{3.13}$$

where E_b is the average energy per bit transmitted and $\eta/2$ is the noise power spectral density. Average energy per bit for a transmitter transmitting with power P is expressed as $E_b = \frac{P}{\pi_q^t}$.

Noise power spectral density is expressed as noise power experienced per bandwidth at the receiver side. Therefore, noise power spectral density for secondary receiver at (x_t, y_t) experiencing interference φ_q^t in channel ch_q of bandwidth B, is given by $\eta = \frac{\varphi_q^t}{B}$. Substituting the values of E_b and η in equation (3.13), we get,

$$BER_q^{DPSK} = \frac{1}{2}e^{-\frac{PB}{\pi_q^t \varphi_q^t}} \tag{3.14}$$

Here, we are using DPSK for the sake of illustration only. We could have used any other modulation scheme and its corresponding BER. If there are Q bits in a transmitted packet then the packet error rate is given by $PER = 1 - (1 - BER)^Q$, assuming all bit transmissions are independent and identically distributed.

3.4 Simulated Spectrum Map and Performance Metrics

We conducted extensive simulation experiments to model the spatial distribution of channel usage and verify its applicability to predict important performances metrics. We use a grid size of 100x100 square units and to emulate primary behavior, we use the model and the range of values from the real-world spectrum data archive of RWTH Mobnets [6]. We consider 50-1000 channels of bandwidth 2MHz-100 kHz each in the 2.4 GHz ISM band. The received power at any receiver from primary nodes was varied from -45 dBm to -80 dBm. We seek to evaluate system performance in three fronts: i) we focus on the channel usage distribution, ii) we measure the correctness of the predicted channel occupancy vectors, and iii) we predict the nature of some key performance metrics.

Figures 3.2, 3.3 and 3.4, show the power spectral density of channel usage for one of the 1000 channels. Locations of the data gathering points used for interpolation are shown in darker shades. Expectedly, the surface plots become increasingly accurate as the number of data points increases; however there is a trade-off between the accuracy of estimation and complexity of calculation.



Figure 3.2 Power spectral density of a channel with 40 sensing locations

Figures 3.5, 3.6, and 3.7 show the received power from primaries, channel capacity, and bit error rate on the same channel, for the same geographic region. The transmitter located at (30,45) is assumed to transmit at 1mW. The region shown in the plots are the potential locations for the receivers. Figure 3.6 shows the spatial distribution of channel capacity calculated using equation (3.8). As expected, the channel capacity gradually decreases when the receiver moves away from the transmitter. Figure 3.7 shows the spatial characteristic of estimated bit error rate from equation (3.13) in the same region. Most of the region showing zero bit error rate, actually have very small non-zero value. It is to be noted that channel capacity is minimum and bit error rate is maximum in regions where noise from primary is higher.

Figure 3.8 depicts the channel capacity for all 1000 channels at an arbitrary receiver location. This result can be exploited by a transmitter-receiver pair in selecting the better channels for communication when multiple options are available.



Figure 3.3 Power spectral density of a channel with 60 sensing locations

In figures 3.9 and 3.10, system throughput and per-user throughput are shown. The nature of system throughput is similar to a conventional wireless network hitting a plateau after a certain point. Interestingly the per-user throughput has a peak value around 10 secondary pairs and then decreases with more secondary pairs.

Fig. 3.11 shows the estimated and actual channel occupancy vectors of two secondary receivers in two different network scenarios for 50 channels. The two scenarios are created with different density and orientation of primary and secondary nodes but with similar transmission characteristics. The actual spectrum occupancy vectors are computed by received signal strength calculation at the secondary receiver for all interfering primary transmissions. It can be seen that in both the cases the prediction of channel occupancy is highly accurate with 6 and 3 false predictions respectively. It is important to note that none of these variations are false negatives which is essential for secondary communication. Our results show that on an average the probability of false positive is as low as 0.06.



Figure 3.4 Power spectral density of a channel with 80 sensing locations

3.5 Summary

In this chapter, we discussed the use Shepard's interpolation technique to estimate the spectrum usage distribution function over space based on the distributed sensing and sharing by secondary nodes in a dynamic spectrum access network. We demonstrated how such estimation can help in predicting channel performance metrics like channel capacity, spectral efficiency, network throughput, and bit error rate. Through simulation experiments, we validated the correctness of our prediction and showed how to compute the distribution of these metrics at any arbitrary location which can potentially be used for network installation and candidate channel selection.



Figure 3.5 Spatial distribution of estimated noise



Figure 3.6 Spatial distribution of channel capacity



Figure 3.7 Spatial distribution of bit error rate



Figure 3.8 Channel capacity for different channels in the spectrum band



Figure 3.9 System throughput



Figure 3.10 Per-user throughput



(b) Actual spectrum occupancy vectors

Figure 3.11 Spectrum occupancy vectors for two different scenarios

CHAPTER 4: CHANNEL ALLOCATION IN IEEE 802.22 NETWORKS

In this chapter, we propose an *on-demand* channel allocation scheme for IEEE 802.22 networks where the base stations allocate free channels to CPEs (i.e., the channels not being used by primary users). We argue that the lack of knowledge about the channel usage scenario at the CPE locations is the primary difficulty in efficient channel assignment. We propose creation and maintenance of *spectrum map* at the base station as a potential solution. To create a spectrum map, the base station selects a subset of CPEs, called *delegates*, to opportunistically share their spectrum usage with the base station. We use an *iterative* clustering technique using tree structured vector quantization (TSVQ) to find the ideal locations for these *delegate CPEs*. The base station then intelligently combines or fuses data from the delegates to create the spectrum map. The spectrum map thus created is used to communicate with a candidate CPE and increase the probability of synchronization between the CPE and the base station. The base station performs proactive performance analysis discussed in Chapter 3 to identify the best candidate channel for a CPE and also determine the best possible CPE for a particular channel. The eventual channel allocation to the CPEs is done taking into consideration one or a combination of the above mentioned parameters. Thus, based on the objective function, the base station allocates the most suitable channel(s) to a CPE which maximizes channel performance and also network throughput.



Figure 4.1 Architecture of an IEEE 802.22 network

4.1 IEEE 802.22 Wireless Regional Area Networks

IEEE 802.22 based wireless regional area network (WRAN) [56] is a cognitive radio network that operates on the underutilized and unused sub-900 MHz bands used primarily for TV services. The core components of an IEEE 802.22 network are the base stations and the consumer premise equipments (CPE) as shown in Fig. 4.1. Secondary nodes (base stations and CPEs) opportunistically access unused or underutilized TV bands when not in use. Channel allocation to CPEs is performed by the base station, which is assumed to have an accurate estimation of spectrum usage of all CPEs in its range.

Though the IEEE 802.22 draft [57] mentions that base stations estimate the spectrum usage at CPE locations by allowing the CPEs to share parameters such as antenna pattern, height, effective isotropic radiated power (EIRP) etc., the actual spectrum usage estimation methodology as well as channel allocation process are unspecified. We argue that efficient channel allocation and sustenance of high data rates with low interference in IEEE 802.22 networks largely rests upon the base station's ability to accurately estimate spectrum usage and allocate unused bandwidth to the CPEs. Therefore, a prior knowledge of the possible transmission activities of the primaries can allow the base station to effectively access the available channels and predict the expected radio and network performances at any CPE location for quality of service (QoS) provisioning. Thus, there is a need to proactively estimate the spectrum usage at any *arbitrary* CPE location and predict the nature of spectrum utilization. The recent ruling by FCC [5] also necessitates the need for secondary networks to create, manage and refer to spectrum usage databases for secondary access. This opened new discussions on design, implementation techniques, and capabilities of such spectrum usage databases. Another challenge in channel allocation that sets IEEE 802.22 apart from other conventional wireless networks (e.g., cellular) is the absence of pre-defined control channels between base station and CPEs. Since base station cannot perform sensing at locations other than itself, it has to rely upon the sensed spectrum reports that are shared by the CPEs. If all the CPEs were to continuously share their spectrum usage reports, the base station would have the most accurate information. However, the communication overhead would become a bottleneck as sharing has to be done on the same channels that the base station is supposed to allocate.



Figure 4.2 State transition diagram of a CPE

4.2 System Model

We consider an IEEE 802.22 network that is divided into cells, each having a base station. A base station can communicate with the CPEs in its cell as well as with its neighboring base stations. The CPEs could be like access points serving other end nodes with the spectrum (channels) that is allocated by the base station.

We assume that all base stations continuously perform channel sensing, i.e., they scan the entire spectrum (from 54 to 862 MHz) and create their respective spectrum usage report. The IEEE 802.22 draft [57] requires all the devices to be installed in fixed locations and the base station to be aware of the locations of all the CPEs under it. We assume that there are no pre-defined control channel(s) in the system and the only means of communication between the base station and the CPE are the free channels that are currently not being used by the primary users. Apart from allocating free channels to the CPE, the base station is also responsible for transmitting beacons to advertise free channels, gather sensed data from the CPEs, and fuse those spectrum data.

4.2.1 State definitions

Depending on the jobs being carried out, the CPEs operate on various logical states. Such state division helps the base station to better perform the channel allocation efficiently. Transitions among the states are shown in Fig. 4.2. It is to be noted that such state transitions do not violate the guidelines of IEEE 802.22 [57].

Idle State: In the idle state, a CPE has no data to transmit neither it has any other special responsibility. However in this state, a CPE may or may not be holding a channel that it has been allocated by the base station. Depending on whether the CPE has a channel or not, the idle state is further divided into two substates. The presence of a channel being held by the CPE along with the instruction by the base station through that channel determines the transition from this state to other possible states.

Initiation State: Whenever a CPE has data to transmit, it transits to the initiation state. In this state, a CPE continuously scans the spectrum looking for beacons from the base station.

Transmission State: If a CPE is successfully allocated a channel by the base station and it undergoes transmission, is said to be in the transmission state. A CPE leaves this state either by ending data transmission (in which case it might or might not hold on to the allocated channel) or by a forced deallocation by the base station. Transition from this state depends on the instruction from the base station.

Sharing State: In this state, a delegated CPE scans the channels periodically and then shares the raw spectrum usage data with the base station. A CPE is mandated to share its sensed data with the base station when the CPE is not undergoing transmission; the channel that was allocated for data transmission is used for sharing. A CPE leaves this state once the base station allows it to start transferring data using the same channel; however, this is subject to base station finding a suitable alternate CPE for spectrum sharing.

4.2.2 Delegation of CPEs

As mentioned before, the underlying principle of efficient channel allocation is the ability of the base station to successfully predict the spectrum usage at any CPE location in the cell. To achieve this, we allow the base station to select a subset of CPEs called *delegation* CPEs which periodically feed the base station with their spectrum usage reports. Base station fuses these spectrum information to create the *spectrum map*. At any instance, only these delegated CPEs take part in sharing their spectrum usage with the base station.

We discuss how such delegation CPEs can be selected and subsequently managed.

4.2.2.1 Selection of delegation CPEs

The choice of the delegation CPE 'locations' and the 'number' of such CPEs have a profound effect on the construction of the *spectrum map*.



Figure 4.3 One cluster with a single representation point

Initial locations: We seek to find representation points (ideal delegation CPE locations) from a set of given primary TV transmitter locations. We apply an *iterative clustering* technique TSVQ to find these representation points. *Vector Quantization* (VQ) is a powerful data compression technique where an ordered set of real numbers is quantized. The idea

of such quantization is to find $|\Delta|$ reproduction points (distinct vectors) from a large set of vectors so that the average distortion is minimized.

Here we discuss an iterative method, where the size of the representation points grows from 1 to the desired value, $|\Delta|$. Now, given the set primary TV transmitter locations, their centroid is the ideal representation point when $|\Delta| = 1$, as the sum of the Euclidean distances to all the primary transmitters is minimum at the centroid. We show an illustrated example in Fig. 4.3 where the solid dot S_1 denotes the centroid of the primaries represented as hollow dots creating a single cluster C_1 .



Figure 4.4 Two cluster with two representation points

Iterative clustering : With iterative clustering, S_1 is split into two points, S_1 and $S_1 + \epsilon$, where ϵ is a small Euclidean distance. Each of the primary locations is grouped on to the closer of the two representation points thereby creating two clusters with two representation points. The centroids of these two clusters are determined and the representation points, S_1 and $S_1 + \epsilon$, are updated with the centroids' position creating new representation points S_1 and S_2 . Clustering is performed again on these two representation points till the desired size of $|\Delta|$ is achieved. Once the final set of representation points is achieved, their nearest CPEs are chosen as delegation members. Fig 4.4 shows the scenario with two such points corresponding to the two clusters C_1 and C_2 . Further splitting into four and iteratively applying the clustering algorithm, we obtain the four centroids along with the four clusters as shown in Fig. 4.5. Note, such binary splitting will yield 2^n clusters.



Figure 4.5 Four clusters with four representation points

Choice of $|\Delta|$: The requirement of $|\Delta|$ in the given scenario differs from the choice of $|\Delta|$ in conventional VQ. In conventional VQ, the main goal of designing a quantizer is to find the representation points and the cluster such that the average distortion is minimized for a fixed number of such points. However, in our system, choice of $|\Delta|$ is governed by the upper bound on the number of data points¹ to be used in interpolation for best approximation. In Chapter 7, we show how estimation deteriorates after the number of delegations crosses 15.

¹We use the delegation CPEs as the data gathering points, hence we also refer to them as 'data points'.

Such bound is in close accordance with Shepard's interpolation technique that we use for estimation. As in the proposed clustering technique $|\Delta| = 2^n$, we maintain $|\Delta| = 8$ or 16 for best approximation.

4.2.2.2 Delegation management

Once all the delegation CPEs are determined for each cluster, the base station maintains three queues for each cluster, namely: AQ (for allocated CPEs), DQ (for delegated CPEs) and HQ (for potential delegation CPEs i.e., idle CPEs with channels). A CPE can be selected as a delegation CPE only after termination of data transmission session (either voluntarily or forcefully) and the channel which was being used for data transmission now serves for sharing spectrum usage data. It is not necessary that the CPE will always participate in sharing (i.e., help the base station) after data transmission is over. There are two possibilities: the CPE can relinquish its channels or it could still hold on to the channels in anticipation of channel requirement in the near future. The amount of time the CPE will be allowed to retain the channels depends on the load of the network. If the load is low, then the CPE can be allowed to retain the channels for a longer time; simply because there is no demand for those channels by other CPEs. However, when the demand (load) is high, the time for which the CPEs can retain the channels shrinks. In the mean time, if the CPE itself starts a new session then it is allowed to keep the channel for the duration of the transmission.



Figure 4.6 IEEE 802.22 network with base station and different types of CPEs

A delegated CPE continues to serve the base station until and unless it is instructed otherwise by the base station. This obligates the CPE to use the channel only as a means to share its spectrum usage with base station even if the CPE wants to go to the transmission state. From the base station's point of view, the decision of keeping a CPE in sharing state even after the CPE's request for data transmission, solely depends on the importance of that CPE in building the spectrum profile. As soon as the base station finds a suitable alternative, it allows the CPE to switch to the transmission state and use the same channel for data communication. In Fig. 4.6, we see how the coverage area of the base station is divided into clusters. The selection algorithm for a new delegation CPE is given in Algorithm 2.

4.2.3 Sharing raw spectrum data

The concept of sharing and fusing spectrum data among cognitive radio enabled devices is not new. In Chapter 3, we have already discussed *distributed* and *centralized* cooperative

Algorithm 2 Delegation management algorithm
1: Assume $ \Delta $ is the number of delegation CPEs
2: Assume θ is the desired lower bound of $ \Delta $
3: if $ \Delta \leq \theta$ then
4: Find the cluster of the CPE to be selected from
5: Extract AQ, HQ, DQ for the cluster
6: if emptyHQ=FALSE then
7: $enDQ=deHQ \setminus Selecting deHQ$ as the replacement
8: else {emptyAQ=FALSE}
9: $enDQ=deAQ \setminus Selecting deAQ$ as the replacement
10: else
11: Find the nearest cluster
12: Repeat from queue extraction (Step 5.)
13: end if
14: end if

spectrum sensing. Our proposed scheme borrows the essence of cooperative spectrum sensing by allowing the delegation CPEs to share their sensed spectrum data periodically with the base station. However, unlike conventional cooperative spectrum sensing where the devices share decision vectors (representing occupancy of channels), the delegation CPEs share their raw spectrum data with the base station which are later fused to estimate spectrum usage at unknown points.

It is important to mention that in most conventional cooperative spectrum sensing techniques, the cognitive radio enabled devices use low bandwidth common control channel which is sufficient for transferring binary decision vectors. Transferring raw spectrum data needs higher bandwidth channels which is the motivation behind allowing the delegation CPEs to use their previously allocated data channels for sharing purpose.

4.2.4 Intelligent beacon broadcast

The IEEE 802.22 draft [57] mandates a base station to broadcast beacons as a part of advertising the availability of free channels to the CPEs. Instead of sending beacons in all the free channels, we adopt an intelligent beacon broadcasting technique where the beacons are sent only on *selected* channels depending on the requirement of idle CPEs. These selected channels are those that belong to the common set of the available channels for allocation and the set of channels which are estimated to be available for the idle CPEs.

Let us assume that there are K CPEs in a IEEE 802.22 cell. If p_{alloc} is the probability that a CPE is allocated at any instance then there are $(Kp_{alloc} - |\Delta|)$ idle CPEs currently in the system. Now the base station can estimate the availability of channels for those $(Kp_{alloc} - |\Delta|)$ idle CPEs from the spectrum map discussed in Chapter 3. We denote that set of channels to be ν_{est} with $\nu_{est} \in \hat{N}$ where \hat{N} is the total set of channels in the spectrum and $|\hat{N}|=N$.

Consider p_{ws}^b be the probability of getting free channel (white space) at the base station and assuming that every CPE is allocated a single channel (both for data channel allocation and delegation), the number of free channels for the base station to allocate is $\{Np_{ws}^b - (Kp_{alloc} + |\Delta|)\}$. Let that set be γ_{free}^b where $\gamma_{free}^b \in \hat{N}$. Therefore a base station only sends beacons in the set of channels $\nu_{est} \cap \gamma_{free}^b$ and the number of beacons sent at a time is $|\nu_{est} \cap \gamma_{free}^b|$, assuming that a single beacon is transmitted on a single channel. Now an idle CPE without holding any channel but wanting to establish connection scans
the free channels hoping to synchronize with these beacon broadcasts. Therefore successful pre-allocation communication between an idle CPE and base station is dependent on proper synchronization between transmissions of the beacon on a particular channel and tuning of the CPE on the same channel. We assume that the actual set of free channels at a CPE c be γ_{free}^c and this contains the channels on which the CPE tunes its radio for beacon reception. Therefore, assuming negligible time for broadcast and propagation, probability of synchronization is given by:

$$P(CPE \ receiving \ beacon) = \frac{|\nu_{est} \cap \gamma_{free}^b \cap \gamma_{free}^c|}{|\nu_{est} \cap \gamma_{free}^b| |\gamma_{free}^c|}$$
(4.1)

A beacon contains the IDs of all the channels on which the beacons are being sent. Therefore, a CPE, c, once receiving a beacon sends back channel allocation requests in all the advertised channels along with the actual spectrum usage at $c \Upsilon^c = \{\varphi_q^c | \forall ch_q \in \hat{N}\}$. The completion of base station-CPE handshaking process is marked by the reception of the channel allocation request by base station in any of the $|\nu_{est} \cap \gamma_{free}^b|$ channels. Once the base station receives such a request from a CPE, it starts finding the best channel to allocate to that CPE. The probability of successful completion of the handshaking process is given as:

$$P(Successful \ handshaking) = \frac{|\nu_{est} \cap \gamma_{free}^b \cap \gamma_{free}^c|}{|\nu_{est} \cap \gamma_{free}^b|^2 |\gamma_{free}^c|}$$
(4.2)

It is important to mention in this context that $\nu_{est} \cap \gamma^b_{free}$ also contains the channels currently being held by some idle CPEs, say ν_{held} . These idle CPEs can hear both the beacons and channel allocation requests on the set of channels ν_{held} but ignores these messages as they do not require to take part in the handshaking process. Allocation or deallocation of such CPEs occur through the channel they are holding onto.

4.3 Performance Metrics based Channel Allocation

After successful beacon reception from a CPE c, the base station receives the set of free channels γ_{free}^c at c. The base station calculates channel performance metrics for the potentially free channels as discussed in Chapter 3 and allocates the best available channel.

4.3.1 Allocation process

Base station initiates the channel allocation process after reception of a channel allocation reply from any CPE c in any of the $\nu_{est} \cap \gamma_{free}^b \cap \gamma_{free}^c$ channels. We already mentioned that reception of such allocation reply is accompanied with $\Upsilon^c = \{\varphi_j^c | \forall ch_j \in \hat{N}\}$ which is nothing but the raw spectrum usage at c. The base station creates the set of available channels $\rho_{avl}^c = \{j | \forall \varphi_j^c < T\}$ allocable to c. Finding the cluster that c belongs to is very important as the channels used by other allocated or delegated CPEs in the interference range of c can not be allocated to c for obvious reasons. The best way to solve this problem is for the base station to find the AQ, DQ and HQ of all the clusters within the interference range of c. From all such AQs, the base station creates the list \widehat{AQ}^c with only those channels which are allocated to CPEs within the interference range of c. Similarly \widehat{DQ}^c and \widehat{HQ}^c are created. As the channels in \widehat{AQ}^c and \widehat{DQ}^c can not be allocated to c to avoid co-channel interference, the set of available channels for allocation ρ_{avl}^c is updated excluding such channels. For all the rest of the channels ch_j in ρ_{avl}^c , expected channel performance (can be any desirable parameter like capacity, efficiency, bit error rate or and weighted average of all these) is calculated and given a score s_j . ρ_{avl}^c is further updated with descending channel scores.

Another issue that a base station needs to address while allocating channels to c is the channels being held by other idle CPEs in the interference range i.e., \widehat{HQ}^c . The purpose of allowing such CPEs to hold onto channels is not making them go through the entire handshaking process and expedite channel allocation. So the intention of the base station will always be to allocate the best channel among $|\rho_{avl}^c|$ channels not belonging to \widehat{HQ}^c . If no such channels are available then the best channel is allocated to c. This is done by revoking the channel held by the corresponding idle CPE. Once a channel is allocated, it is added to AQ of the corresponding cluster and removed from corresponding HQ (if applicable).

Channels acquired by a CPE can either be released by the CPE or revoked by the base station. The channel can only released by the CPE in case of successful completion of data transmission. In such a case, the base station can allow the CPE to hold onto the channel depending upon its demand. A channel is revoked either when (i) there is a change in spectrum usage scenario at either the base station or the CPE because of transmission from primary or (ii) base station deciding on using that channel for delegation purpose. In the first case, the channel can not be used until free. The process of allocation in discussed

in Algorithm 3.

Algorithm 3 Allocation Algorithm

Require: Threshold T , Spectrum range N , Available set					
	of channels for idle CPEs ν_{est} , Set of free channels γ^b_{free}				
1:	for all channels $ch_q \in \nu_{est} \cap \gamma^b_{free}$ do				
2:	Send beacon and listen				
3:	if receives reply from any CPE c then				
4:	Extract $\Upsilon^c = \{\varphi_j^c \forall ch_j \in \hat{N}\}$				
5:	Create $\rho_{avl}^c = \{j \mid \forall \varphi_j^c < T\}$				
6:	Extract AQs, DQs and HQs for all nearby clusters of c				
7:	Create $\widehat{AQ}^c, \widehat{DQ}^c$ and \widehat{HQ}^c				
8:	Update $\rho_{avl}^c = \{j \mid \forall ch_i \notin \widehat{AQ}^c, \widehat{DQ}^c\}$				
9:	for all channels $ch_j \in \rho_{avl}^c$ do				
10:	Calculate the channel performance metrics and assign score s_j				
11:	end for				
12:	Update $\rho_{avl}^c = \{j s_1 > s_2 > \dots > s_{ \rho_{avl}^c } \}$				
13:	if $\widehat{HQ}^c \bigcap \rho_{avl}^c \neq \text{NULL then}$				
14:	for all channels $ch_j \in \rho_{avl}^c$ do				
15:	if $ch_j \notin \widehat{HQ}^c$ then				
16:	Allocate ch_i to c				
17:	Add ch_j to AQ of that cluster				
18:	Exit inner loop				
19:	end if				
20:	end for				
21:	else				
22:	Allocate ch_1 to c				
23:	Add ch_1 to AQ of that cluster				
24:	end if				
25:	end if				
26:	end for				

4.4 Summary

In this chapter, we proposed a channel allocation scheme in an IEEE 802.22 cell using the *spectrum map*. We showed how delegate CPEs are selected using iterative clustering techniques and the data gathered only from such delegated CPEs can be used to evaluate the channel occupancy vector which is then used to communicate with the idle CPEs. The pro-

posed channel allocation algorithm is flexible enough to allocate channels based on different performances metrics.

CHAPTER 5: CONTENTION BASED MAC PROTOCOL

In this chapter, we consider a cognitive radio based dynamic spectrum access network where stationary sensors are deployed solely for the purpose of gathering and sharing the spectrum usage statistics with the cognitive radios that are randomly scattered over the area of interest. We design a contention based MAC protocol where the secondary nodes contend for the common control channel. Winning the contention prompts the secondary nodes to gain access to the usable data channels. We analyze the performance of the proposed MAC protocol in terms of blocking probability of channel access, idle channel grabbing, idle channel utilization, and PU QoS degradation. We also propose provisions for prioritized reservation of data slots for secondaries based on their different QoS requirements and demonstrate higher channel utilization achieved by such provisions.

5.1 System Model and Assumptions

We consider a set of secondary users randomly scattered over a relatively small area of interest. Due to their physical proximity, we assume that all nodes experience the same primary activities. As the secondary users do not undergo the sensing process themselves, a centrally located dedicated sensor is used that continuously senses the primary activities. The sensor also periodically broadcasts beacons containing primary usage information on a common control channel. These beacons (i.e., binary vectors showing if channels are occupied or unoccupied) are heard by all the secondary users. On hearing these beacons, the secondary users go through a contention process to acquire data channels before they can begin data transmissions.

Assumptions: We make the following additional assumptions on the system settings:

- 1. All secondary users are time synchronized, which is achieved through the same sensing beacons.
- 2. All channels have identical propagation characteristics and there is no preference for any particular channel.
- 3. The secondaries are allowed to grab only one channel per data transmission slot.
- 4. To aid increased secondary user throughput, the secondary users can be equipped with two radios, one for contention and another for simultaneous data transmission. Availability of more than one transceivers has shown to increase secondary throughput [58].

Primary ON-OFF Model: Availability of spectrum depends on the activity of the primaries. We consider the commonly used primary activity ON-OFF model [59]. According to this model, every channel has two states: ON (channel busy) and OFF (channel idle) depending on primary user activity. ON and OFF period duration are independently and exponentially distributed with parameters λ_p and μ_p . Thus, for any channel, the duration of ON period x is an exponentially distributed random variable with mean $\frac{1}{\lambda_p}$ and is given by

$$f_1(x) = \begin{cases} \lambda_p e^{-\lambda_p x} & \forall \ x \ge 0 \\ 0 & \forall \ x < 0 \end{cases}$$
(5.1)

Similarly, the duration of OFF period denoted by the random variable y with mean $\frac{1}{\mu_p}$ has the distribution,

$$f_2(y) = \begin{cases} \mu_p e^{-\mu_p y} & \forall \ y \ge 0\\ 0 & \forall \ y < 0 \end{cases}$$
(5.2)

5.2 The Proposed MAC Protocol

We propose the MAC protocol by describing the frame structure, channel access method, mode of operation, and design optimizations.

5.2.1 The frame structure

We assume that there is one common control channel that is used for the beacon broadcasts by the sensor as well for the contention among the secondary nodes. The sensor sends a beacon periodically every T_c seconds indicating the channels that are idle at that point of time. The beacon duration is T_b . The time between two beacons (i.e., T_c) is divided into three equal sized windows for request-to-send (RTS), clear-to-send (CTS), and acknowledgment (ACK) as shown in Fig. 5.1. The RTS, CTS, and ACK windows are further divided into N_S mini-slots each. The time-slotted data channels are also synchronized with the aid of the common control channel. Nodes acquiring data channels after winning contentions get to transmit during the *next* data slot which is of duration $T_d = T_c + T_b$. The packets transmitted by the secondary nodes are assumed to be of fixed duration of one data slot.



Figure 5.1 MAC frame structure

5.2.2 The contention process

The secondary users that want to transmit data must go through the contention process to acquire data channels. All such contending nodes randomly pick one of the N_S mini-slots in the RTS window. In that mini-slot, a secondary user transmits its intention of transmission and who the intended receiver is. Of course, more than one secondary node might decide to transmit during the same mini-slot. In such cases of RTS collisions, the colliding nodes try again in the next RTS window, but random mini-slots. Also, there might be RTS mini-slots that are chosen by none; those RTS mini-slots go idle. Thus, a RTS mini-slot is successful, if one and only one secondary user contends on that mini-slot, just like a successful transmission in slotted-ALOHA.

Upon receiving a successful RTS from a transmitting secondary user, the intended receiver transmits CTS in the *same* mini-slot in the CTS window. Thus, only the successful RTS mini-slots would have their corresponding CTS mini-slot transmissions. Once the transmitter receives the CTS, it responds in the *same* mini-slot of the ACK window confirming which particular channel is to be used among the usable channels. The ACK also contains a network allocation vector (NAV) specifying the duration for which the channel will be in use so that (i) no other node tries to use that data channel, and (ii) the sensor node is aware of the data channel being used by a SU transmitter-receiver pair. The NAV also contains the category of the secondary based on it's priority/demand for multiple data-slots reservation to be discussed in Section 5.4.

5.2.3 Data channel grabbing and transmissions

The outcome of the contention process marks each mini-slot as either 'successful' or 'unsuccessful'. The winners of the contention grab the available data channels in a sequential manner. Thus, the winner of the first successful mini-slot gets to pick one of the N_A channels, where N_A is defined as the number of available channels. The ACK contains the information of the channel grabbed; thus the remaining winners refrain from grabbing that channel. The second winner gets to pick next and lets other know about the channel grabbed through the ACK. Thus, as long as the number of winners is less than or equal to N_A , all winners are guaranteed to grab a data channel. If N_A is less than the numbers of winners, then the first N_A winners will get one data channel each. The remaining winners will be blocked (i.e., they run out of data channels). After the data channels are grabbed, the secondary transmitters start transmission on the channel grabbed in the next data slot.

5.2.4 Mode of operation

The design of the MAC protocol is flexible enough to support two modes of operation: i) transmission on the next data slot only, and ii) transmission on multiple successive data slots. Choice of the mode depends on the traffic of secondary users contending for minislots. Further insight on the mode selection is given in Section 5.2.5. However, a secondary user transmitting through multiple data slots needs to listen to the beacons following every data slot in order to make sure the channel is still free from primary activity. If a primary arrives on a data channel *during an ongoing secondary transmission*, then the secondary user has to relinquish that channel at the end of that data transmission slot. Thus, the duration T_d is suitably chosen to keep the interference caused to primary within a tolerable range.

5.2.5 Design optimizations

So far, the discussion on the design of the MAC protocol has been on its working principle. To achieve the best performance, some of the protocol design parameters need to be optimized, which are discussed here.

Number of mini-slots in a RTS window, N_S : The number of mini-slots N_S for the RTS/CTS/ACK must consider several system variables like number of active secondary nodes and the number of available channels. It is easy to see that, if N_S is small compared to the number of secondary nodes then the RTS contention probability will be high. Also, since a successful RTS mini-slot can result in acquiring one data channel, the value of N_S must allow the provision of potentially using all available data channels. We discuss optimal N_S in Chapter 7.

One versus multiple data slots: Once a data channel is successfully acquired and transmission begins, the question that arises is whether the transmitting node should relinquish the channel after one data slot or should use the same channel for multiple successive data slots. If multiple data slot transmission is allowed, then how many can be reserved at a time? It is intuitive that low secondary activity would allow longer retention of the data channels. With increase in secondary activity, the number of data slots that can be reserved should decrease. However, later we will observe that there exists a convexity of the probability of

winning the contention with the number of contenders. Therefore, with very high secondary activity, the number of contention winners becomes less and fewer data slot reservation will lead to inefficient utilization. Thus, the number of data slots reservation should be a function of the number of secondary users winning the contention.

5.3 Analysis of the Proposed MAC Protocol

We analyze the performance of the proposed MAC protocol in terms of some of the commonly used metrics. First, we provide their definitions in our context.

Definition 5.1. (*RTS Success Probability*) This is the probability of successfully winning a *RTS mini-slot by any secondary node*.

Definition 5.2. (Idle Channel Grabbing) This is a measure of how many channels the secondary nodes have grabbed among the idle channels after successfully winning the contention. It is calculated by the expected number of channels successfully grabbed through the contention slot (regardless of their eventual utilization in the data transmission slot).

Definition 5.3. (Blocking Probability) The blocking probability is defined as the probability that a contending secondary will be deprived of a channel even after winning the contention. This is calculated as the ratio of total deprived or blocked winners to the total number of contending secondaries in the contention window. **Definition 5.4.** (Secondary Usage) Secondary usage is the number of channels that are successfully utilized by the secondary users without any interruption from primary nodes for at least one data transmission slot.

Definition 5.5. (PU QoS Degradation) We define PU QoS degradation as the amount of time the primary user experiences interference from any secondary node either continuously or intermittently, i.e., the time after which the primary does not perceive any interference from secondaries whatsoever.

5.3.1 The primary ON-OFF model

The probability of any channel being idle in the contention window (p_{idle}) is the steady state probability of that channel in OFF state. As already mentioned, the ON and OFF duration are exponentially distributed random variables. Using the Gilbert-Elliott 2-state classical Markov model, we get,

$$p_{idle} = Prob\{\text{a channel is in OFF state}\}$$
$$= \frac{\bar{t}_{OFF}}{\bar{t}_{ON} + \bar{t}_{OFF}} = \frac{1/\mu_p}{1/\lambda_p + 1/\mu_p} = \frac{\lambda_p}{\lambda_p + \mu_p}$$
(5.3)

Therefore, the average number of available channels in the system N_A is expressed as $N_A = p_{idle} \times N_T$, where N_T is the total number of channels in the system.

We seek to find the distribution of inter-arrival times of the ON/OFF periods from traditional ON-OFF model. The random variable representing the primary inter-arrival time \mathbf{z} is the sum of two independent random variables for ON and OFF periods \mathbf{x} and \mathbf{y} respectively, i.e., $\mathbf{z} = \mathbf{x} + \mathbf{y}$. Therefore, the distribution of \mathbf{z} is obtained as:

$$f_Z(z) = f_X(x) * f_Y(y)$$

= $\int_{-\infty}^{+\infty} f_X(z-y) f_Y(y) dy$
= $\frac{\lambda_p \mu_p [e^{-\lambda_p T_c} - e^{-\mu_p T_c}]}{(\lambda_p - \mu_p)}$ (5.4)

The commonly used notations are shown in Table 5.1.

Table 5.1 Notations used for MAC analysis

N_T	Number of total channels in the spectrum of interest			
N_S	Number of mini-slots in RTS contention window			
N_A	Number of available channels in the spectrum of interest			
N_{SW}	Number of mini-slots won in RTS window			
N_{CG}	Number of channels grabbed in a contention slot			
N_{CU}	Number of channels utilized in a data slot			
N_{DS}	Number of consecutive data-slots reserved by a winning SU			
\bar{t}_{ON}	Average PU ON time per contention window $(= 1/\lambda_p)$			
\bar{t}_{OFF}	Average PU OFF time per contention window $(= 1/\mu_p)$			
λ_s	Secondary rate of contention per mini-slot (Poisson)			
λ_p	Primary arrival rate on a channel (Poisson)			
μ_P	Primary average duration of stay on a channel (Poisson)			
T_c	Duration of contention window			
T_d	Data transmission slot duration			
T_b	Beacon duration			
p_s	Probability of a successful RTS contention			
p_c	Probability of selecting a free channel			
p_{idle}	Probability of a channel being idle			
Λ	Number of secondaries contending per RTS window			

5.3.2 RTS success probability

Winning a RTS mini-slot is just like transmissions in a slotted ALOHA system where a successful transmission occurs if and only if there is one node transmitting during a minislot. With secondary users generating request at a rate of λ_s per RTS mini-slot, the RTS success probability is given by $p_s = \lambda_s e^{-\lambda_s}$, where $\lambda_s = \frac{\Lambda}{N_s}$.

In order to find the condition for maximum number of contention winners, we equate the derivative of success probability to 0, i.e., $e^{-\lambda_s}(1-\lambda_s) = 0$, resulting in $\lambda_s = 1$ Therefore, the maximum success probability is achieved when $\Lambda = N_s$.

5.3.3 Idle channel grabbing

Getting hold of idle channels by the secondary nodes during the ACK window depends on how many mini-slots have been successfully won by the secondaries in the RTS window. Successfully winning a mini-slot means that only one secondary has selected that mini-slot. We define N_{SW} as the expected number of successful mini-slots won by the secondaries in the RTS window.

$$N_{SW} = N_S \times p_s \tag{5.5}$$

Therefore, the expected number of channels grabbed by the secondaries in a contention window (N_{CG}) is the minimum of N_{SW} and N_A . Thus,

$$E[Idle channel grabbing] = N_{CG} = \begin{cases} N_{SW} & \forall N_{SW} \le N_A \\ & & \\ N_A & \text{otherwise} \end{cases}$$
(5.6)

5.3.4 Blocking probability

Successfully winning a RTS mini-slot does not necessarily mean that the winner will get a data channel. This is because, the RTS mini-slot winners claim data channels in a sequential manner starting with the winner of the first mini-slot. By the time the winner of the *j*th mini-slot tries to claim a data channel, there might not be any channel available, as the previous ones (i.e., the winners of mini-slots 1 through (j - 1)) could grab all the available data channels N_A . However, if the number of available channels N_A is more than the number of mini-slots N_S , then all the winners grab channels and there is no blocking.

Since each RTS mini-slot is won independently of each other, each with probability p_s , the expected number of slot winners is N_{SW} . When $N_A \ge N_{SW}$, then blocking probability is 0 as all N_A winners are bound to grab channels. However, for $N_A < N_{SW}$, only the first N_A winners will grab channels and the remaining $N_{SW} - N_A$ winners will be blocked. Therefore the average blocking probability of the system is,

$$BP = \begin{cases} 0 & \forall N_A \ge N_{SW} \\ \\ \frac{N_{SW} - N_A}{\lambda_s \times N_S} & \text{otherwise} \end{cases}$$
(5.7)

5.3.5 Secondary usage

We argue that in order to utilize an idle channel, winning the contention and grabbing the channel is not enough. A grabbed channel is defined to be utilized if that secondary is allowed uninterrupted access (i.e., without any primary activity) on that channel in the following data transmission slot. Therefore, any grabbed channel needs to be free from any primary activity from the start of the next transmission slot till the end of that slot (i.e., T_d duration) to be successfully utilized by a secondary user. Interestingly, the PU can even arrive during the contention slot (duration T_c) when that idle data channel is being contested for. But the channel will only be utilized if the PU vacates the channel before start of the following data transmission slot.

Through Fig. 5.2 and Table 5.2, we show all the different cases of primary arrivals and departures within two inter-beacon periods (i.e., two data-transmission periods) with respect to secondary usage. We also point out the idle channel grabbing and possible usage in such scenarios.



Figure 5.2 Consecutive data and contention slots

Table 5.2 PU arrivals and corresponding channel grabbing and secondary usage

Cases	Primary Arrival	Primary Departure	Grabbing in	Utilization in
			1st cont. slot	2nd data slot
Ι	Before B_1	Before B_2	NO	NO
II	Before B_1	After B_2 & Before B_3	NO	NO
III	After B_1 & Before B_2	After B_2 & Before B_3	YES	NO
IV	After B_1 & Before B_2	After B_3	YES	NO
V	After B_1 & Before B_2	Before B_2	YES	YES
VI	After B_2 & Before B_3	After B_3	YES	YES

We define, $P_{PU}^{Q \to S}$ as the probability of primary to arrive anytime from the start of the second data slot (time Q) till the end of that slot (time S). Then P', the probability of

no primary interruption during this time is given by,

$$P' = \operatorname{Prob}\{\operatorname{Case} V\} + \operatorname{Prob}\{\operatorname{Case} VI\}$$

$$= \operatorname{Prob}\{\operatorname{PU} \operatorname{arrival} + \operatorname{ON} \operatorname{duration} \leq T_c\} + (1 - P_{PU}^{Q \to S})$$

$$= \operatorname{Prob}\{z + x \leq T_c\} + (1 - P_{PU}^{Q \to S})$$

$$= \frac{\lambda_p \mu_p [e^{-\lambda_p T_c} - e^{-\mu_p T_c}]}{(\lambda_p - \mu_p)^2} - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)}$$

$$+ \frac{\lambda_p \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)} + \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}$$
(5.8)

Therefore,

$$E[\text{Secondary usage}] = N_{CG} \times P' \tag{5.9}$$

Later in Chapter 7, we use Eqn. (5.9) to evaluate the optimal N_S in order to maximize the utilization. Possible values of N_S and other design variables are also evaluated.

5.3.6 PU QoS degradation

When a PU initiates transmissions on its licensed channel, there can be two arrival scenarios for the PU: either during a contention slot or during a data slot. These scenarios lead to different degradation depending on the presence of secondary nodes on that channel. We illustrate the PU degradation scenarios using Fig. 5.2. **Case I:** PU arrives during the contention slot between P and Q in Fig. 5.2. In such a case, the PU will find the channel to be free as contention for that channel is going on among the secondary nodes. However, depending on the result of contention, the channel may be used by a secondary for T_d duration (from Q to S) causing PU degradation (average value $\frac{T_c}{2} + T_d$) or may not be used at all with no PU degradation. It is to be noted that such PU arrival will be reflected in beacon B_2 resulting the channel being vacated by secondary beyond S.

Case II: PU arrives at any time during the data slot (between Q and S in Fig. 5.2). The channel can be either be free or busy resulting in no or some degradation (average value $\frac{T_d}{2}$) respectively.

In order to evaluate the expected PU QoS degradation (D_{PU}) , we first calculate the probabilities of the above two scenarios. The probability of PU arriving between P and Qis given by,

$$P_{PU}^{P \to Q} = \text{Prob}\{z \le T_c\} = 1 - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)}$$
(5.10)

Similarly, the probability of PU arriving between Q and S is given by,

$$P_{PU}^{Q \to S} = 1 - \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}$$
(5.11)

As degradation occurs only when a secondary nodes grabs the PU channel, we need to find the probability of a secondary node grabbing such a channel (either Case I or II). The events of PU arrival on a channel and secondary node winning the contention and grabbing the same channel are mutually independent. Thus,

Prob{Secondary grabbing a channel|PU arrival on the same channel} = Prob{Secondary grabbing a channel}. Therefore probability of secondary grabbing a channel (P_{SU}) is expressed as,

$$P_{SU} = \operatorname{Prob}\{\operatorname{SU winning any slot} k\} \times \operatorname{Prob}\{k \le N_A\}$$
$$= p_s \times \begin{cases} 1 & \forall N_A > N_S \\ \sum_{k=1}^{N_A} {N_A \choose k} (\frac{1}{N_S})^k (1 - \frac{1}{N_S})^{N_A - k} & \text{otherwise} \end{cases}$$
(5.12)

Therefore, the expected PU QoS degradation D_{PU} is expressed as,

$$D_{PU} = E[PU \text{ deg. for Case I}] \times P_{PU}^{P \to Q} + E[PU \text{ deg. for Case II}] \times P_{PU}^{Q \to S}$$

$$= \left[E[PU \text{ deg. when ch. is grabbed}]P_{SU} + E[PU \text{ deg. when ch. is free}](1 - P_{SU})\right]P_{PU}^{P \to Q}$$

$$+ \left[E[PU \text{ deg. when ch. is grabbed}]P_{SU} + E[PU \text{ deg. when ch. is free}](1 - P_{SU})\right]P_{PU}^{Q \to S}$$

$$= \left[\left(\frac{T_c}{2} + T_d\right) \times P_{SU} + 0 \times (1 - P_{SU})\right]P_{PU}^{P \to Q} + \left[\frac{T_d}{2} \times P_{SU} + 0 \times (1 - P_{SU})\right]P_{PU}^{Q \to S}$$

$$= P_{SU}\left[\left(\frac{T_c}{2} + T_d\right) \times P_{PU}^{P \to Q} + \frac{T_d}{2} \times P_{PU}^{Q \to S}\right]$$
(5.13)

5.4 Differential QoS through multiple slots reservation

In this section, we determine the relation between the number of contention winning secondary users and the number of successive data-slots to be reserved by each winning secondary user. Utilization of an idle channel is evaluated for both single and multiple data-slots reservation scenarios.

5.4.1 Multiple data-slots

The secondary users always have to resort to the contention process irrespective of their traffic intensity. For low loads, i.e., when there are plenty of data slots for the contending secondary users, it does not make sense for the secondary users to contend for each and every data slot. The possibility of reserving consecutive data slots by a secondary user eradicates the need for slot by slot contention. In terms of utilizing channel idle time, such reservation ensures utilization for at least that many data slots. The number of data slots to be reserved depends on the number of secondary users that have won the contention rather than the total number of contending secondaries. A secondary user can easily gauge the number of winners in a contention window by the number of NAVs received in the ACK window. Using number of contenders as a metric to reserve multiple slots can be misleading as higher number of contenders does not necessarily mean higher number of winners. It is the winners who have the prerogative of utilizing the idle channels. The designed multiple slot reservation scheme serves three purposes: it is fair to the contention winners, maximizes idle channel utilization and minimizes signaling overhead. A slotted ALOHA-like contention process incurs such signaling overhead when the secondary users have to resort to contention irrespective of their load/traffic intensity. By allowing secondaries to reserve channels for multiple data slots we save multiple such contentions, thereby saving signaling overhead.

When $N_{SW} \ge N_A$, the number of winners are more than the number of channels available. Therefore, not all the contention winners get channels, i.e., only the first N_A winners are allowed to grab channels. In such cases, to ensure fairness, the winning secondary users are allowed to use the free channels only for one data slot. The right to use the channels for the next data slot is determined by another contention.

In case of $N_{SW} < N_A$, i.e., when there are less winners than available channels, each winner is allowed to reserve channel for $\lfloor N_A/N_{SW} \rfloor$ slots. Therefore, the number of data slots reserved by a winning secondary, N_{DS} is given by,

$$N_{DS} = \begin{cases} 1 & \forall N_{SW} \ge N_A \\ \left\lfloor \frac{N_A}{N_{SW}} \right\rfloor & \text{otherwise} \end{cases}$$
(5.14)

5.4.2 Differential QoS

Sometimes it is required to allow unequal share of the idle channels to different secondary users. Such differential QoS is necessitated when secondaries have different bandwidth requirements. In our proposed MAC protocol such differential QoS is manifested through reservation of data channels for multiple slots rather than allowing secondaries reserve multiple data channels. However, unlike allowing all the winning secondaries to reserve same number of channels (i.e., concept discussed in Section 5.4.1), we allow the secondaries to reserve slots according to their demands or priorities.

Let us assume that there are k classes of secondaries in the system with w_1, w_2, \dots, w_k being their priorities/demands based on the MAC design. The MAC protocol is flexible to such categorization; these k classes along with their priorities can be either pre-determined or dynamic and based on the demand of the winning secondaries. In the latter case, the winning secondaries advertise their demands (w_i) in the NAVs. We assume that the number of winners in class i is n_i , i.e., $\sum_i n_i = N_{SW}$. The number of data slots reserved by a winning secondary in class i, is given by,

$$N_{DS}^{i} = \begin{cases} 1 & \forall N_{SW} \ge N_{A} \\ \left\lfloor N_{A} \times \frac{w_{i}}{\sum_{i} w_{i} n_{i}} \right\rfloor & \text{otherwise} \end{cases}$$
(5.15)

The relation between equations 5.14 and 5.15 is given as,

$$N_{DS} = \frac{\sum N_{DS}^i}{N_{CG}} \tag{5.16}$$



Figure 5.3 A scenario with multiple data-slots reservation

Figure 5.3 shows an illustrative example with multiple data slots reservation provisioning. We see that in the *m*th data slot there are three winners who grabbed channels. However, due to differential QoS provisioning, SU12, SU28 and SU9 reserve three, two and one data slots respectively. In the (m + 1)th data slot we see Ch4 and ChN are grabbed by new winners of the previous (mth) contention slot and are allowed to reserve the channel for different duration. In (m + 4)th slot, there are more winners in comparison to previous slots and $N_{SW} \ge N_A$ condition is satisfied. Therefore, all the channels are grabbed by secondaries and each is allowed to use the channel for only a single slot. However, SU2 is allowed to continue using Ch3 for the duration reserved in (m + 3)th slot.

5.4.3 Idle channel utilization

Idle channel utilization is defined as percentage of the channel idle time that is utilized by a secondary. Therefore, the steady state idle channel utilization is the number of data slots reserved as a fraction of total available channels, i.e.,

$$E[Idle Channel Utilization] = \frac{N_{DS} \times N_{CG}}{N_A}$$
(5.17)

We compare idle channel utilization for both single and multiple slot reservation scheme in Chapter 7 and show almost 100% utilization through multiple slots reservation.

5.5 Summary

We proposed a contention based MAC protocol where SUs are not expected to carry out the channel sensing duties on their own. The protocol is flexible to allow multiple classes of secondary users and takes into consideration, different QoS criteria, which include primary user service interruption rate, secondary user interruption rate, blocking probability etc. The exploitation of idleness has been quantified, both for grabbing and utilizing those channels.

CHAPTER 6: MULTI-CHANNEL, MULTI-HOP ROUTING IN COGNITIVE RADIO NETWORKS

In this chapter we discuss the challenges of cognitive routing over traditional wireless ad-hoc routing. We propose a novel spectrum map aided multi-channel multi-hop routing scheme for low cost secondary devices without sensing capability. We describe the system model, route discovery and route maintenance schemes for different routing scenarios. We also describe secondary power management while routing for primary contour protection. We analyze the sufficient connectivity conditions with respect to secondary network deployment.

6.1 Challenges in Cognitive Routing

A typical multi-hop routing scenario in a CRN is depicted in Fig. 6.1 where SUs with/without sensing capability co-exit with primary networks. Primary transmitter-receiver pairs use different channels with varying channel capacities. Therefore, the SUs observe varying spectrum availability due to their spatial diversity. The problem of routing in multi-hop CRNs addresses the creation and the maintenance of wireless multi-hop paths among SUs by deciding both the relay nodes and the channel to be used at each hop of the route. Such routing decisions can be aided by local or global spectrum knowledge as was discussed in Chapter 2.



Figure 6.1 Routing among SUs in the presence of primary transmitters and receivers

The main challenges for routing in multi-hop CRNs over conventional ad-hoc networks are [60]:

- **Spectrum-awareness:** Designing efficient routing solutions for multi-hop CRNs requires a tight coupling between the routing module(s) and the spectrum management functionality such that the routing module(s) can be continuously aware of the surrounding physical environment to take more accurate decisions. In this regard, three scenarios might arise:
 - the information on the spectrum occupancy is provided to the routing engine by external entities (e.g., SUs may have access to a database of white spaces of TV towers [5]);

- the information on spectrum occupancy is to be gathered locally by each SU through local and distributed sensing mechanisms;
- a combination of the previous two.

In any case, any routing solution designed for multi-hop CRNs must be tightly coupled to the entire cognitive cycle of spectrum management [61].

- Route quality: The concept of route-quality is re-defined under CRN scenario. The classical ways of measuring/assessing the quality of end-to-end routes (bandwidth, throughput, delay, energy efficiency, and fairness) is coupled with novel measures on path stability, spectrum availability/PU presence. As an example, if the PU activity is moderate to low, the topology of the secondary network is almost static, and classical routing metrics adopted for wireless mesh networks can be leveraged. On the other hand, if PUs become active very frequently, routing techniques for disconnected networks can be of favorable assistance [62].
- Route maintenance: The sudden appearance of a PU may render a given channel unusable in a given area, thus resulting in unpredictable route failures, which may require frequent path re-routing either in terms of nodes or used channels. In this scenario, effective signaling procedures are required to restore broken paths with minimal effect on the perceived quality.

Our proposed routing protocol addresses these routing challenges and goes a step further by enforcing secondary transmission power control in order to protect primary receivers from interference.

6.2 System Model

We consider a two-dimensional network region of $l \times l$ square unit consisting of primary networks, secondary networks, and a collection of sensors that periodically sense primary activity and create the spectrum map as was discussed in Chapter 3.

6.2.1 Primary network

We consider a primary network consisting of a collection of licensed transmitters and receivers which operate independently of secondary users. We assume that the primary transmitter location distribution follows a Poisson point process with density λ_p . These primary transmitters operate on a pre-defined spectrum band and follow a well-known ON-OFF model for transmission pattern. We assume that the signal strength diffuses isotropically in the environment and is received at any location with transmission power P multiplied by a loss factor due to isotropic dispersion and absorption in the environment. In our work, we do not assume any fixed transmission range/radius for the primary like the Boolean model. Rather, we use the received signal strength at any location to determine the presence of the primary at that location.

6.2.2 Secondary network

Secondary users seek to access the the channels not being used by the primaries. The secondary network has two components: intelligent sensors in the control plane and unintelligent secondary nodes in the data plane. The routing mechanism is designed to route data packets through the secondary nodes with the help of sensors.

Sensors: The sensors are deployed in the area of interest at strategic locations using the iterative clustering technique discussed in Chapter 4. Therefore these sensor locations are dependent on the primary location distribution and intended for ideal construction of the spectrum map. The sensors' responsibilities are broadly two-fold: spectrum map creation and route discovery. For the former, the sensors periodically sense the primary activities, share their information among themselves and build the spectrum map. The latter function includes receiving route requests (RREQ) from secondary nodes, finding routes to the destination or the edge nodes, and caching potential routes. Sensors communicate with each other using a control channel. The same control channel is used to communicate with the secondary nodes as well. Each sensor has a transmission range of r_s and secondary nodes within the corresponding disc are under the purview of the sensor unless they belong to an overlapping region of two or more discs.

Secondary Nodes: Secondary nodes are deployed irrespective of primary and sensor locations as a two dimensional Poisson point process with density λ_s . These secondary nodes have no sensing capability and are instructed by the sensors to use a particular channel intended for a particular destination. Like a primary transmitter, a secondary node is a transceiver with no fixed transmission range. The connectivity among secondary nodes is a function of the availability of free channels, secondary transmission power, path loss and other propagation characteristics like shadowing and fading. Secondary nodes under the purview of a single sensor are called non-edge nodes while nodes lying in the overlapping regions are called *edge* nodes. Although the edge nodes reside in the overlapping region, they are associated to only one sensor at a time. However, they can cache other sensors' IDs for use in route discovery. Secondary nodes outside the disc of any sensor is an uncovered node. A pictorial representation of the system model is shown in Fig. 6.2.

6.3 Proposed Routing Scheme

Discovery of a route is initiated when a secondary node sends a route request (RREQ) to its associated sensor on the control channel. The proposed routing scheme employed by the sensor determines three aspects of routing: next hop selection, channel selection, and secondary power control for primary receiver protection. The routing scheme ensures primary receiver protection and is flexible enough to maximize any desired performance metric e.g., channel capacity, data rate etc. In our system, we design the routing scheme to find routes which have the maximum aggregate channel capacity.



Figure 6.2 A region of interest with primary transmitters, primary receivers, sensors, edge, non-edge, and uncovered secondary nodes

6.3.1 Route discovery

A route from source to destination can be of two kinds depending on their relative locations: intra-domain and inter-domain. When the source and destination are under the purview of the same sensor then it is called intra-domain and when under different sensors it is inter-domain. We will first discuss intra-domain routing and then explain how inter-domain routing is treated as a collection of intra-domain routing.

6.3.1.1 Intra-domain routing

A sensor upon receiving the RREQ checks whether the destination is associated with it i.e., is within r_s from it. If so, for each source node i, the sensor consults the most recent spectrum map and eliminates all the channels which are occupied. For the available channels in the spectrum, P_{ub}^n is calculated which is the upper bound on secondary transmission power while using channel n ($n \in N$) in order to protect the primary receivers on that channel. Details of P_{ub}^n calculation is discussed later.

Graph creation: We define $P_{opt}^n = min\{P_{hw}, P_{ub}^n\}$ be the optimum power to be used on channel *n* which will maximize the channel performance while protecting the primary receivers on that channel. P_{hw} is the maximum secondary transmission power due to hardware constraints and we assume it to be same for all secondary nodes. Now for every other node $(j, j \neq i)$ under the sensor, if $RSS_{ij}^n/e_j^n > \gamma$ then there exists an edge between nodes *i* and *j* on channel *n*. Here, RSS_{ij}^n is the received signal strength at node *j* on channel *n* when node *i* transmits with power P_{opt}^n estimated by the sensor. e_j^n is the noise on channel *n* at *j* from the spectrum map and γ is the signal to noise threshold for successful secondary communication. The sensor in consideration can easily calculate RSS_{ij}^n using any sophisticated pass-loss model; the more sophisticated the model is, better is the estimation. Each such
edge is associated with a cost C_{ij}^n which in our case is inversely proportional to the ensuing capacity of channel n raised to the power α . The channel capacity is calculated using the bandwidth of channel n and signal to noise ratio RSS_{ij}^n/e_j^n . With the edges calculated for each pair of secondary nodes, the sensor creates the connectivity graph within its domain for the current primary usage scenario. Employing well known Dijsktra's algorithm or any shortest path algorithm, the sensor determines the shortest path between the source and destination within its domain. The shortest path thus contains the next hop IDs, channel to be chosen for each hop, and secondary transmission power for each such channel. Once the path is determined, the sensor sends the routing instructions to the corresponding nodes along the path on the control channel.

 P_{ub}^n calculation : Evaluating P_{ub}^n is an intuitive reverse calculation to protect primary contour. As shown in Fig. 6.3, d_i^n is the distance between node *i* and the nearest location to it where channel *n* is occupied by the primary. This distance can easily be measured by the sensor from the spectrum map. Therefore, the disc with radius d_i^n with node *i* at the center has the smallest area where the primary receivers are guaranteed to be protected on channel *n*. It is to be noted that this so-called *safe zone* for the primary receivers is independent of the primary receiver distance from the secondary node in consideration. Now if $RSS_{ub}^n = f(d_i^n, P_{ub}^n)$ is the estimated received signal strength at the perimeter of the disc, then P_{ub}^n is calculated by equating RSS_{ub}^n to the primary interference threshold.



Figure 6.3 Safe zone around secondary node i for channel n

6.3.1.2 Inter-domain routing though selective flooding

When the the source and destination nodes are not under the same sensor, the idea is to flood the route request in the neighboring domains. Therefore once the sensor determines the need of inter-domain routing, it finds the shortest route from the source to each of the edge nodes currently covered under it. The edge nodes, upon the reception of a RREQ where the edge node itself is not the final destination, try to connect to the other sensor/s and initiate a RREQ. For example if any edge node k has $\{S_2, S_5, S_1\}$ in its sensor priority, which means that edge node k is currently covered by S_2 and it also lies within the disc of S_5 , and S_1 . Such priorities can be based on the sequence of beacons received from the sensors while the edge node is first powered up. Once the neighboring sensor receives the RREQ, it follows the same recursive process of finding a route to the destination or to the edge nodes until the final destination is found. The route discovery scheme employs selective flooding where a sensor does not cater to the same RREQ request through its domain. In case of an edge node receiving same RREQ from two different nodes, the edge node forwards on first come first serve basis and drops duplicate RREQs. In Fig. 6.4 and Fig. 6.5, we show how selective flooding works and explain duplicate RREQ scenarios. Such selective flooding considerably decreases the route discovery overhead without compromising the discovery of multiple routes to the destination.

In Fig. 6.4, we show how the RREQ flows from source to destination. We also show the control messages from sensors directing relay nodes along the path. We show the case of a sensor getting the same RREQ from two edge nodes: sensors S_2 and S_4 receives same route request from E_1, E_2 , and E_4, E_7 respectively. However, they only forward one RREQ in first come first serve basis, i.e., RREQs from E_2 and E_4 for S_2 and S_4 respectively. It is to be noted that S_2 forwards RREQ from E_2 to E_1 as well as the latter is an edge node, assuming RREQ from E_2 was sent earlier to S_2 . E_1 receiving same RREQ from E_2 does nothing as it was a duplicate. Same set of events happen for S_4 with E_4 and E_7 . In this figure, we also illustrate power control by relay nodes. Edge node E_3 forwards RREQ directly to E_6 bypassing a potential relay node N_1 with a seemingly high transit power. This was achieved because the channel used for transmission between E_3 and E_6 was free in a vast region around E_3 and such high secondary transmission power was not causing interference to primary receivers around E_3 . In Fig. 6.5, we show the RREP packet flow from destination to the source. There is no sensor involvement during RREP flow. The complete route discovery scheme is explained with the help of a flowchart in Fig. 6.6.



Figure 6.4 Inter-domain routing through selective flooding



Figure 6.5 Inter-domain routing through selective flooding

6.3.2 Route maintenance

Route maintenance in cognitive routing is more involved than traditional wireless routing. Caching routes for future use may not be a great idea as routes can be non-existent due to temporal variation of available channels. In our system, route maintenance is carried out only by sensors as they are aware of the current spectrum usage scenario. Route caching at secondary nodes can reduce signalling overhead and latency, but it cannot guarantee primary protection as such sensing disabled nodes have no way to gauge primary activity. Therefore, only the sensors are responsible for caching routes. Sensors cache only those routes which connect each edge nodes in their domain to all other edge nodes in their domain. This is because those routes connecting the edge nodes are the most popular routes for inter-domain routing and in most cases include subsets of intra-domain routes as well. Sensors use the cached route only when there is negligible change in the spectrum maps of the times when the route was cached and when it is being used. Secondary nodes lying within such cached routes automatically benefit from such caching.

6.4 Mathematical Modeling

We model the routing scheme for a deployment of sensors in a deterministic grid pattern equidistant from horizontal and vertical neighbors. This particular orientation is chosen for relative simplicity of mathematical analysis. However, the principles of our mathematical deduction hold true for any deployment of sensors and secondary nodes. We consider a grid of $l \times l$ dimension as our area of interest. The distance d_{ij} between sensors i and j are kept in such manner that every sensor domain overlaps with the four neighboring sensors but the overlapping regions of the domains do not overlap with each other. We assume all the sensors with same domain radius r_s . An example of such a deployment is shown in Fig. 6.7. Note, that for the following deployment $\sqrt{2}r_s \leq d_{ij} \leq 2r_s$.



Figure 6.6 Flowchart for route discovery

6.4.1 Edge node probability

Definition 6.1. Edge node probability is defined as the probability of any secondary node to be an edge node, *i.e.*, be in an overlapping region.



Figure 6.7 Deterministic grid deployment of sensors with the overlapping regions

_		
	\mathcal{N}_{ch}	Number of channel in the spectrum of interest
_	\mathcal{N}_{PU}^{TX}	Number of primary transmitters
_	\mathcal{N}_{PU}^{RX}	Number of primary receivers
	\mathcal{N}_{SU}	Number of secondary nodes
	\mathcal{N}_{sen}	Number of sensors
	p_{idle}	Probability of a channel being idle
	r_s	Radius of a sensor domain
	d_{xy}	Euclidean distance between points x and y

Table 6.1 Notations used for routing analysis

For the above mentioned deployment, the total number of overlapping regions, N_{overlap} , is $2\sqrt{N_{sen}}(\sqrt{N_{sen}}-1)$. N_{sen} is the number of deployed sensors in the grid. The area under each overlapping region is:

$$A_{\text{overlap}} = r_s^2(\theta - \sin\theta); \tag{6.1}$$

where $\theta = 2 \tan^{-1} \left(\frac{\sqrt{4r_s^2 - d_{ij}^2}}{d_{ij}} \right)$

Therefore edge node probability can be expressed as:

$$p_{edge} = \frac{N_{\text{overlap}} \times A_{\text{overlap}}}{l \times l} \tag{6.2}$$

The expected number of edge nodes is:

$$E[\text{Number of edge nodes}] = \mathcal{N}_{SU} \times p_{edge}$$
(6.3)

where \mathcal{N}_{SU} is the number of secondary nodes in the grid.Eqn. 6.3

6.4.2 Connectivity condition

Multi-hop inter-domain routing from any source to destination needs two conditions to be satisfied: i) both source and destination need to be associated with some sensor, i.e., located in some domains and ii) those domains need to be connected with each other directly or indirectly though other domains. The first condition is fulfilled when the source and destination are any edge or non-edge nodes under the purview of a sensor. A combination of higher \mathcal{N}_{sen} and r_s ensures minimum number of uncovered nodes. The second condition is dependent on the overlapping regions of the domains and presence of edge nodes in those overlapping regions. This is because, edge nodes are essential for inter-domain RREQ spreading. The number and locations of such overlapping regions in turn depend on the deployment of the sensors and their relative orientation. We further investigate the conditions that dictate the connectivity of sensor domains.



Figure 6.8 Deployment to undirected grid mapping

Definition 6.2 (Connectivity Condition). The connectivity condition of any secondary network is defined as the sufficient condition for the existence of at least one path from any domain to all other domains in the network. We formulated the *Connectivity Condition* by mapping the secondary network into a connected undirected graph with domains as vertices and overlapping regions as the edge between the vertices as shown in Fig. 6.8.

Definition 6.3 (Mapped Graph). The graph representation of a secondary network with domains as vertices and overlapping regions as edges is called a mapped graph.

Lemma 6.1 provides the connectivity condition of such a mapped graph.

Lemma 6.1. The connectivity condition for a secondary network is that there exists at least one edge node at each of the edges of any one of the minimum spanning trees of the mapped graph.

Proof. A minimum spanning tree (MST) of an undirected unweighted connected graph connects all the nodes in the graph and has the minimum number of edges. Let $G_{n \times n}$ be a mapped graph of any above mentioned sensor deployment with n^2 nodes. Let us assume that it has $\tau(G_{n \times n})$ MSTs. Then each such MST has $(n^2 - 1)$ edges that connect all the nodes. If we remap the MST into a sensor deployment then it represents a network of minimum number of overlapping regions connecting all domains. Presence of any edge node in each of such overlapping regions will guarantee at least one path from all covered nodes to all other covered nodes in the secondary network. Thus the total number of overlapping regions is a measure of minimum number of edge nodes required for a network to be connected. Hence proved.

For a secondary network deployment shown in Fig. 6.7, there are \mathcal{N}_{sen} sensors; hence \mathcal{N}_{sen} domains. Therefore the mapped graph of the network will look like a $\sqrt{\mathcal{N}_{sen}} \times \sqrt{\mathcal{N}_{sen}}$ grid. The number of edges in any of the MSTs of such a mapped graph is the count of minimum number of edge nodes required for the corresponding secondary network to be connected. If τ is the total number of possible minimum spanning trees in such a grid, then each MST contains $(\mathcal{N}_{sen} - 1)$ edges.

Therefore, the probability of connectivity condition is given as:

$$p_{conn} = \tau \times \operatorname{Prob}\{Z_1 \ge 1; Z_2 \ge 1; \cdots Z_{\mathcal{N}_{sen}-1} \ge 1\} \quad \forall \quad Z_1 + Z_2 + \cdots + Z_{\mathcal{N}_{sen}-1} \le \mathcal{N}_{SU}$$

$$(6.4)$$

where Z_i is the random variable denoting the number of edge nodes in the *i*th edge of the mapped graph. For a $\sqrt{\mathcal{N}_{sen}} \times \sqrt{\mathcal{N}_{sen}}$ square grid, $\tau \approx 3.209^{\mathcal{N}_{sen}}$ for $\mathcal{N}_{sen} \to \infty$ [63, 64]. In Chapter 7, we will evaluate p_{conn} for a given secondary deployment.

6.5 Summary

In this chapter we discussed the challenges of routing in cognitive radio network over a traditional as-hoc network. We proposed a multichannel multihop routing technique for data packet routing among secondary nodes with a aid of a spectrum map created by few sensors. A *selective flooding* technique is also devised to spread the route requests in the network without causing network wide flooding overhead. We analyzed the connectivity

condition among secondary nodes using a mapped graph and found the conditions for a MST to exist on such graph.

CHAPTER 7: SIMULATION MODEL AND RESULTS

In this chapter, we discuss the simulation models, experiments and corresponding results of our work. We have already discussed the nature and accuracy of the proposed spectrum map in Chapter 3. This chapter focuses on simulation results of proposed channel allocation in IEEE 802.22 networks, contention based multichannel MAC protocol, and the multi-channel multi-hop power controlled routing scheme.

7.1 IEEE 802.22 Channel Allocation

We conduct extensive simulation experiments to verify the accuracy of the spectrum usage estimation technique for the purpose of efficient and quick channel allocation in IEEE 802.22 networks. We simulate TV stations in a 500x500 sq. miles grid as shown in Fig 7.1(a) taking reference from TV station location distribution given in [6] [7]. The grid contains both dense and sparse populations of TV stations mimicking big cities and small towns. All the primary TV stations transmit continuously on different channels. The total number of channels considered is 50 with bandwidth of 6 MHz each in accordance with the DTV system. The power-profile of the TV stations are chosen randomly and ranges between 10kW-1MW.



(a) Simulation grid with primary transmitters and IEEE 802.22 base stations



Figure 7.1 Simulation environment

We identify two regions with different primary densities and deploy two IEEE 802.22 networks (WRAN cells) in those two regions as shown in Fig. 7.1(b) and Fig. 7.1(c) (which are magnified versions of regions from Fig. 7.1(a)). The selection of two different primary densities is simply to test the performance of the IEEE 802.22 networks under two different scenarios. The total number of CPEs, their density, and the number of delegated CPEs are

fixed for both the scenarios. The maximum number of CPEs was fixed at 255 as per the IEEE 802.22 draft [57]. The performance evaluation is done on three fronts: i) nature and accuracy of spectrum usage estimation, ii) predicting performance metrics, and iii) performance of the allocation algorithm.

7.1.1 Nature and accuracy of estimation

In figures 7.2, 7.3, 7.4 and 7.5, 7.6, 7.7, we show the estimated and actual signal strength for different scenarios with the error in estimation. It is quite evident from the figures that the interpolation technique has been successfully able to capture the very nature of spectrum usage in the regions. In Fig. 7.4, the difference between the actual and estimated is very low and in the order of 10^{-6} which is too small to alter the occupancy decision vector. For scenario 2, the errors are seemingly higher (fig. 7.7) than scenario 1, because of the presence of CPEs close to the primaries. The region with signal strength values more than 10^{-5} mW are regarded as occupied and thus over-estimation in those region does not affect the occupancy vector.

In Fig. 7.8, we show how occurrences of such false positives vary with the probability of getting white space. We vary the total number of available channels (bandwidth of each channel) in order to determine its effect on the occurrences of false positives. We observe that as there are more channels available for the secondary nodes to use, the conservative approach of the estimation technique becomes more predominant. However, we see that even with 80% probability of getting free channels the ratio of instances of false positives to total number of channels is less than 0.1.



Figure 7.2 Estimated signal strength of a channel



Figure 7.3 Actual received signal strength of same channel

Fig. 7.9 depicts the accuracy of the estimation technique in terms of instances of both false positives and false negatives with varying number of delegation CPEs consulted for the interpolation purpose. We see a sharp increase in both instances of false positives and false negatives when more than 15 delegation CPEs are selected. This finding is in accordance with Shepard's [52] claim about the existence of upper and lower bounds on the number of data-points to be used for most accurate estimation. This upper bound on number of delegation CPEs helps us to choose optimal search radius depending on the density and topology of the IEEE 802.22 cell.



Figure 7.4 Error in estimation



Figure 7.5 Estimated signal strength of a channel



Figure 7.6 Actual received signal strength of same channel



Figure 7.7 Error in estimation

7.1.2 Channel allocation

Fig. 7.10 and Fig. 7.11 collectively portray how the available channels in the spectrum are utilized by the proposed allocation technique. In Fig. 7.10, a 45° slope signifies 100% utilization which occurs when there are more channels available to allocate to the CPEs.



Figure 7.8 Instances of false positives in estimation for different values of probability of getting free channels in the spectrum



Figure 7.9 Accuracy of estimation with varying number of delegation CPEs for interpolation

However even with 50 channels with probability of 0.6, we see that 17 free channels are allocated resulting 57% (17/[50x0.6]) utilization.

Nature of free channel utilization with varying number of available channels is better understood in Fig. 7.11 where we vary the total number of channels in the spectrum and probability of getting white space thereby indirectly varying number of free channels to utilize. We observe that even with a very low probability of white space 0.4 (with respect to TV spectrum), the proposed allocation scheme ensures more than 50% utilization of free spectrum in most occasions. The total number of allocable CPEs are kept at 255 for all the scenarios above which is the maximum number of CPEs that an IEEE 802.22 cell can have [57].



Figure 7.10 Number of channel allocated from total available channels

In Fig. 7.12, we show the efficiency of the proposed allocation technique by calculating the number of CPEs being allocated a pair of uplink and downlink channels. We observe that with 400 channels and a probability of getting white space of 0.8, we can allocate 106 (i.e., 212 channels) CPEs from the possible 160 pairs (320 channels).



Figure 7.11 Utilization of available channels for different probabilities of white space



Figure 7.12 Number of allocated CPEs for different number of channels in the spectrum

In Fig. 7.13, we show the characteristic of the number of free channels allocated with different number of simultaneous idle CPEs. These results are also very encouraging as we

see that on an average more than 50% of the free channels of the spectrum are being utilized by the IEEE 802.22 network with increasing demand from idle CPEs.



Figure 7.13 Number of channels allocated with varying number of idle CPEs

7.2 Contention based MAC Protocol

We conduct simulation experiments in MATLAB to find the empirical results of the proposed contention based MAC protocol. As input to the simulation model we kept total number of channels, $N_T = 30$, time for contention window, $T_c = .00003 \times N_S$ and beacon interval, $T_b = T_c/100$, where N_S is the number of mini-slots in each RTS/CTS/ACK sub-window.

RTS Success Probability: We show the characteristics of RTS success probability with number of active secondaries in Fig. 7.14. It shows the typical nature of slotted ALOHA throughput with the peak success probability 0.37. With more mini-slots, the peak value 109

is reached with more secondaries in the system, i.e., with more secondaries contending per mini-slot, λ_s .



Figure 7.14 RTS success probability.



Figure 7.15 Idle channel grabbing characteristics, with $N_T = 30$ and $\lambda_s = 3$.

Channel Grabbing: We investigate the nature of expected idle channel grabbing against the number of mini-slots for different values of p_{idle} . N_{CG} shows steady increase with number of slots grabbed N_{SW} till it reaches the point where N_{SW} crosses number of available channels N_A after which it becomes a steady value. For higher values of p_{idle} , the value of N_A increases and so as the steady state value.

In Fig. 7.16, we show how idle channel grabbing varies with the rate of secondary contention per mini-slot. The nature mimics typical slotted-ALOHA throughput curve. Higher probability of p_{idle} results in higher peak value of N_{CG} . Here, we keep N_S fixed at 100.



Figure 7.16 Idle channel grabbing characteristics with $N_T = 30$ and $N_S = 100$

Slotted-ALOHA like characteristic is seen in Fig. 7.17 where we plot the same N_{CG} vs. λ_s but for different values of N_S keeping p_{idle} fixed at 0.5. We see similar nature in Fig. 7.16 but with no increase in the peak value of N_{CG} for different N_S . This is because the peak value is the value of N_{SW} which does not change for $N_S = 50$ to 300. However, we do see that with lower N_S , the peak value has fewer instances for different λ_s .



Figure 7.17 Idle channel grabbing characteristics with $N_T = 30$ and $p_{idle} = 0.5$

Blocking Probability: The nature of average blocking probability with mean secondary arrival rate, λ_s , is shown in Fig. 7.18. We see that the convexity mimics the nature of exponential distribution with average blocking probability peaking at a certain λ_s and then exponentially decreasing. This characteristic can be attributed to the fact that for a certain number of N_A , when the total number slot winner N_{SW} reaches the peak, blocking probability is also has the maxima at that point as maximum number of winners are blocked at that λ_s . However with more contending secondaries, we have less winners due to contention resulting in a sharp decline in average blocking probability.

In Fig. 7.19, we show how the average blocking probability varies with number of mini-slots in each contention window. We notice that for low values of N_s , average blocking

probability value is zero as *all* the winning secondaries are able to grab channels. After a certain N_S , when total number of winning mini-slots go beyond N_A (for a particular p_{idle}), average blocking probability becomes non-zero. The average blocking probability continues to increase with N_S till it reaches the saturation point when most of the winning secondaries are blocked. With higher p_{idle} , such saturation point for average blocking probability is reached at a higher N_S and also has a lower peak value as an increased N_A results in more winning secondaries to grab channels.



Figure 7.18 Average blocking probability with $N_T = 30$, $N_S = 200$, $p_{idle} = 0.5$

Channel Utilization: Nature of idle channel utilization with number of mini-slots is demonstrated in Fig. 7.20. We see that with the increase in number of mini-slots, the utilization increases linearly till it reaches the inflection point. The existence of the maxima for a particular p_{idle} is a measure of optimal number of slots for the system. Such convexity exists because larger contention window leads to more probability of PU arrival (higher value of $\bar{P}_{PU}^{P \to S}$) and thus less utilization. For example, when $p_{idle}=0.6$, the optimal N_S is around 120 for maximum idle channel utilization.



Figure 7.19 Average blocking probability with $N_T = 30, \lambda = 1$



Figure 7.20 Idle channel utilization with $N_T = 30$ and $\lambda_s = 3$

In Fig. 7.21, we see that the nature of channel utilization with varying number of secondaries is similar to that of channel grabbing in Fig. 7.16. However the peak value of average channel utilized for each p_{idle} is less than that of average channels grabbed as some channels will encounter interference from PUs.



Figure 7.21 Idle channel utilization with $N_T = 30$ and $N_S = 100$

Fig. 7.22 shows that the peak value of idle channel utilization decreases with more mini-slots in the system. With more N_S , the utilization saturates at a lower value because of higher probability of PU reclaiming the channel.

Primary Degradation: In Fig. 7.23, we show how expected PU QoS degradation varies with number of active secondary nodes. We see that the normalized peak value of the degradation is very small. We also notice that the maxima for all values of p_{idle} is obtained at the same value of number of secondary nodes (at $\Lambda = 100$) where RTS success rate is maximum in Fig. 7.14 (at $N_S = 100$). Maximum RTS success signifies maximum channel grabbing and eventual utilization resulting peak PU degradation.



Figure 7.22 Idle channel utilization with $N_T = 30$ and $p_{idle} = 0.5$



Figure 7.23 Expected PU degradation with $N_T = 30$ and $N_S = 100$

In Fig. 7.24, we see that with varying number of mini-slots, the average PU degradation increases linearly and then slowly starts to decrease. We notice the peak value for all p_{idle} occurs at the same value of N_S . However, this critical value of N_S is much higher that the optimal N_S obtained from Fig. 7.20 for maximum utilization.



Figure 7.24 Expected PU degradation with $N_T = 30$ and $\Lambda = 100$

Multiple slots reservation: Consequences of multiple data slots reservation are demonstrated in Fig. 7.25 and Fig. 7.26. In Fig. 7.25, the number of data slots reserved, N_{DS} , by each winning secondary is shown for different λ . For low λ (values 0-10 shown in the magnified plot), the contention process has few winners and therefore each winner gets higher N_{DS} . For a large range of λ , the contention process has large number of winners (N_{SW}) and therefore each is allowed to reserve only 1 data slot. N_{DS} starts to increase exponentially when λ is so high that eventual N_{SW} is low.



Figure 7.25 Number of successive data-slots reserved by winning SUs with $N_T = 30$ and $N_S = 100$

Comparison between idle channel utilization for single and multiple data slot reservation schemes is shown in Fig. 7.26. We see that multiple slot is either better or same in terms of utilization for all the values of λ_s and therefore λ as well. Single slot scheme looses ground when there are too many contenders and therefore less winners. However, multiple slots scheme ensures almost 100% utilization for all values of λ . The instances where utilization is lower is because of the floor function in Eqn. 5.14. Although theoretically multiple slots should ensure complete utilization, some idle channel time is wasted due to indivisibility of data channels.

Performance comparison: We compare the performance of our proposed scheme with two of the latest MAC schemes, opportunistic sensing based MAC [9] (OS-MAC) and OMC-MAC [8]. Both these work consider common control channels for control messaging and have

shown better performance than other existing schemes in the literature. For the comparison we keep $p_{idle} = 0.5$ and $N_S = 100$ for all schemes.



Figure 7.26 Average idle channel utilization for single and multiple data-slots with $N_T = 30$ and $N_S = 100$

In [9], the authors evaluated the performance of their proposed scheme through implementing the OS-MAC in their simulation environment. In Fig. 7.27, we compare the steady state throughput of our proposed scheme with that of OS-MAC shown in [9]. For fairness of comparison, we assumed $N_T = 40$, $\bar{t}_{ON} = \bar{t}_{OFF} = 300s$, and transmission rate for data channel to be 1 *Mbps*. These values are same as what was used in [9]. The figure shows that the proposed scheme clearly outperforms OS-MAC in terms of steady state throughput.

In Fig. 7.28, we compare the average channel utilization of our proposed scheme with OMC-MAC against varying number of active secondary nodes. For OMC-MAC, we used the values of $T_{BI}, t_{DIFS}, t_{SIFS}, \sigma, P_t, T_{spc}$ and T_{con} equal to the values used in [8]. We compare our results with OMC-MAC with variable T_{DT} as that is proved to be better performing 119

than fixed T_{DT} . We see that for different values of N_T , our proposed scheme performs better than OMC-MAC not only in terms of number of channel utilized, but also does not decay with secondaries in the system. This happens because in OMC-MAC, sensing of channels is performed in the same cycle of beacon interval with contention and transmission. Such serialization takes its toll on the average utilization when there are more channels to scan as the sensing takes up considerable time from beacon interval duration.



Figure 7.27 Throughput comparison with OS-MAC with $p_{idle} = 0.5$, $N_T = 40$ and $N_S = 100$ s

Also, OMC-MAC [8] used probability of sensing error per channel as a key variable to gauge the robustness of the MAC protocol against possible false negatives. Such probability of misdetection is a variable independent of the MAC scheme for both our proposed MAC and OMC-MAC. In Fig. 7.29, we compare the normalized primary degradation for different probabilities of sensing error. We observe that although the degradation in OMC-MAC does not depend on Λ , the amount of degradation in our proposed scheme for different Λ values is much less than that of OMC-MAC. Therefore, our proposed MAC outperforms OMC-MAC in terms of primary degradation caused by misdetection.



Figure 7.28 Expected channel utilization comparison with OMC-MAC with $p_{idle} = 0.5$ and $N_S = 100$.



Figure 7.29 Normalized primary degradation comparison with OMC-MAC with $p_{idle} = 0.5$, $N_T = 25$ and $N_S = 100$.

7.3 Spectrum Map based Multihop Routing

We conduct extensive simulation experiments in C and MATLAB to gauge the performance of the proposed multi-channel, multi-hop routing protocol. The primary transmitters are deployed in a 100×100 area using the deployment model used in [6, 7]. We consider varying number of channels from 5-30 with 1 MHz bandwidth each. The primary channel selection at any point is random. Each primary transmitter has a transmission power of 50 Watts and the primary detection threshold is kept at -116 dBm to conform with TVWS standard [5]. Nine sensors are deterministically deployed in a grid patter as discussed in Chapter 6. The secondary nodes are deployed following a Poisson Point Process to ensure that their locations are not inter-dependent. The secondary transmission power is ketp at 100 mW. We used a highly sophisticated path-loss model proposed in [65] which mimics the real life propagation characteristics in an urban macro-cell. The co-channel interference threshold for primary receivers caused due to secondary communication is kept at -80dBm which is the interference threshold for digital TV due to analog TV signals.

Edge Node Probability: In Fig. 7.30, we show the nature of probability of edge nodes (p_{edge}) with varying radius of sensors, r_s . The value of r_s is varied from $\sqrt{2}r_s \leq d_{ij} \leq 2r_s$ as this is the range where the domains start overlapping but the overlapping regions do not overlap with each other as discussed in Chapter 6. We see that within this range of r_s , p_{edge} increases rapidly.


Figure 7.30 Edge node probability with varying sensor radius

In Fig. 7.31, we plot Eqn. 6.3 against the same range of r_s and compare the numerical and simulation values. We see marked similarity with Fig. 7.30 as the nature of the curve shows rapid increase between $r_s = 17$ to 23. The simulation results closely match with the numerical trend from Eqn. 6.3 which in turn validates the mathematical analysis.

Connectivity: In Fig. 7.32, we show how the probability of connectivity p_{conn} varies with r_s . Here N_{SU} is kept constant at 100. We see as p_{edge} increases with r_s , so does p_{conn} . The secondary network reaches complete connectivity at $r_s=23$ i.e., at this point at least one edge node is present on each edge of at least one of the spanning trees of the mapped graph. The nature is obtained by taking average of more than 1000 different network topology.

The nature of p_{conn} with varying N_{SU} is shown in Fig. 7.33. We kept r_s at 20. We see that with a denser network of secondary node the connectivity increases. With 300 secondary nodes, the network is fully connected i.e., there is at least one route from each

domain to each other. We take an average of more than 1000 different network topologies to obtain the plot.



Figure 7.31 Expected number of edge nodes for simulation and numerical models



Figure 7.32 Probability of connectivity condition with varying sensor radius



Figure 7.33 Probability of connectivity condition with varying number of secondary nodes



Figure 7.34 Reachability of the secondary nodes without power control for different scenarios

Reachability: In figures 7.34(a)-7.35(c), we show how each secondary node is reachable from other secondary nodes. Non-edge connections are shown in black and edge connections are shown in blue. We see that between domains, the only entry or exit points are the edge nodes. In figures 7.34(a) and 7.34(b), we show the reachability with no power control, i.e., if

two nodes have the same free channel and they are within the range of each other, then they are reachable. The scenario does not take into account the primary hidden terminal problem and thus does not protect any primary receivers that may be present in the communication range. With more channels the reachability increases. It is to be noted that in this scenario each link is bidirectional, i.e., a link represents both nodes are reachable from each other. Similar properties can be observed in figures 7.35(a) and 7.35(b) but with much fewer links when power control is applied on the secondary nodes. We see that to protect possible secondary receivers, the secondaries had to use much less power thus the reachability decreases considerably. With increase in number of channels, the reachability increases marginally. The minimum signal-to-noise ratio (SINR) is kept at -15 dB which is higher in comparison with most wireless services. However in Fig. 7.35(c), when we change the minimum SINR requirement to -75dB, which is more comparable with commercial wireless standards, we see reachability increasing even with power control. However, unlike no power control, each link may or may not be bidirectional. This is due to the fact that it is not always true that both nodes connecting the links will not cause interference to primary receivers.

As a different representation, we show in Fig. 7.36 the percentage of non-existing or bad links to the total number of links with no power control. These links do not exist when nodes use power control for primary protection. The value typically ranges from 0.35 to 0.5. We observe that with 10 channels, the average percentage of non-existent links is more than 20 channels.



(a) Reachability with 5 channels

(b) Reachability with 20 channels



(c) Reachability with 20 channels and minimum SNR $-75\mathrm{dB}$

Figure 7.35 Reachability of the secondary network with power control for different scenarios

Routing Nature: In figures 7.37 and 7.38, we compare routing between the same pair of nodes under identical network conditions with and without power control respectively. We see that without power control the route takes less number of hops and also uses the same channel throughout the route. However, when we use power control to protect the primary receivers, number of hops increases and also the channels change along the route.



Figure 7.36 Percentage of non-existent channels for using power-control in routing



Figure 7.37 Routing without power control between Node 158 and Node 42

Routing Performance: Fig. 7.39 shows the average route capacity with varying r_s . This metric is nothing but the inverse of average hop count per route. We see that for both inter-domain and intra-domain routing, with higher r_s , the average hop count increases as

there are more routes available with higher capacity. Thus the percentage average route capacity decreases sharply with r_s until it reaches a steady state when chances of finding better routes saturate.



Figure 7.38 Routing with power control between Node 158 and Node 42



Figure 7.39 Average route capacity with sensor radius



Figure 7.40 Bottleneck capacity with sensor radius

We show the nature of bottleneck capacity to average route capacity is observed in Fig. 7.40. With higher r_s , network connectivity increases, thus the proposed routing scheme identifies better routes with higher bottleneck capacity. With inter-domain routing, the probability of a finding a lower capacity link increases, thus we observe reduction in bottleneck capacity.

Lastly, in Fig. 7.41, we show the maximum number of times channels have been switched during a route. Frequent channel switching along the a route incurs switching delays and is not a desirable property for routing in secondary network. We investigated the trends for routes with up to 50 hops. The maximum number of times channels were switched for any such route was 4. Such small number of channel switching can be attributed to the fact that probability of finding routes with best capacity is more on the same channel in nearby geographic location. Such trend is observed when the primary occupancy is moderately dynamic like in TVWS. When a highly dynamic primary network is modeled, then routing with capacity maximization will result in more frequent channel switching.



Figure 7.41 Maximum occurrences of channel switches with hop count in routes

CHAPTER 8: CONCLUSIONS

The thesis discussed how Shepard's interpolation technique is applied to create a spectrum map, i.e., an estimate of the spectrum usage at any arbitrary location in a secondary cognitive radio network. This is achieved by sharing and fusing raw spectrum data sensed at various strategic locations which were found by iterative clustering. We demonstrated how the spectrum map can help in predicting channel performance metrics like channel capacity, spectral efficiency, network throughput, and bit error rate. Through simulation experiments, we validated the correctness of the map and showed how we can compute the distribution of these metrics at any arbitrary location, which can potentially be used by secondary networks for better channel selection such that the spectrum usage is maximized. We also used the proposed map to help attain near perfect channel allocation in IEEE 802.22 networks by improving the channel rendezvous probability and guaranteed allocation of best candidate channel. We also proposed a contention based MAC protocol where secondary users are not expected to carry out the channel sensing duties on their own and take help of sensors periodically sensing and building spectrum maps. The proposed MAC protocol allows multiple classes of secondary users and takes into consideration, different QoS criteria, which include primary user service interruption rate, secondary user interruption rate, blocking probability etc. The proposed scheme outperforms existing MAC schemes in terms of system throughput and average channel utilization. The MAC scheme is also more robust to misdetection of primaries than other MAC schemes in literature. Finally we used the map to perform multi-channel multi-hop routing among sensing incapable low cost secondary devices. The map acts as a reference to find the best channels along a route that not only maximizes channel capacity but also protects primary receivers through secondary power control. We gauged the performance of the proposed routing technique through metrics like average hop count, achievable bottleneck capacity etc. We also performed simulations to examine the benefits of power control on primary protection and free channel reuse among secondary nodes.

Overall, the thesis seeks to open a new direction of whitespace networking where the secondary access is proactive rather than legacy reactive 'sense and use' techniques. The thesis sheds light on possible implications of such paradigm shift by proposing cross-layer protocols and through this intends to be the flagship work on such proactive whitespace networking and engage the cognitive networking community for deeper investigation.

LIST OF REFERENCES

- [1] http://www.sharedspectrum.com/papers/spectrum-reports/.
- [2] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: new directions in wireless networking using coordinated dynamic spectrum," in World of Wireless Mobile and Multimedia Networks, WoWMoM. Sixth IEEE International Symposium on a, pp. 78–85, June 2005.
- [3] F. communications commission (FCC), "Notice of proposed rule making," May 2004. ET Docket no. 04113.
- [4] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks Jour*nal (ELSEVIER), vol. 50, pp. 2127–2159, 2006.
- [5] "FCC adopts rule for unlicensed use of television white spaces." http://www.fcc.gov/.
- [6] J. Riihijarvi, P. Mahonen, M. Wellens, and M. Gordziel, "Characterization and modelling of spectrum for dynamic spectrum access with spatial statistics and random fields," in *Personal, Indoor and Mobile Radio Communications, PIMRC. IEEE 19th International Symposium on*, pp. 1–6, Sept. 2008.
- [7] J. Riihijarvi and P. Mahonen, "Exploiting spatial statistics of primary and secondary users towards improved cognitive radio networks," in *Cognitive Radio Oriented Wireless Networks and Communications, CrownCom. 3rd International Conference on*, pp. 1–7, May 2008.
- [8] S. Jha, U. Phuyal, M. Rashid, and V. Bhargava, "Design of OMC-MAC: An opportunistic multi-channel MAC with QoS provisioning for distributed cognitive radio networks," *Wireless Communications, IEEE Transactions on*, vol. 10, pp. 3414–3425, Oct. 2011.
- [9] W. S. Jeon, J. A. Han, and D. G. Jeong, "A novel MAC scheme for multichannel cognitive radio ad hoc networks," *Mobile Computing, IEEE Transactions on*, vol. 11, pp. 922–934, June 2012.
- [10] Y. Li, T. T. Quang, Y. Kawahara, T. Asami, and M. Kusunoki, "Building a spectrum map for future cognitive radio technology," in *Proceedings of the 2009 ACM workshop* on Cognitive radio networks, CoRoNet, (New York, NY, USA), pp. 1–6, ACM, 2009.

- [11] M. A. McHenry, "NSF spectrum occupancy measurements project summary," 2001.
- [12] T. Harrold, R. Cepeda, and M. Beach, "Long-term measurements of spectrum occupancy characteristics," in New Frontiers in Dynamic Spectrum Access Networks, DyS-PAN. IEEE Symposium on, pp. 83–89, May 2011.
- [13] S. Geirhofer, L. Tong, and B. Sadler, "A measurement-based model for dynamic spectrum access in WLAN channels," in *Military Communications Conference, MILCOM. IEEE*, pp. 1–7, Oct. 2006.
- [14] A. Stirling, "Exploiting hybrid models for spectrum access: Building on the capabilities of geolocation databases," in New Frontiers in Dynamic Spectrum Access Networks, DySPAN. IEEE Symposium on, pp. 47–55, May 2011.
- [15] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, "Senseless: A database-driven white spaces network," *Mobile Computing, IEEE Transactions on*, vol. 11, pp. 189–203, Feb. 2012.
- [16] S. Sengupta, R. Chandramouli, S. Brahma, and M. Chatterjee, "A game theoretic framework for distributed self-coexistence among IEEE 802.22 networks," in *Global Telecommunications Conference*, *GLOBECOM. IEEE*, pp. 1–6, Dec. 2008.
- [17] C.-H. Ko and H.-Y. Wei, "Game theoretical resource allocation for inter-bs coexistence in IEEE 802.22," Vehicular Technology, IEEE Transactions on, vol. 59, pp. 1729–1744, May 2010.
- [18] V. Gardellin, S. Das, and L. Lenzini, "A fully distributed game theoretic approach to guarantee self-coexistence among WRANs," in *INFOCOM IEEE Conference on Computer Communications Workshops*, 2010, pp. 1–6, March.
- [19] H.-S. Chen, W. Gao, and D. Daut, "Signature based spectrum sensing algorithms for IEEE 802.22 WRAN," in *International Conference on Communications*, *ICC. IEEE*, pp. 6487–6492, 2007.
- [20] H. Kim and K. G. Shin, "Asymmetry-aware real-time distributed joint resource allocation in IEEE 802.22 WRANS," in *Proceedings of the 29th conference on Information communications*, INFOCOM'10, (Piscataway, NJ, USA), pp. 543–551, IEEE Press, 2010.
- [21] H.-S. Chen and W. Gao, "Spectrum sensing for tv white space in north america," Selected Areas in Communications, IEEE Journal on, vol. 29, pp. 316–326, Feb. 2011.
- [22] A. Min, K. Shin, and X. Hu, "Secure cooperative sensing in IEEE 802.22 WRANs using shadow fading correlation," *Mobile Computing, IEEE Transactions on*, vol. 10, pp. 1434–1447, Oct. 2011.

- [23] H. Kim and K. G. Shin, "In-band spectrum sensing in IEEE 802.22 WRANs for incumbent protection," *Mobile Computing, IEEE Transactions on*, vol. 9, pp. 1766–1779, Dec. 2010.
- [24] S. Sengupta, M. Ahmad, and M. Chatterjee, "Initializing mesh architecture for cognitive radio based IEEE 802.22," in *Cognitive Radio Oriented Wireless Networks and Communications, CrownCom. 2nd International Conference on*, pp. 519–523, Aug. 2007.
- [25] D. Niyato, E. Hossain, and Z. Han, "Dynamic spectrum access in IEEE 802.22-based cognitive wireless networks: a game theoretic model for competitive spectrum bidding and pricing," *Wireless Communications, IEEE*, vol. 16, pp. 16–23, Apr. 2009.
- [26] S. Liu, L. Lazos, and M. Krunz, "Cluster-based control channel allocation in opportunistic cognitive radio networks," *Mobile Computing, IEEE Transactions on*, vol. 11, pp. 1436–1449, Oct. 2012.
- [27] A. Muqattash and M. Krunz, "POWMAC: a single-channel power-control protocol for throughput enhancement in wireless ad hoc networks," *Selected Areas in Communications, IEEE Journal on*, vol. 23, pp. 1067 – 1084, May 2005.
- [28] J. Mo, H.-S. So, and J. Walrand, "Comparison of multichannel mac protocols," Mobile Computing, IEEE Transactions on, vol. 7, pp. 50–65, Jan. 2008.
- [29] J. So and N. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in In ACM MobiHoc, pp. 222–233, 2004.
- [30] C. Cormio and K. R. Chowdhury, "A survey on MAC protocols for cognitive radio networks," Ad Hoc Networks, vol. 7, pp. 1315–1329, Sept. 2009.
- [31] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks," *Selected Areas in Communications*, *IEEE Journal on*, vol. 26, pp. 118–129, Jan. 2008.
- [32] P. Pawelczak, S. Pollin, H.-S. So, A. Bahai, R. Prasad, and R. Hekmat, "Performance analysis of multichannel medium access control algorithms for opportunistic spectrum access," *Vehicular Technology, IEEE Transactions on*, vol. 58, pp. 3014–3031, July 2009.
- [33] C. Xin, B. Xie, and C.-C. Shen, "A novel layered graph model for topology formation and routing in dynamic spectrum access networks," in New Frontiers in Dynamic Spectrum Access Networks, DySPAN. First IEEE International Symposium on, pp. 308–317, Nov. 2005.
- [34] X. Zhou, L. Lin, J. Wang, and X. Zhang, "Cross-layer routing design in cognitive radio networks by colored multigraph model," *Wireless Personal Communications*, vol. 49, pp. 123–131, 2009.

- [35] Q. Wang and H. Zheng, "Route and spectrum selection in dynamic spectrum networks," in *Consumer Communications and Networking Conference*, CCNC. IEEE, vol. 1, pp. 625–629, Jan. 2006.
- [36] Y. T. Hou, Y. Shi, and H. D. Sherali, "Spectrum sharing for multi-hop networking with cognitive radios," *Selected Areas in Communications, IEEE Journal on*, vol. 26, pp. 146–155, Jan. 2008.
- [37] Y. Shi and Y. Hou, "A distributed optimization algorithm for multi-hop cognitive radio networks," in *Proceedings of the 29th conference on Information communications*, INFOCOM'10, pp. 1292–1300, April.
- [38] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Spectrum aware on-demand routing in cognitive radio networks," in New Frontiers in Dynamic Spectrum Access Networks, DySPAN. 2nd IEEE International Symposium on, pp. 571–574, April 2007.
- [39] H.-P. Shiang and M. Van der Schaar, "Distributed resource management in multihop cognitive radio networks for delay-sensitive transmission," *Vehicular Technology, IEEE Transactions on*, vol. 58, no. 2, pp. 941–953, Feb. 2009.
- [40] I. Pefkianakis, S. Wong, and S. Lu, "SAMER: Spectrum aware mesh routing in cognitive radio networks," in New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on, pp. 1–5, Oct. 2008.
- [41] A. Abbagnale and F. Cuomo, "Gymkhana: A connectivity-based routing scheme for cognitive radio ad hoc networks," in *INFOCOM IEEE Conference on Computer Communications Workshops.*, pp. 1–5, March 2010.
- [42] I. Filippini, E. Ekici, and M. Cesana, "Minimum maintenance cost routing in cognitive radio networks," in *Mobile Adhoc and Sensor Systems*, MASS. IEEE 6th International Conference on, pp. 284–293, Oct. 2009.
- [43] K. R. Chowdhury and M. D. Felice, "Search: A routing protocol for mobile cognitive radio ad-hoc networks," *Computer Communications Journal (ELSEVIER)*, vol. 32, pp. 1983–1997, Dec. 2009.
- [44] W. Gardner, "Signal interception: a unifying theoretical framework for feature detection," Communications, IEEE Transactions on, vol. 36, pp. 897–906, Aug 1988.
- [45] R. Tandra and A. Sahai, "Fundamental limits on detection in low SNR under noise uncertainty," in Wireless Networks, Communications and Mobile Computing, 2005 International Conference on, vol. 1, pp. 464 – 469 vol.1, June 2005.
- [46] Y. Zeng and Y.-C. Liang, "Maximum-minimum eigenvalue detection for cognitive radio," in Personal, Indoor and Mobile Radio Communications, PIMRC. IEEE 18th International Symposium on, pp. 1–5, 2007.

- [47] Z. Tian and G. B. Giannakis, "A wavelet approach to wideband spectrum sensing for cognitive radios," in *Cognitive Radio Oriented Wireless Networks and Communications*. *1st International Conference on*, pp. 1–5, June 2006.
- [48] H. Urkowitz, "Energy detection of unknown deterministic signals," Proceedings of the IEEE, vol. 55, pp. 523 – 531, April 1967.
- [49] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio, part I: Two user networks," Wireless Communications, IEEE Transactions on, vol. 6, pp. 2204 – 2213, June 2007.
- [50] G. Ganesan and L. Ye, "Cooperative spectrum sensing in cognitive radio, part II: Multiuser networks," Wireless Communications, IEEE Transactions on, vol. 6, pp. 2214 -2222, June 2007.
- [51] S. Mishra, A. Sahai, and R. Brodersen, "Cooperative sensing among cognitive radios," in *International Conference on Communications*, *ICC. IEEE*, vol. 4, pp. 1658–1663, June 2006.
- [52] D. Shepard, "A two-dimensional interpolation function for irregularly-spaced data," in Proceedings of the 1968 23rd ACM national conference, ACM '68, (New York, NY, USA), pp. 517–524, ACM, 1968.
- [53] C. E. Shannon, "A mathematical theory of communication," SIGMOBILE Mob. Comput. Commun. Rev., vol. 5, pp. 3–55, Jan. 2001.
- [54] S.-W. Jeon, N. Devroye, M. Vu, S.-Y. Chung, and V. Tarokh, "Cognitive networks achieve throughput scaling of a homogeneous network," *Information Theory*, *IEEE Transactions on*, vol. 57, pp. 5103 –5115, Aug. 2011.
- [55] J. G. Proakis, *Digital Communications*. McGraw-Hill, 4th ed., 2001.
- [56] "IEEE 802.22, working group on wireless regional area networks (WRAN)." http://grouper.ieee.org/ groups /802/22.
- [57] "IEEE P802.22/d1.0 draft standard for wireless regional area networks part 22: Cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: Policies and procedures for operation in the TV bands, april 2008.," April 2008.
- [58] A. Benslimane, A. Ali, A. Kobbane, and T. Taleb, "A new opportunistic MAC layer protocol for cognitive IEEE 802.11-based wireless networks," in *Personal, Indoor* and Mobile Radio Communications, PIMRC. IEEE 20th International Symposium on, pp. 2181–2185, 2009.
- [59] B. Vujicic, N. Cackov, S. Vujicic, and L. Trajkovic, "Modeling and characterization of traffic in public safety wireless networks," in *In Proc. of SPECTS*, pp. 214–223, 2005.

- [60] M. Cesana, F. Cuomo, and E. Ekici, "Routing in cognitive radio networks: Challenges and solutions," Ad Hoc Networks, vol. 9, no. 3, pp. 228 248, 2011.
- [61] I. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *Communications Magazine*, *IEEE*, vol. 46, no. 4, pp. 40–48, April 2008.
- [62] H. Khalifé, N. Malouch, and S. Fdida, "Multihop cognitive radio networks: to route or not to route," Netwrk. Mag. of Global Internetwkg., vol. 23, pp. 20–25, July 2009.
- [63] R. Shrock and F. Y. Wu, "Spanning trees on graphs and lattices in d dimensions," Journal of Physics A: Mathematical and General, vol. 33, no. 21, p. 3881, 2000.
- [64] F. Y. Wu, "Number of spanning trees on a lattice," Journal of Physics A: Mathematical and General, vol. 10, no. 6, p. L113, 1977.
- [65] Z. Ren, G. Wang, Q. Chen, and H. Li, "Modelling and simulation of rayleigh fading, path loss, and shadowing fading for wireless mobile networks," *Simulation Modelling Practice and Theory*, vol. 19, no. 2, pp. 626 – 637, 2011.