Spectrum Opportunity Duration Assurance: A Primary-Secondary Cooperation Approach for Spectrum Sharing Systems

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ABSTRACT (Academic)

The radio spectrum dependent applications are facing a huge scarcity of the resource. To address this issue, future wireless systems require new wireless network architectures and new approaches to spectrum management. Spectrum sharing has emerged as a promising solution to address the radio frequency (RF) spectrum bottleneck. Although spectrum sharing is intended to provide flexible use of the spectrum, the architecture of the existing approaches, such as TV White Space [1] and Citizen Broadband Radio Services (CBRS) [2], have a relatively fixed sharing framework. This fixed structure limits the applicability of the architecture to other bands where the relationship between various new users and different types of legacy users co-exist. Specifically, an important aspect of sharing that has not been explored enough is the cooperation between the resource owner and the opportunistic user. Also in a shared spectrum system, the users do not have any information about the availability and duration of the available spectrum opportunities. This lack of understanding about the shared spectrum leads the research community to explore a number of core spectrum sharing tasks, such as opportunity detection, dynamic opportunity scheduling, and interference protection for the primary users, etc. This report proposes a Primary-Secondary Cooperation Framework to provide flexibility to all the involved parties in terms of choosing the level of cooperation that allow them to satisfy different objective priorities. The cooperation framework allows exchange of a probabilistic assurance: Spectrum Opportunity Duration Assurance (SODA) between the primary and secondary operations to improve the overall spectrum sharing experience for both the parties. This capability will give the spectrum sharing architectures new flexibility to handle evolutions in technologies, regulations, and the requirements of new bands being transitioned from fixed to share usage.

In this dissertation we first look into the regulatory aspect of spectrum sharing. We analyze the Federal Communications Commission's (FCC) initiatives with regards to the commercial use of the 150 MHz spectrum block in the 3.5 GHz band. This analysis results into a Spectrum Access System (SAS) architecture and list of required functionalities. Then we address the nature of primary-secondary cooperation in spectrum sharing and propose to generate probabilistic assurances for spectrum opportunities. We use the generated assurance to observe the impact of cooperation from the perspective of spectrum sharing system management. We propose to incorporate primary user cooperation in the auctioning and resource allocation procedures to manage spectrum opportunities. We also analyze the improvement in spectrum sharing experience from the perspective of the primary and secondary users as a result of cooperation. We propose interference avoidance schemes that involve cooperation to improve the achievable quality of service.

Primary-secondary cooperation has the potential to significantly influence the mechanism and outcomes of the spectrum sharing systems. Both the primary and secondary operations can benefit from cooperation in a sharing scenario. Based on the priorities of the primary and secondary

operations, the users may decide on the level of cooperation that they are willing to participate. Also access to information about the availability and usability of the spectrum opportunity will result in efficient spectrum opportunity management and improved sharing performance for both the primary and secondary users. Thus offering assurances about the availability and duration of spectrum opportunity through primary-secondary cooperation will significantly improve the overall spectrum sharing experience. The research reported in this dissertation is expected to provide a fundamental analytical framework for characterizing and quantifying the implications of primary-secondary cooperation in a spectrum sharing context. It analyzes the technical challenges in modeling different level of cooperation and their impact on the spectrum sharing experience. We hope that this dissertation will establish the fundamentals of the spectrum sharing to allow the involved parties to participate in sharing mechanisms that is suitable to their objective priorities.

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GENERAL AUDIENCE ABSTRACT

As the world of technology steps into the era of ubiquitous communication to anything and everything, a system's ability to wirelessly communicate in a heterogeneous environment plays a significant role in shaping our ways of life. The wireless communication systems and standards are evolving at an unprecedented rate to cope up with the explosive growth for uninterrupted mobile broadband service demand and the increasing diversity of high quality of service (QoS) use cases ranging from social communication and professional networking to cyber security and public safety. The rapid evolution of wireless communication systems and service applications has resulted in high demand for new and dedicated spectrum blocks in both the licensed and unlicensed bands. Also the predicted future wireless systems and applications indicate important characteristics of future broadband traffic demand: nomadic and sporadic bursty demand. But the existing static spectrum assignment limits the potential of the radio frequency spectrum resource. It imposes the challenge of spectrum scarcity onto radio spectrum dependent applications and technologies. This unprecedented increase in mobile data traffic along with the nomadic and sporadic bursts in data demand will disruptively shape the spectrum usage philosophy of the future wireless communication networks. It calls for new wireless network architectures and new approaches to spectrum management. Spectrum sharing has emerged as a promising solution to address the radio frequency (RF) spectrum bottleneck. Although spectrum sharing is intended to provide flexible use of the spectrum, the architecture of the existing approaches have a relatively fixed structure in the mechanism for which spectrum is shared. This fixed structure limits the applicability of the architecture to other bands where the relationship between various new users and different types of legacy users co-exist. Specifically, an important aspect of sharing that has not been explored enough is the cooperation between the resource owner and the opportunistic user. Also in a shared spectrum system, the users do not have any information about the availability and duration of the available spectrum opportunities. This lack of understanding about the shared spectrum leads the research community to explore a number of core spectrum sharing tasks, such as opportunity detection, dynamic opportunity scheduling, and interference protection for the primary users, etc.

In this dissertation we propose a Primary-Secondary Cooperation Framework that provides flexibility to all the involved parties in terms of choosing the level of cooperation and allow them to satisfy different objective priorities. The cooperation framework allows exchange of a probabilistic assurance: Spectrum Opportunity Duration Assurance (SODA) between the primary and secondary operations to improve the overall spectrum sharing experience for both the parties. This capability will give the spectrum sharing architectures new flexibility to handle evolutions in technologies, regulations, and the requirements of new bands being transitioned from fixed to share usage. Based on their operational priorities, the users may decide on the level of cooperation that they are willing to participate. Also access to information about the availability and usability of the spectrum opportunity influences the mechanism and outcomes of the spectrum sharing systems

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DEDICATION

To My Family

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my advisor Dr. Jeffrey H. Reed. During the course of last six years, I have benefited tremendously from his guidance and support. He is a visionary, a trend setter. His unique blend of energy, vision, technical knowledge and generosity will be an inspiring role model for my future career.

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Preface

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Chapter 1

Introduction

Chapter 1: Introduction to the Dissertation

Introduction

"Norm for spectrum use should be sharing, not exclusivity."

-The President's Committee of Advisors on Science and Technology on setting the direction towards an empowering and inspiring vision of dynamic spectrum sharing paradigm in the 2012 PCAST Report [4].

The radio frequency spectrum plays an important role in every aspect of our life, from social communication to economic affairs. Access to spectrum has become an increasingly important foundation for economic growth and technological leadership. Few developments hold as much potential as wireless technologies to enhance the economic growth and improve the field of communications, business, and public service activities like public safety, healthcare, education, and electric utilities. Wireless technologies have become an indispensable element of our overall quality of life. As a result of this ubiquitous demand, radio spectrum dependent applications are facing the scarcity of this resource. Wireless communities throughout the world have recognized the shortage of spectrum for commercial broadband use and acknowledged the urgent need for a global effort to make additional spectrum available for broadband data. Ericsson reported that there will be 6.5 billion mobile broadband subscriptions globally by 2018 [5]. Total smartphone subscriptions are expected to grow to 5.6 billion in 2019 and 85% of North American mobile subscriptions will be LTE by 2019. Mobile data traffic is expected to grow at a Compound Annual Growth Rate (CAGR) of around 45% (2013–2019) and will result in a 10-fold increase by the end of 2019. The Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021, predicts that annual global mobile data traffic will increase 7-fold between 2016 to 2021, and will be more than half zettabyte per year by 2021 [6]. Another Cisco report: *Zettabyte Era Trends and Analysis* [7], identified several trends that are contributing towards this explosion of data traffic. Globally, devices and connections (10.7% CAGR) are growing faster than both the population (1.1% CAGR) and Internet users (9.2% CAGR). This trend is accelerating the increase in the average number of devices and connections per household and per Internet user (1.5 mobile devices per capita by 2021). The

Internet of Everything (IoE) phenomenon is showing tangible growth. Globally, there will be 11.6 billion mobile-connected devices by 2021, including M2M modules - exceeding the world's projected population at that time (7.8 billion). Smartphones will represent over 50% of global devices and connections by 2021 [6]. Applications such as video surveillance, smart meters, smart cars, asset and package tracking, chipped pets and livestock, digital health monitors, and a host of other next-generation M2M services are driving this growth. By 2018, digital TV and online video will be the two most highly penetrated services and will result in an accelerated busy-hour traffic growth. Smartphones will account for 86% of the total mobile data traffic in 2021 and more than three quarter of the mobile data traffic will be video traffic. Metro-only traffic will grow nearly twice as fast as long-haul traffic and busy-hour Internet use will grow at a CAGR of 28%. By 2021 63% of the total mobile data traffic was offloaded onto the fixed network by means of Wi-Fi devices and femtocells. These predictions clearly indicate an explosive growth in broadband traffic demand. To meet this demand, future generations of wireless technology and services must continue to increase their yield of bits/hertz/second. Future wireless traffic demands also require new wireless network architectures and new approaches to spectrum management. The predicted future applications imply important characteristics of future broadband traffic demand: nomadic and sporadic bursty demand. IoT and multidevice ownership will significantly contribute towards localized and sporadic demands. Live TV and online video streaming on mobile platforms will result in increased demand as indicated by the increased busy-hour and metro-only traffic prediction. The unprecedented growth in worldwide mobile data traffic along with the nomadic and sporadic bursts in data demand will disruptively shape the spectrum usage philosophy of the future wireless communication networks [5, 6, 8]. In order to embrace such growth opportunities, network operators in some metropolitan areas are even planning for 1000-fold network capacity [9, 10].

The growth inevitably will lead to spectrum scarcity in the very near future. Therefore, how to efficiently and flexibly utilize radio spectrum resources becomes a key design challenge of the next generation wireless network. Access to new below 6 GHz spectrum blocks is not a viable solution as clearing and reallocating licenses are extremely expensive and time consuming. For example, the National Telecom & Information Administration (NTIA) of U.S. reported that the reallocation of 95 MHz (1755-1850 MHz) band would cost $18 billion US dollars over ten years [11]. To address this nomadic and sporadic bursty demand, opportunistic communications has been and will play a significant role. Opportunistic and dynamic small-cell devices promise the potential to deliver speed, quality, and agility to address the demand of broadband traffic. Also the recent technological advancements such as LTE's dual connectivity [12] and carrier aggregation [13], coordinated multipoint transmission/ reception [14, 15], licensed assisted access (LAA) [16], spectrum sensing [2, 17], and database driven spectrum management (IEEE 802.22 TV Whitespace [18]) serve as enabling mechanisms for Dynamic Spectrum access (DSA) which allows opportunistic use of otherwise unused spectrum dynamically as a function of time and geographical location. Accordingly, dynamic spectrum sharing and small cell approaches have emerged as the solution to address the issue of spectrum scarcity through better utilization of the limited spectrum resource[19, 20].

Spectrum Sharing Initiatives by the Regulatory Authorities

As part of the global effort to address the seemingly never-ending surge in the demand for wireless broadband capacity, the wireless communities throughout the world have undertaken innovative initiatives such as tiered-access to shared spectrum. The European Telecommunications Standards Institute ("ETSI") is working towards Licensed Shared Access ("LSA") paradigm to enable mobile broadband services in the 2.3-2.4 GHz band [21]. The LSA framework enables a licensed network operator to tightly manage access to the spectrum and provides the command and control structure necessary to utilize and vacate the spectrum as needed by the incumbent users. The wireless communities in the United States have undertaken initiatives towards popularizing the dynamic and opportunistic use of spectrum. The Federal Communications Commission (FCC) has proposed a dynamic spectrum management framework for a Citizen Broadband Radio Service (CBRS) governed by a Spectrum Access System (SAS) [2]. The implementation of a SAS capable of dynamic frequency assignment and interference management is critical for the success of the spectrum sharing paradigm proposed by the Commission.

Following the spectrum policy objectives laid out by the National Broadband Plan [22] and the President's Council of Advisors on Science and Technology (PCAST) report [4], and building on the experience gained through spectrum sharing in the television white spaces (TVWS) [1, 23], FCC has taken a series of steps towards sharing Federal spectrum, especially Department of Defense (DoD) owned spectrum, with commercial broadband applications. In 2010, the National Telecommunications and Information Administration (NTIA) identified the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz, and 4380-4400 MHz Bands as potential spectrum blocks for sharing [24]. Later that year, the NTIA recommended the 1695-1710 MHz and 3550-3650 MHz (3.5 GHz) bands as "fast track" bands. The 3.5 GHz band was selected for spectrum sharing primarily due to its limited propagation characteristics and geographically limited incumbent operations. In 2012 the FCC issued a Notice of Proposed Rule Making (3.5 GHz NPRM) and proposed a three-tier access framework for the 3.5 GHz band to create a new Citizens Broadband Radio Service

(CBRS) in in which the higher tier users receive interference protection from lower tier users [3]. The 3.5 GHz NPRM encouraged deployment of small cells and introduced an innovative General Authorized Access (GAA) tier, in addition to the Incumbent Access (IA) and Priority Access (PA) tiers, to facilitate opportunistic and non-interfering basis spectrum use within designated geographic areas. It also proposed a Spectrum Access System (SAS) as the governing entity that serves as a bridge between the primary and secondary operations. In 2013, considering the response of the stakeholders to the 3.5 GHz NPRM, FCC proposed an expanded eligibility of the PA tier and issued two Public Notices (PNs) requesting specific comments on the CBRS licensing approach [25] and the proposed SAS [26]. Based on the comments from the stakeholders in response to the 3.5 GHz NPRM, and Licensing and SAS PN, in 2014 the FCC issued a further NPRM with regards to the commercial operations in the 3.5 GHz band (3.5 GHz FNPRM) [27]. Interested stakeholders from industry and academia commented on the proposed rules in the notice. We published a survey paper highlighting different aspects of the 3.5 GHz FNPRM and the response it received from the stakeholders [2]. On April, 2015, the FCC issued a Second FNPRM along with 3.5 GHz Rule and Order (3.5 GHz R&O) which established the Citizens Broadband Radio Service under a new part 96 of the Commission's rules [28]. In this second FNPRM, FCC requested feedback from the stakeholder on i) the "Use" of Priority Access License (PAL) areas to determine the availability of spectrum for GAA use and ii) the optimal protections for licensed in-band and out-of-band FSS earth stations. After the adoption of the 3.5 GHz R&O, on June, 2015, FCC issued a public notice through which the Wireless Telecommunications Bureau (WTB) reminded licensees in the 3.5 GHz band and non-federal radiolocation services in the 3550-3650 MHz band of their rights and responsibilities regarding the operation of registered stations [29]. By July 2015, a number of interested parties filed petitions for reconsideration on different rules of the 3.5 GHZ R&O such as licensing rules for PALs, allowed transmission power for different scenarios, FSS protection rules, geolocation rules for position accuracy, reconfiguration response time after being notified by the ESC, etc. Later that year, on October 23, 2015, WTB released another Public Notice seeking comment on the appropriate methodology for determining the contours for protecting existing 3650-3700 MHz wireless broadband licensees from CBRS users during a fixed transition period (3650-3700 MHz Protection Contours PN) [30]. Also, as directed by the Commission in the 3.5 GHz R&O, WTB and the Office of Engineering and Technology (OET) released a Public Notice seeking proposals for future SAS Administrator and Environmental System Capability (ESC) operators in the 3.5 GHz Band (SAS/ESC Proposal PN) [31]. The SAS/ESC Proposal PN summarized the requirements for both SAS Administrators and ESC operators, as established in the 3.5 GHz R&O, and described the process for submitting proposals. It also briefly described the process that WTB/OET will use to evaluate prospective SAS Administrators and ESC operators. Finally on May, 2016 the Commission issued Order on reconsideration and Second R&O (3.5 GHz Second R&O) to finalize the rules governing the innovative Citizens Broadband Radio Service in the 3.5 GHz Band [32].

What Motivated the Work

Challenges with the Current Approach

Although the NTIA identified a number of potential spectrum blocks as candidates for spectrum sharing [24], the first-track bands (1695-1710 MHz and 3.5 GHz) are the focus of recent spectrum sharing initiatives. The regulatory initiatives mentioned in the previous subsection mostly concern the 3.5 GHz band. But the use cases for the spectrum blocks identified for sharing purpose might have very distinct operational aspects. For example, Table 1 presents the wide range of stakeholders that are interested in accessing the spectrum sharing band and voiced their perspectives in response to the 3.5 GHz NPRMs [2]. Similarly other spectrum blocks have their own range of use cases. The objectives and operational requirements of the primary user operations may vary depending on the nature of their operations. Some primary user prioritizes operational privacy, whereas others define revenue maximization as their primary objectives. Even within the same shared band different primary users may have different operational objectives. Spectral location of the sharing bands also play important role in deciding the nature of applications suitable for each of these bands. The use cases for sub 3 GHz spectrum sharing system will be different from those for sub 6 GHz bands. So the secondary users involved in the sharing may desire different levels and types of Quality of Service (QoS) requirements from these shared bands. The perspective of spectrum sharing in each of these spectrum blocks vary significantly based on the spectral location of the bands, and the type of primary and secondary user operations in the band. So the spectrum sharing rules and framework requires to be flexible to accommodate this diverse range of spectral characteristics, user characteristics, and operational objectives. This need for an adaptive framework has helped motivate this research reported in this dissertation.

The existing spectrum sharing approaches do not offer any flexibility to the involved parties in choosing the sharing mechanisms. For example, the NPRMs and the FNPRMs issued by the FCC for 3.5GHz band offers a one-size-fits-all approach for dynamic spectrum management that involves SAS. The SAS would collect information about the incumbents regarding their spectrum utilization and manage the secondary use of the available spectrum opportunities. But the dynamic spectrum management approach naturally discourages investment and participation from the industry (the cellular industry in the case of 3.5 GHz band) by putting them outside the comfort zone of their existing technological capability and administrative structure. So in this case the dilemma in front of FCC is to promote dynamic spectrum management and at the same time ensure participation of the wireless industry in the CBRS.

Table 1: Stakeholders in the 3.5 GHz Spectrum Sharing System

Interest Group		Members/Commenters
SAS/TVWS Administrators		Google, Telcordia Technologies, Comsearch, Spectrum Bridge
Dynamic Spectrum Access Industry		Federated Wireless LLC, InterDigital Inc., Microsoft Corporation, Shared Spectrum Company, xG Technology Inc., Whitespace Alliance,
Wireless Broadband Industry		Cambium Networks, Ltd., CTIA-The Wireless Association, Tarana Wireless, UK Broadband Limited, Vanu, Inc., Xchange Telecom Corp., CommScope, Neptuno Media, Inc., Cloud Alliance, LLC., Lockard & White, NMS Enterprises LLC.,
Cellular Industry	Mobile Network Operator	AT&T, Sprint Corporation, T-Mobile, Verizon and Verizon Wireless
	Vendors	Alcatel-Lucent, Ericsson, Motorola Mobility, Nokia, QualComm Inc.,
	Wireless Industry Association	4G Americas, IEEE DySPAN-SC (Standard Committee), IEEE 802 LMSC, New America Foundation and Public Knowledge, Telecommunications Industry Association, PCIA - The Wireless Infrastructure Association and HetNet Forum, Wi-Fi alliance, Wireless Innovation Forum, Wireless Internet Service Providers Association, Competitive Carriers Association, WiMAX Forum,
Satellite Earth Station	S-Band Satellite Operation	Satellite Industry Association, Baron Services Inc., Astrium Services Government, Inc.
	C-Band satellite Operation	Content Interest, National Public Radio, National Cable and Telecommunications Association

Utilities and CII		American Petroleum Association, Entelec, Exelon, Motorola Solutions, Iberdrola USA Networks, Oncor Electric Delivery Company, Siemens Industry Inc., Southern Company Services, Utilities Telecom Council, Xcel Energy Services, CenterPoint Energy Houston Electric,
Backhaul Network		BLiNQ Networks, Inc., Cohere Technologies, Sprint Corporation
Others	Terrestrial Fixed Microwave Communications	Fixed Wireless Communications Coalition
	Communications for Underserved Communities and Tribal Lands	Blooston 3.65 GHz Coalition, Salt River Project Agricultural Improvement and Power District
	Public Safety and FirstNet	Harris Corporation
	Industry Associations	Consumer Electronics Association, Content Companies, National Association of Broadcasters, Public Interest Spectrum Coalition, Enterprise Wireless Alliance,
	Financial Organization	Cantor Telecom Services L.P., Allied Communications LLC

Shared Spectrum vs. Dedicated Spectrum

We start this submission by asking a question: *what is the fundamental difference between shared spectrum systems and dedicated spectrum systems?* The immediate answer would be the right of spectrum usage for the secondary users. The secondary users are allowed to use the shared spectrum in a way that ensures uninterrupted primary user operation. As expected, researchers have focused on opportunity detection, dynamic opportunity scheduling, and interference protection for the primary users [17, 33-36]. But the fundamental difference between shared and dedicated spectrum systems, as a consequence of dissimilar spectrum usage rights, that leads us to the above mentioned research areas is the lack of knowledge about the availability and duration of spectrum opportunities. For wireless systems with dedicated spectrum we know which channels are available for use and the duration for which the channels can be used. Unsurprisingly, in the case of dedicated spectrum system, some of these problems do not exist and there are well established and matured solutions for the other ones. In a shared spectrum system, the users do not know which channel they can use and for how long. So the lack of information about the availability and duration of spectrum opportunity is the root problem that the research community tries to overcome indirectly by exploring the above mentioned research areas.

We also want to draw reader's attention to another important aspect of the existing spectrum sharing approaches. The rules proposed for spectrum sharing impose majority of the sharing responsibilities, such as opportunity identification, maintaining desired interference environment, etc., on the secondary users and/or the middle entities such as the SAS and Environmental Sensing Capability (ESC) system proposed in the 3.5 GHz NPRMs and R&Os [3, 27, 28, 32]. So the existing approaches do not involve the cooperation between the resource owner and the opportunistic user who wants to share the resource. A primary user operation that wants to protect its sensitive operational characteristics and usage information would consider the operational privacy as its most prioritized objective. So any primary user seeking privacy will be hesitant to cooperate and exchange information with an external entity. On the other hand, if a primary user operation is more concerned about the interference environment, it is in its best interest to cooperate with the secondary user in order to achieve the desired operating environment. At this moment, ongoing research efforts are more concerned about the operational privacy of the incumbent operations as the NTIA identified spectrum sharing blocks belong to incumbent users for whom privacy is an important aspect of their operations. With the advances of technology and successful implementation of the opportunistic spectrum access, it is likely that the spectrum sharing concept will extend to other spectrum blocks. The incumbent operations in those blocks may be less concerned about privacy and more interested in maximizing the revenue generated from sharing agreements (for example Public Safety operations in the D-Block [37]). They might be more interested in making their product (spectrum available for sharing) more attractive through cooperation and information exchange amongst the parties involved in a spectrum sharing system.

Primary-secondary cooperation has the potential to significantly influence the mechanism and outcomes of the spectrum sharing systems. Both the primary and secondary operations can benefit from cooperation in a sharing scenario. Based on the priorities of the primary and secondary operations, the users may decide on the level of cooperation that they are willing to participate. Also access to information about the availability and usability of the spectrum opportunity will result in efficient spectrum opportunity management and improved sharing performance for both the primary and secondary users. Thus offering assurances about the availability and duration of spectrum opportunity through primary-secondary cooperation will significantly improve the overall spectrum sharing experience.

Contribution of the Dissertation

In this submission, we propose a cooperation approach that involves information exchange between the primary and secondary user operations and thus allows the system to improve the spectrum sharing performance. Through this cooperation approach, we make the information about the availability and duration of spectrum opportunities accessible for the parties involved in spectrum sharing. Figure 1 presents the spectrum sharing system based on the proposed primary-secondary cooperation framework. In this dissertation, we look into the important aspect of successful secondary user operation in the shared band and analyze the QoS achievable by opportunistically accessing the shared spectrum. Within the context of spectrum sharing, depending on the operational status of the primary user, secondary users may need to stop operating in the current opportunity and switch to other available opportunities. The secondary user might have to terminate ongoing session frequently resulting in a temporal connection loss. In addition, if a secondary user is unable to cease its operation and leave the opportunity in a timely manner, it would interfere with the primary users. The temporal connection loss and the interference can be significantly reduced if the secondary users have knowledge about the duration of the opportunities, and use that knowledge to either avoid or take additional measures while using these opportunities.

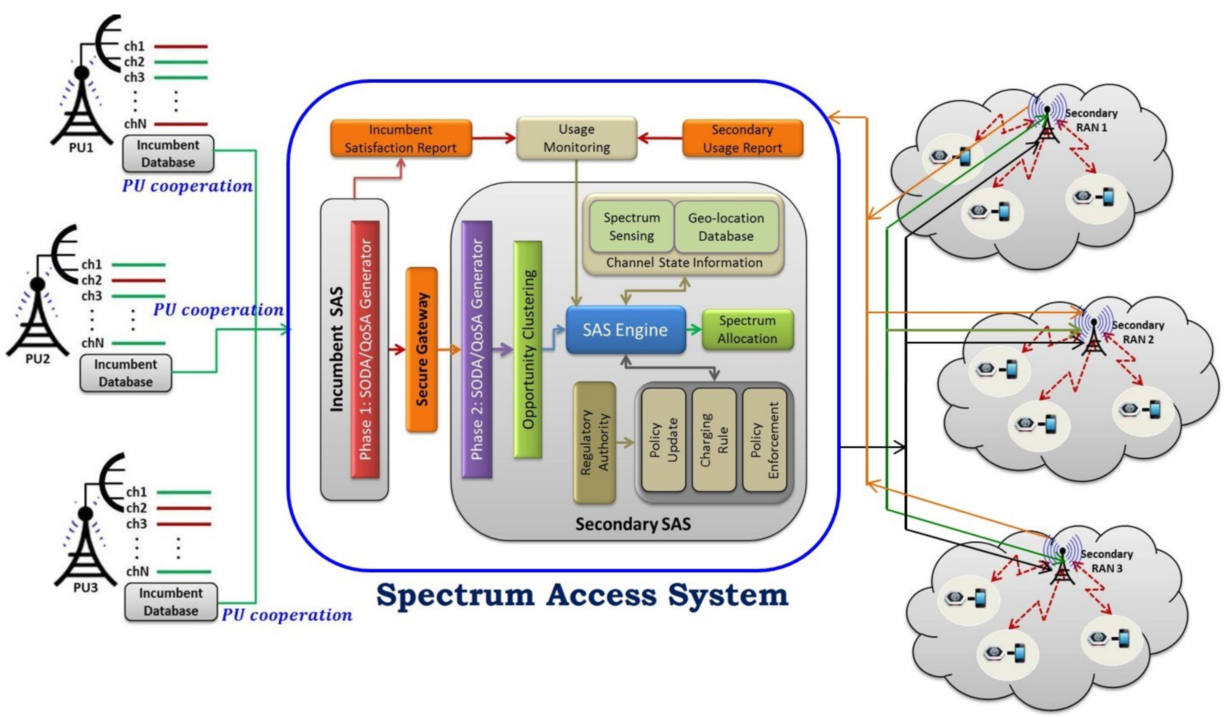

Figure 1: Primary-Secondary Cooperation Framework for Spectrum Sharing Systems

Therefore, the secondary users should have the capability to consider the probability of channel being available for a given time period while making the decision to opportunistically access the channel. Without any prior information about the availability and duration of spectrum opportunities, the secondary user operations need to continuously monitor the spectrum blocks under consideration in order to identify the opportunities and also the return of the primary user operations. This continuous monitoring results in significant consumption of time, energy, and spectrum resources. As expected, the continuous monitoring approach adversely impacts the achievable QoS while accessing the shared channels. Also the performance of the detection techniques influences the outcome of the continuous monitoring. The QoS predictability of a shared spectrum is highly influenced by the duration of the available spectrum opportunity [38]. In order to achieve any desired level of QoS, the service providers need information about the QoS predictability of the channel. The primary-secondary cooperation can have significant impact on the spectrum sharing performance from the perspective of either side. Figure 2 presents the research topics explored and reported in this dissertation. In the remaining of this dissertation, we first present the regulatory standpoint of the spectrum sharing governing authorities. After that we discuss the generation procedure of the desired form of primary-secondary cooperation. Using the primary-secondary cooperation, we then present dynamic spectrum access procedure and dynamic spectrum opportunity auction scheme. The reminder of this dissertation is organized as follows:

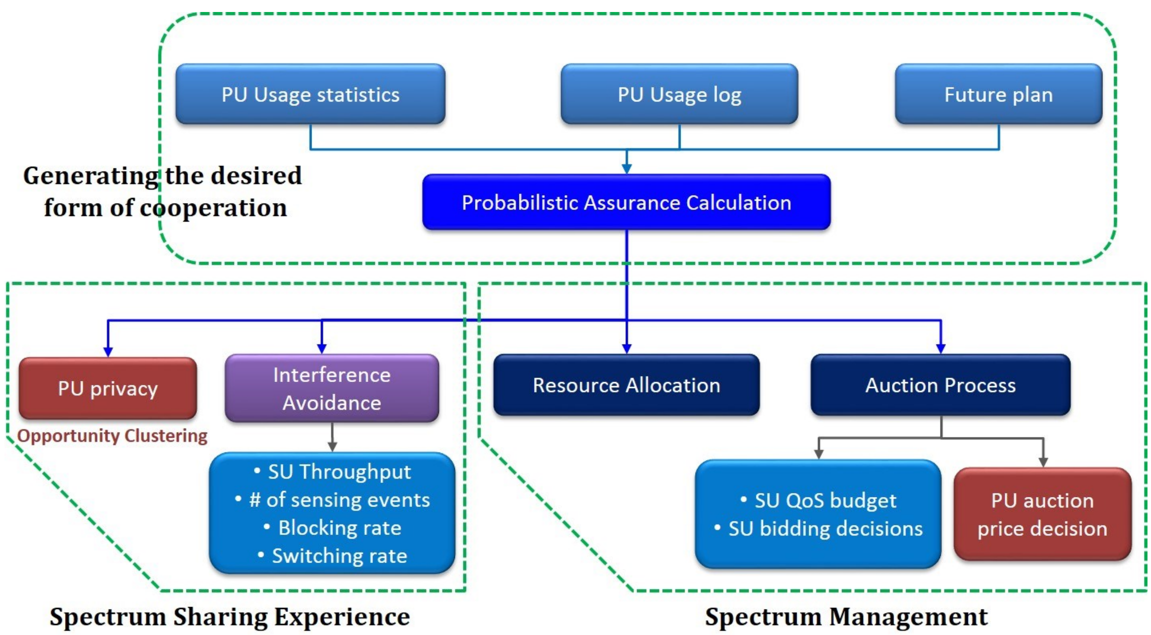

Figure 2: Research Work reported in the Dissertation: Primary-Secondary Cooperation Framework for Dynamic Management of Spectrum Opportunities

Chapter II: Regulatory Perspective – Spectrum Access System for Citizen Broadband Radio Services (CBRS)

As a part of the global effort to address the overwhelming demand for wireless broadband capacity, the wireless industry stakeholders in the United States have undertaken initiatives towards popularizing the dynamic and opportunistic use of spectrum. Following the spectrum policy objectives laid out by the National Broadband Plan [22] and the President's Council of Advisors on Science and Technology (PCAST) report [4], and building on the experience gained through spectrum sharing in the television white spaces (TVWS) [1, 23], the Federal Communications Commission (FCC) has taken a series of steps towards sharing Federal spectrum, especially Department of Defense (DoD) owned spectrum, with commercial broadband applications. The Commission has proposed a dynamic spectrum management framework for a Citizen Broadband Radio Service (CBRS) governed by a Spectrum Access System (SAS) [2, 26]. In Chapter II, we discuss these efforts towards a dynamic spectrum sharing system in the U.S. context and look forward to initiate a more focused analysis of the required SAS composition and functionalities to support the dynamic management of the 3.5 GHz band. We also analyze the position of the Commission on different aspect of the CBRS through the 3.5 GHz R&O [28] and the Second R&O [32] in order to address criticism of the proposed 3-tier system. We present a brief summary of a survey of the stakeholder's comments in response to the 3.5 GHz FNPRM [27]. The stakeholders responded to different aspects of the FNPRM from their industry perspective. We look at these responses from the perspective of a dynamic SAS capable of facilitating the dynamic spectrum management approach. Our analysis yielded a number of important issues which are required to be addressed for successful operation of the proposed CBRS. In this chapter, we propose a SAS architecture and identify the required functionalities, technical capabilities, and composition of the SAS to support the dynamic spectrum management approach envisioned in the CBRS. The successful implementation of the dynamic spectrum management approach will significantly improve the spectrum usage efficiency and influence the management approach of other spectrum bands. This calls for a coordinated effort from the government, industry, and academia to expedite the development of the dynamic SAS and move forward towards the dynamic spectrum management regime. We hope the discussion presented in Chapter II will help the readers understand the policy and regulatory aspects of the spectrum sharing initiatives and will initiate further awareness and more informed discussions and research towards efficient dynamic spectrum sharing systems.

Chapter III: Generation of Desired Form of Cooperation

In Chapter III, we address the generation of the probabilistic assurance about the availability and duration of spectrum opportunities using primary-secondary cooperation. In order to realize dynamic spectrum access based spectrum sharing, different channel monitoring techniques are applied to detect spectrum opportunities. If secondary users, limited by their available resources and technical abilities, randomly or sequentially sense the channels until a spectrum opportunity is detected then significant amount of energy, time, and spectrum resources will be wasted, since secondary users transmit only after a decision has been made. On the other hand, with the use of an intelligent predictive method, secondary users can learn from the past activities of each channel to predict the next channel state. Duration of spectrum opportunity is also another important aspect of successful secondary user operation in a spectrum sharing system. Predicting the probability of spectrum opportunities being available for certain duration improves resource allocation and interference avoidance mechanisms. In Chapter III, we discuss the generation of a probabilistic assurance about the availability and duration of the available spectrum opportunities – the Spectrum Opportunity Duration assurance (SODA). A method to statistically ensure spectrum availability using Non-Stationary Hidden Markov Models was proposed. We also introduce primary user cooperation into the prediction algorithms to improve the prediction accuracy and reduce the computational complexity of the prediction algorithms. The Incumbent SAS, enabled with primary user cooperation, performs the Non-Stationary Hidden Markov Model approach to re-estimate the model parameters and forward it to the Secondary SAS. The Secondary SAS uses the re-estimated model parameters to run the prediction algorithm in real time using the current channel monitoring results received from the Environmental Sensing Capability (ESC) system and/or the secondary users. The Spectrum Opportunity Duration Assurance (SODA) values determined for each of the shared channels helps the spectrum sharing systems to achieve the availability and duration information about spectrum opportunities. Thus the secondary user resource management system and/or the SAS perform intelligent dynamic spectrum access and improve the spectrum sharing experience of both the primary and secondary users.

Chapter IV: Spectrum Opportunity Access using Primary-Secondary Cooperation

In this section we explore the impact of primary-secondary cooperation on the dynamic access of spectrum opportunities. We look in to the ways to efficiently use the primary user cooperation in order to improve the spectrum sharing experience of both primary and secondary operations. The SODA metric generated periodically by SAS is used to facilitate cognitive use of the spectrum opportunities. The cooperation from primary users in the form of SODA values allow us to propose spectrum opportunity access schemes based on the principle of interference avoidance. The SODA metric provides the SAS and the secondary user resource manager (SU-RM) a probabilistic estimation about the availability of the spectrum opportunities for specific time period. This helps the SAS and the SU-RM to develop efficient resource allocation algorithms and improves achievable QoS from the perspective of the secondary user operation without exposing the primary user operations. The SODA approach allows the spectrum sharing system to consider interference avoidance techniques while allocating the available spectrum opportunities. The resource allocation algorithms can have flexibility to vacate different spectrum opportunities at different instances of the opportunity duration based on the probabilistic assurance SODA. Thus the incumbent operations can ensure desired interference environment through the SAS by providing required information towards the SODA metric. In order to reduce the overhead in frequently generating and accessing this information, we propose to maximize the utility duration of the SODA information using the concept of "Time Discounted Value of Information". We determine the effective value of the information at any particular time instant within the assured duration and decide whether to improve the assurance by employing sensing techniques or not. In this analysis, we propose interference avoidance schemes that use channel monitoring based on the time discounted value of the PU cooperation to reduce the number of time slots in collision between the primary and secondary operations. The interference avoidance schemes use a combination of primary user cooperation and channel monitoring techniques to reduce the resource consumption for channel monitoring during the early stage of the assured duration and at the same time reduce the likelihood of interference in the later stage of the duration with help of channel monitoring. The SODA approach improves the secondary user throughput even without employing sensing. But the absence of channel monitoring results in degraded interference avoidance performance. If sensing is employed in the later part of the opportunity, it improves the secondary user performance without significantly degrading the interference situation between the primary and the secondary user operations. We analyze and theoretically model the reduction in number of sensing events which is required to achieve a desired interference environment and also the improvement in secondary user throughput as a result of primary user cooperation. A comprehensive analysis of the secondary user throughput promises interesting insights towards a quantitative metric for shared band capacity.

Chapter V: Spectrum Opportunity Auction using Primary-Secondary Cooperation

An important aspect of dynamic spectrum management is the pricing of spectrum from the perspective of both the primary and secondary users. Due to their perceived fairness and allocation efficiency, auctions are among the best-known market-based mechanisms to allocate spectrum. However, spectrum auction differs from conventional auctions in that it has to address radio interference. Spectrum auction is essentially a problem of interference-constrained resource allocation. Existing auction-based spectrum sharing models so far has missed out on an important aspect of successful secondary user operation: the duration of the available spectrum opportunity. In this chapter we proposed an auction-based spectrum sharing framework that statistically accounts for the estimates of spectrum opportunity duration. The framework allows both the primary and the secondary user operations to act on the current auction state to update their bidding in order to obtain a price combination that maximizes both the primary and secondary users' auction goals.

This chapter presents a dynamic and self-adjusting auction scheme for dynamic spectrum access based spectrum sharing systems. The dynamic auction scheme accounts for the quality of the available spectrum opportunity in terms of the probabilistic assurance generated by the SAS within the primary-secondary cooperation framework. The dynamic auction procedure allows both the primary and secondary operations to adjust their evaluation of the available opportunities based on their experiences with the channel quality from past usage statistics and past auction results, and over time achieves a price combination that maximizes both the primary and secondary user objectives. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users. The primary-secondary cooperation is manifested in the form of spectrum opportunity duration assurance (SODA) in the auction process. The SODA approach, as opposed to the QoS prediction approach, estimates the spectrum opportunity duration for operations with non-deterministic or unknown spectrum reservations or usage patterns. Knowing the realistically achievable QoS based on the uncertainty of the primary user return allows the secondary user access points to more effectively determine the number of spectrum opportunities for which the secondary user will participate in the auction process. The quantitative measure of the usability of a spectrum opportunity has great impact on the performance of any spectrum sharing system, and should be incorporated in spectrum opportunity management. The proposed channel quality based dynamic auction scheme allows the secondary users to take advantage of the predictive models of spectrum availability, prioritize spectrum opportunities accordingly, and bid for their preferred channels to maximize spectrum utilization while minimizing the occurrence of disruptions to primary users.

Publications

The work reported in this dissertation resulted in a number of publications in peer reviewed transactions, journals, and conferences proceedings. In this section, we present the list of publications emanated from the work reported in the dissertation. The list presents the publications according to the chapters of the dissertation. We also include future publications and submissions along with the name of the journals and conferences and the tentative date of submission.

Publications related to Chapter 1: Introduction

1. Sohul, Munawwar M., et al. "Next generation public safety networks: a spectrum sharing approach." IEEE Communications Magazine 54.3 (2016): 30-36. [37]
2. Dudley, Stephen M., et al. "Practical issues for spectrum management with cognitive radios." Proceedings of the IEEE 102.3 (2014): 242-264. [39]

Publications related to Chapter 2: Regulatory Perspective – Spectrum Access System for Spectrum Sharing Systems

1. Sohul, Munawwar M., et al. "Spectrum access system for the citizen broadband radio service." IEEE Communications Magazine 53.7 (2015): 18-25. [2]
2. Sohul, Munawwar M., et al. "Spectrum Access System for Primary-Secondary cooperation based spectrum sharing systems." IEEE Communications Magazine 2017 (Submission date: July 2017)

Publications related to Chapter 3: Generation of Probabilistic Assurance

1. Sohul, Munawwar M., et al. "Spectrum Opportunity Duration Assurance: A Primary-Secondary Cooperation Approach for Spectrum Sharing Systems." (submitted) IEEE Transactions on Cognitive Communications and Networking 2017.
2. Sohul, Munawwar M., et al. "Multiuser automatic modulation classification for cognitive radios using distributed sensing in multipath fading channels." Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on. IEEE, 2012. [40]
3. Sohul, Munawwar M. "Performance of linear decision combiner for primary user detection in cognitive radio". Southern Illinois University at Carbondale, 2011. [41]

Publications related to Chapter 4: Dynamic Access to Spectrum Opportunities using Primary-Secondary Cooperation

1. Sohul, Munawwar M., et al. “A Primary-Secondary Cooperation Approach for Dynamic Spectrum Opportunity Access.” (submitted) IEEE Transactions on Vehicular Technology 2017.
2. Sohul, Munawwar M., et al. "Quality of service assurance for shared spectrum systems." Military Communications Conference (MILCOM), 2014 IEEE. IEEE, 2014. [42]
3. Sohul, Munawwar M., et al. "Information Assurance of LTE-Advanced Self-Organizing Networks," in SDR-WInnComm 2014, 2014 [43]

Publications related to Chapter 5: Dynamic Auction for Spectrum Opportunities using Primary-Secondary Cooperation

1. Sohul, Munawwar M., et al. "Quality of Service Assurance-based Auction for Spectrum Sharing Systems," Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio, SDR WInnComm 2016. [44]

   *** Received the Best Paper award in the Cognitive Technology, Spectrum Management, and Spectrum Efficient area in the Wireless Innovation Forum Conference on Wireless Communications Technologies 2016.*
2. Sohul, Munawwar M., et al. "Quality of service assurance-based auction for spectrum sharing systems." Analog integrated circuits and signal processing 91.2 (2017): 203-216. [45]
3. Sohul, Munawwar M., et al. "An overview of the state of the art Dynamic Auctioning in Spectrum Sharing Systems.” IEEE Communications Magazine 2017 (Submission date: July 2017)

Other Publications related to the Dissertation

1. X. Ma, et al. “Efficient Spectrum Utilization in Prioritized OFDMA-Based Wireless LANs.” IEEE Transactions on Vehicular Tech 2017.
2. M. Yao, et al. “Energy-Efficient Radio Resource Management for 5G New Radio Exploiting Degrees of Freedom.” Springer Journals: Wireless Personal Communications, 2017
3. M. Yao, et al. “A Digital Predistortion Scheme Exploiting Degrees-of-Freedom for Massive MIMO Systems.” IEEE Communications Letters, 2017
4. M. Yao, et al. “Semidefinite Relaxation-Based PAPR-Aware Precoding for Massive MIMO-OFDM Systems.” IEEE Transactions on Vehicular Technology, 2017
5. M. Yao, et al. “Recurrent Neural Network-Inspired PAPR-Aware System for Massive MIMO OFDM Networks.” (under review) IEEE Transactions on Wireless Communications, 2017

6. M. Yao, et al. “Sustainable Green Networking: Exploiting Spatial Degree of Freedom towards Energy-efficient 5G Systems.” (under review) Springer Journals: Wireless Networks, 2017
7. K. S. Hasan, et al. “A Model for Least Distance Protocol in MANET Using Artificial Intelligence Search Techniques.” International Journal of Electrical & Computer Sciences IJECS, 2011
8. A. Kabir, et al. “Locating Mobile Station Using Received Signal Parameters.” Journal Bangladesh Electron, vol.11, pp.57-64, 2011.
9. Sohul, Munawwar M., et al. "LTE Communications over 3.5 GHz band for Broadband Public Safety Applications.” Wireless@VT: Wireless Personal Communications Symposium, 2015
10. Sohul, Munawwar M., et al. "Dynamic Spectrum Access Enabled LTE Testbed for Public Safety Applications.” in UKC 2014, 2014.
11. Sohul, Munawwar M., et al. "Poster Paper: LTE Communication over 3.5GHz band for Broadband Public Safety Application.” Wireless Personal Communications Symposium, 2014
12. Sohul, Munawwar M., et al. "Poster Paper: Information Assurance for LTE-Advanced Self-Organizing Networks.” Wireless@VT: Wireless Personal Communications Symposium, 2013
13. Sohul, Munawwar M., et al. "Poster Paper: Multiuser automatic modulation classification for cognitive radios using distributed sensing in multipath fading channels.” Wireless Internet Center for Advanced Technology (WICAT) 2012

Chapter 2

Regulatory Initiatives for Dynamic Spectrum Management Framework

Chapter 2: Regulatory Initiatives for Dynamic Spectrum Management Framework

Introduction

As a part of the global effort to address the overwhelming demand for wireless broadband capacity, the wireless communities in the United States have undertaken initiatives towards popularizing the dynamic and opportunistic use of spectrum. The Federal Communications Commission (FCC) has proposed a dynamic spectrum management framework for a Citizen Broadband Radio Service (CBRS) governed by a Spectrum Access System (SAS) [2, 26]. The comprehensive regulatory scheme includes licensing, technical, and service rules to enable dynamic sharing between three tiers of users in the 3.5 GHz Band. The Spectrum Access System (SAS) is the advanced frequency coordinator necessary to assign rights and maximize efficiency in the band. The SAS will incorporate information from the Environmental Sensing Capability (ESC), which will be used to increase available spectrum in coastal areas while continuing to protect incumbent Department of Defense (DoD) radar systems [31]. The implementation of a SAS capable of dynamic frequency assignment and interference management is critical for the success of the spectrum sharing paradigm proposed by the Commission. In this chapter we present the efforts taken by FCC and other regulatory and administrative entity toward spectrum sharing systems in the U.S. context. We present an analysis on FCC's position on different aspects of the proposed CBRS framework, and the required SAS composition and functionalities. We also present a brief discussion by summarizing a survey on different interest group's standpoint on the FCC proposed framework. Thus this chapter of the dissertation serves to update us about the policy and regulatory aspects of spectrum sharing, the associated technical challenges, and the ongoing research efforts to address these challenges.

To address the demand for wireless broadband capacity, the FCC has undertaken innovative initiatives such as tiered-access to shared spectrum. Following the spectrum policy objectives laid out by the National Broadband Plan [22] and the President's Council of Advisors on Science and Technology (PCAST) report [4], and building on the experience gained through spectrum sharing in the television white spaces (TVWS) [1, 23], FCC has taken a series of steps towards sharing Federal spectrum, especially Department of Defense (DoD) owned spectrum, with commercial broadband applications. In 2010, the National Telecommunications and Information Administration (NTIA) identified the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz, and 4380-4400 MHz Bands as potential spectrum blocks for sharing [24]. Later that year, the NTIA recommended the 1695-1710 MHz and 3550-3650 MHz (3.5 GHz) bands as "fast track" bands. The 3.5 GHz band was selected for spectrum sharing primarily due to its limited propagation characteristics and geographically limited incumbent operations. The technical characteristics of the 3.5 GHz Band and the existence of important incumbent operations in the band in many areas of the country make the band an ideal platform to explore innovative approaches to shared spectrum use and small cell technology [24].

In 2012 the FCC issued a Notice of Proposed Rule Making (*3.5 GHz NPRM*) and proposed a three-tier access framework for the 3.5 GHz band to create a new Citizens Broadband Radio Service (CBRS) in in which the higher tier users receive interference protection from lower tier users [3]. The 3.5 GHz NPRM encouraged deployment of small cells and introduced an innovative General Authorized Access (GAA) tier, in addition to the Incumbent Access (IA) and Priority Access (PA) tiers, to facilitate opportunistic and non-interfering basis spectrum use within designated geographic areas. It also proposed a Spectrum Access System (SAS) as the governing entity that serves as a bridge between the primary and secondary operations. In 2013, considering the response of the stakeholders to the 3.5 GHz NPRM, FCC proposed an expanded eligibility of the PA tier and issued two Public Notices (PNs) requesting specific comments on the CBRS licensing approach [25] and the proposed SAS [26]. Based on the comments from the stakeholders in response to the 3.5 GHz NPRM, and Licensing and SAS PN, in 2014 the FCC issued a further NPRM with regards to the commercial operations in the 3.5 GHz band (*3.5 GHz FNPRM*) [27]. Interested stakeholders from industry and academia commented on the proposed rules in the notice. We published a survey paper highlighting different aspects of the 3.5 GHz FNPRM and the response it received from the stakeholders [2]. On March 24, 2015, NTIA filed a letter recommending a framework that would reduce the geographic area of the zones by approximately 77 percent. NTIA's letter also recommended the use of sensor technology to permit commercial use inside the zones, providing a roadmap to full nationwide commercial use of the band [46]. On April, 2015, the FCC issued a Second FNPRM along with 3.5 GHz Rule and Order (*3.5 GHz R&O*) which established the Citizens Broadband Radio Service under a new part 96 of the Commission's rules [28]. In this second FNPRM, FCC requested feedback from the stakeholder on i) the "Use" of Priority Access License (PAL) areas to determine the availability of spectrum for GAA use and ii) the optimal protections for licensed in-band and out-of-band FSS earth stations. After the adoption of the 3.5 GHz R&O, on June, 2015, FCC issued a public notice through which the Wireless

Telecommunications Bureau (WTB) reminded licensees in the 3.5 GHz band and non-federal radiolocation services in the 3550-3650 MHz band of their rights and responsibilities regarding the operation of registered stations [29]. By July 2015, a number of interested parties filed petitions for reconsideration on different rules of the 3.5 GHZ R&O such as licensing rules for PALs, allowed transmission power for different scenarios, FSS protection rules, geolocation rules for position accuracy, reconfiguration response time after being notified by the ESC, etc. Later that year, on October 23, 2015, WTB released another Public Notice seeking comment on the appropriate methodology for determining the contours for protecting existing 3650-3700 MHz wireless broadband licensees from CBRS users during a fixed transition period (3650-3700 MHz Protection Contours PN) [30]. Also, as directed by the Commission in the 3.5 GHz R&O, WTB and the Office of Engineering and Technology (OET) released a Public Notice seeking proposals for future SAS Administrator and Environmental System Capability (ESC) operators in the 3.5 GHz Band (SAS/ESC Proposal PN) [31]. The SAS/ESC Proposal PN summarized the requirements for both SAS Administrators and ESC operators, as established in the 3.5 GHz R&O, and described the process for submitting proposals. It also briefly described the process that WTB/OET will use to evaluate prospective SAS Administrators and ESC operators. Finally on May, 2016 the Commission issued Order on reconsideration and Second R&O (*3.5 GHz Second R&O*) to finalize the rules governing the innovative Citizens Broadband Radio Service in the 3.5 GHz Band [32].

The rules adopted in the *3.5 GHz R&Os* for commercial use of 150 megahertz in the 3550-3700 MHz band (3.5 GHz Band) opens a new chapter in the administration of the electromagnetic radio spectrum. It establishes a roadmap for making the entirety of the 3.5 GHz Band available for commercial use in phases. The 3.5 GHz Band's physical characteristics make it particularly well-suited for mobile broadband employing small cell technology. The introduction of CBRS in this band will add much-needed capacity to meet the ever-increasing demands of wireless innovation.

Incumbent users in the 3.5 GHz Band

The 3550-3650 MHz band is allocated to the Radiolocation Service (RLS) and the ground based Aeronautical Radionavigation Service on a primary basis for federal use [28, 47]. Both fixed and mobile high-powered DoD radar systems on ground-based, shipborne, and airborne platforms operate in this band. These radar systems are used in conjunction with weapons control systems and for the detection and tracking of air and surface targets. The U.S. Navy uses the band for radars on guided missile cruisers. The U.S. Army uses the band for a firefinder system to detect enemy projectiles [48]. The U.S. Air Force uses the band for airborne radar station equipment throughout the United States and to assist pilots in formation flying and to support drop-zone training.

The 3500-3600 MHz and 3600-3650 MHz bands are allocated to RLS on a secondary basis for non-federal use. Survey operations, using transmitters with a peak power not to exceed five watts, may be authorized for federal and non-federal use on a secondary basis to other federal radiolocation operations. There are three non-federal RLS licensees, which are authorized to operate radiolocation land stations (station class LR) and radiolocation mobile stations (station class MR) using frequencies in the 3300-3500 MHz and 3500-3650 MHz bands. The 3600-3650 MHz band is also allocated to the Fixed Satellite Service (FSS) on a primary basis for non-federal use.

The 3650-3700 MHz band is also allocated for terrestrial non-federal use [47]. All stations operating in this band must employ a contention-based protocol. Base and fixed stations are limited to 25 watts per 25 megahertz equivalent isotropically radiated power (EIRP) and the peak EIRP power density shall not exceed 1 watt in any 1 megahertz slice of spectrum; mobile and portable stations are limited to 1 watt per 25 megahertz EIRP and the peak EIRP density shall not exceed 40 mW in any 1 megahertz slice of spectrum. Base and fixed stations may only be located within 150 kilometers of an FSS earth station if the licensee of the earth station agrees to such operation [49]. Requests for base or fixed station locations closer than 80 kilometers to three Federal Government radiolocation facilities are only approved upon successful coordination by the Commission with NTIA. The 3650-3700 MHz band is allocated for primary use by the federal RLS at three designated sites. The 3650-3700 MHz band is also allocated for use by ship stations located at least 44 nautical miles from shore in offshore ocean areas on a non-interference-basis.

Several of the allocations discussed above extend below 3550 MHz such as the primary allocations for shipborne, airborne, and ground based radars operated by DoD. FSS, which has a co-primary allocation at 3600-3650 MHz, also makes extensive use of the 3700-4200 MHz band (C-Band) in the United States and globally in order to provide video distribution, mobile voice and data backhaul, retail services, aeronautical applications, and other uses, to commercial and government customers. Terrestrial microwave services licensed under Part 101 of the Commission’s rules also operate in this band [47].

Citizen Broadband Radio Service

Facing ever-increasing demands of wireless innovation and constrained availability of clear sources of spectrum, the CBRS is an opportunity to add much-needed capacity through innovative sharing. CBRS aims to dissolve the age-old regulatory divisions between commercial and federal users, exclusive and non-exclusive authorizations, and private and carrier networks. The comprehensive regulatory scheme adopted in the 3.5 GHz R&O included specific licensing, technical, and service rules to enable dynamic sharing. The 3.5 GHz R&O established a three-tier framework for making the entirety of the 3.5 GHz Band available for shared commercial use utilizing an SAS to coordinate operations between and among users in different tiers. The SAS will serve as the advanced frequency coordinator necessary to assign rights and maximize efficiency in the band [26]. It incorporates information from the Environmental Sensing Capability (ESC) [31], which will be used to increase available spectrum in coastal areas while continuing to protect incumbent DoD radar systems.

Incumbent Access users represent the highest tier in this framework and receive interference protection from all CBRS users. Protected incumbents include federal shipborne and ground-based radar operations and FSS earth stations in the 3600-3700 MHz band and, for a finite period, grandfathered terrestrial wireless operations in the 3650-3700 MHz portion of the band. An ESC is used to detect transmissions from DoD radar systems and transmit that information to an SAS to ensure that federal Incumbent Users are protected from interference. The CBRS consists of two tiers—PA and GAA - both assigned in any given location and frequency by the SAS. PA operations receive protection from GAA operations. PALs will be assigned via competitive bidding in up to 70 megahertz of the 3550-3650 MHz portion of the band. GAA use will be licensed by rule throughout the 150 megahertz band. GAA users will be permitted to operate on any frequencies not assigned to PALs. GAA users will receive no interference protection from other CBRS users, including other GAA users, and must not interfere with higher tier operations.

The core idea of the proposed 3-tier framework is to promote dynamic spectrum management approach while ensuring protection to the Federal incumbents. But this dynamic approach naturally discourages investment and participation from the Mobile Network Operators (MNOs) in the CBRS. The MNOs with their existing technical capabilities feel more comfortable with static spectrum management approach. So the dilemma in front of the FCC was to promote dynamic spectrum management and at the same time ensure participation of the MNOs in the CBRS. Keeping this in mind, the FCC expanded the eligibility for the PA tier in the 3.5 GHZ FNPRM that allowed the MNOs to enjoy priority status within the CBRS. The most critical entity of the proposed 3-tier access framework and the spectrum management approach is the SAS. The primary hesitation of the critics of the 3-tier framework is that the scale and complexity of the dynamic SAS functionalities are enormous and it will require significant time and effort to develop and mature these functionalities.

In this discussion we analyze the position of the Commission on different aspect of the CBRS through the 3.5 GHz R&O and the Second R&O in order to address this hesitation of the critics of the proposed 3-tier system. The 3.5 GHz R&O provided the regulatory and technological foundation of the CBRS. With the Second R&O, FCC finalized the rules governing the innovative Citizens Broadband Radio Service in the 3550-3700 MHz band (3.5 GHz Band). In addition to reaffirming the rules issued in the 3.5 GHz R&O, the Second R&O agrees to increase the power level for non-rural Category B CBSDs and for greater flexibility in how to measure and direct the power. The Commission also revised the measurement of Out of Band Emission (OOBE) limits to conform to the well-established root mean square (RMS) measurement technique. FCC also adopted a limited exception to the PAL assignment rules that would allow a single PAL to be issued in License Areas located in Rural Areas in the absence of mutually exclusive applications. The stakeholders of the 3.5 GHz band include incumbent fixed satellite service (FSS) earth stations, incumbent utilities and critical infrastructure industry (CII), adjacent C-Band incumbent satellite operations, cellular industry, potential database/SAS administrators, and dynamic spectrum access industry. Table 2 presents a tabular representation of different interest groups among the stakeholders.

We will present a brief summary of a survey of the stakeholder's comments in response to the 3.5 GHz FNPRM. The stakeholders responded to different aspects of the FNPRM from their industry perspective. We look at these responses from the perspective of a dynamic SAS capable of facilitating the dynamic spectrum management approach. Our survey yielded a number of important issues which are required to be addressed for successful initial launch and operation of the proposed CBRS. We identify the required functionalities, technical capabilities, and composition of the SAS to support the dynamic spectrum management approach envisioned in the CBRS. To address the complexity of the SAS functionalities and scale of SAS responsibilities, as pointed out by the critics of the 3-tier framework, a modular SAS composition with close interaction among different modules will best serve the access framework. For every aspect of the proposed CBRS, we identify the required functionality, and the corresponding minimum set of information and the SAS module.

Table 2: Interest groups among the stakeholders

Interest Group		Members/Commenters
SAS/TVWS Administrators		Google, Telcordia Technologies, Comsearch, Spectrum Bridge
Dynamic Spectrum Access Industry		Federated Wireless LLC, InterDigital Inc., Microsoft Corporation, Shared Spectrum Company, xG Technology Inc., Whitespace Alliance,
Wireless Broadband Industry		Cambium Networks, Ltd., CTIA-The Wireless Association, Tarana Wireless, UK Broadband Limited, Vanu, Inc., Xchange Telecom Corp., CommScope, Neptuno Media, Inc., Cloud Alliance, LLC., Lockard & White, NMS Enterprises LLC.,
Cellular Industry	Mobile Network Operator	AT&T, Sprint Corporation, T-Mobile, Verizon and Verizon Wireless
	Vendors	Alcatel-Lucent, Ericsson, Motorola Mobility, Nokia, QualComm Inc.,
	Wireless Industry Association	4G Americas, IEEE DySPAN-SC (Standard Committee), IEEE 802 LMSC, New America Foundation and Public Knowledge, Telecommunications Industry Association, PCIA - The Wireless Infrastructure Association and HetNet Forum, Wi-Fi alliance, Wireless Innovation Forum, Wireless Internet Service Providers Association, Competitive Carriers Association, WiMAX Forum,
Satellite Earth Station	S-Band Satellite Operation	Satellite Industry Association, Baron Services Inc., Astrium Services Government, Inc.
	C-Band satellite Operation	Content Interest, National Public Radio, National Cable and Telecommunications Association
Utilities and CII		American Petroleum Association, Entelec, Exelon, Motorola Solutions, Iberdrola USA Networks, Oncor Electric Delivery Company, Siemens Industry Inc., Southern Company Services, Utilities Telecom Council, Xcel Energy Services, CenterPoint Energy Houston Electric,
Backhaul Network		BLiNQ Networks, Inc., Cohere Technologies, Sprint Corporation

Others	Terrestrial Fixed Microwave Communications	Fixed Wireless Communications Coalition
	Communications for Underserved Communities and Tribal Lands	Blooston 3.65 GHz Coalition, Salt River Project Agricultural Improvement and Power District
	Public Safety and FirstNet	Harris Corporation
	Industry Associations	Consumer Electronics Association, Content Companies, National Association of Broadcasters, Public Interest Spectrum Coalition, Enterprise Wireless Alliance,
	Financial Organization	Cantor Telecom Services L.P., Allied Communications LLC

Different Aspects of the CBRS

The FCC finalized rules for different aspects of the CBRS operation in the 3.5 GHz R&O and the Second R&O [28, 32] in accordance with the NTIA recommendations filed as the letter from the NTIA Office of Spectrum Management to the FCC Office of Engineering and Technology (*NTIA Letter*) [46]. FCC issued the 3.5 GHZ NPRM [3] and the 3.5 GHZ FNPRM [27] to lay out the rules and policy discussion about the dynamic spectrum sharing approach through the tired-access system. With these NPRMs, the Commission requested the interested entities from industry, academia, and research community to provide their feedback on the feasibility, technical correctness, and time to initial roll out of the proposed CBRS system. The stakeholders responded to these rules from the perspective of their operational priority. We used these perspectives to reshuffle the presentation of these aspects and group them according to their importance to the stakeholders. First we present the proposed rules for the CBRS general framework that provide the setup for the 3-tiered CBRS with IA, PA and GAA tiers. The general framework also lays out the authorization rules for the CBRS users. Then we present the spectrum allocation proposal that addressed the distribution of available shared spectrum among different tiers of users. Based on the general framework for the CBRS and the allocation proposal, FCC proposed rules for dynamic spectrum assignment by the SAS. We also present the proposed rules for the definition of PA License (PAL) units and it assignment process. Then we present the CBRS device (CBSD) general and radio requirements proposed in the FNPRM. The discussion of the above mentioned aspects of the CBRS provides the required platform to discuss about the proposed rules for protection of the federal and non-federal incumbent users.

Table 3: Different aspects of the proposed CBRS

Different Aspect of CBRS	Focus of proposed rules
General Framework	• 3-tier Access Framework • Eligibility for Priority Access • Registration and Authorization
Allocation Proposal	• GAA spectrum pool • Opportunistic GAA access to unused PALs • Dynamic frequency assignment by SAS • 70 MHz Spectrum for PA tier
Priority Access License	• Definition of PAL • Bandwidth of PAL • Duration of PAL • Operational area of PAL • PAL assignments through competitive bidding • Light-touch leasing for secondary assignment
CBSD General Requirements	• Geolocation reporting capability • Interference reporting capability • Interoperability throughout the band
General Radio Requirements	• Transmission power • Receive signal strength at the area boundaries • Out-of-Band emission • Interference tolerance • Measurement of the operating limits
Protection of Federal Incumbents	• Environmental Sensing Capability (ESC) • Geographic exclusion zone • Coordinated Protection zone • Advanced interference mitigation techniques
Concerns for the Non-Federal Incumbents	• Expanded eligibility of the PA tier • Inclusion of 3.65 GHz band in the CBRS • Provision for Contained Access (CA) users • Impact of CBRS on adjacent channel Incumbents

Protection of the Non-Federal Incumbents	• Grandfather status for limited time • Advanced interference mitigation techniques

We also present different aspects of the CBRS that resulted in concerns from the non-federal incumbent users. Table 3 presents different aspect of the CBRS as presented in this discussion. For each of the aspects of the CBRS proposed in the NPRM/FNPRM, we summarize the proposed rule, summary of the stakeholder's standpoint on the rules, and focus on identifying the required SAS functionalities. A large number of the commenters, especially the MNOs expressed their opposition against the proposed dynamic spectrum management approach as this approach is outside the comfort zone of their existing technological capability and administrative structure. For successful realization of the proposed CBRS, it is imperative that the SAS has the capability to efficiently carry out these important functionalities. While surveying the comments of the stakeholders on different aspects of the FNPRM, we followed an "F-I-C" (Functionality-Information set-Composition) approach. In principle we agree with the Commission's vision of dynamic spectrum management approach to maximize the spectrum usage efficiency. We identified the composition and functionalities of a dynamic able to facilitate dynamic access to the shared spectrum with favorable interference environment for different tiers of the FCC proposed CBRS.

3-Tier Access Framework

Proposed Rules

The 3.5 GHz FNPRM proposed a 3-tier access framework consisting of IA tier, PA tier, and GAA tier for the CBRS. Existing primary operations – including federal users and grandfathered Fixed Satellite Service (FSS) earth stations – would make up the IA tier and would receive interference protection consistent with the proposed rules. The CBRS would be divided into PA and GAA tiers of service, each of which would be required to operate on a non-interference basis with the IA tier. The FCC proposed an expanded eligibility for the CBRS such that any party satisfying basic eligibility requirements under the Communications Act will be eligible to hold a PA license (PAL) or, when authorized, operate a CBSD on a GAA basis in the CBRS.

The Commission also proposed rules for CBSD authorization. The FNPRM requires the CBSDs used for PA to register with the SAS by providing all information required by FCC rules and comply with its instructions consistent with CBSD general requirements. To get the authorization the PALs must demonstrate the applicant's qualifications to hold an authorization and state how a grant would serve the public interest, convenience, and necessity. The CBSDs are required to provide the SAS with information regarding its geographic location, antenna height, requested authorization status, unique FCC identification number, user contact information, and unique serial number. If the submitted information satisfies the authorization requirements, the SAS permits the CBSDs to operate in accordance with the frequency assignments and power limitations set by the SAS. The FNPRM also proposed that the authorization process and requirements may be reasonably automated by SAS administrators.

Stakeholders Standpoint

The critics of the Commission's proposed 3-tier framework argued that it is an unproven and untested dynamic spectrum management approach. In the 3-tier framework, the Commission does propose to simultaneously implement novel spectrum management concepts [50, 51]. First, the dynamic sharing of the spectrum with incumbent federal ground-based, airborne, and ship-borne radar systems and among two tiers of commercial users, each with distinct spectrum access rights. Second, the nationwide implementation of the licensed small cells. Third, implementation of the granular licensing approach for commercial operations, especially without any expectation of license renewal. As a result, the network and device ecosystem and SAS technology required for such a novel spectrum management approach is unproven.

The critics also argued that the dynamic SAS, as the central entity governing the proposed spectrum management approach, requires time to develop and mature in order to carry out its complex functionalities [52, 53]. According to the critics, the proposed 3-tier framework requires innovation from the perspective of technology, system security, regulations, and administration [54, 55]. The CBSDs will require modification of the existing air interfaces to communicate with the SAS and to ensure security of the communications. The GAA devices will require innovations to satisfy the proposed geo-location and interference reporting capability. Also regulatory and administrative innovations are required to efficiently coordinate the small cell site locations and management of border area interference among different license service providers.

The proponents of alternate access frameworks emphasized relying on known and proven licensing model to provide spectrum users with the certainty and stability needed to invest and deploy innovative services in the band. The core idea is to provide greater segregation between the various tiers of users, limiting the potential for interference. They also argued that the commercial systems are built to operate at a fixed band and dynamic assignment of spectrum would require significant modification of the existing protocols, interfaces, and device ecosystem. The proposed alternate frameworks are primarily aimed towards providing required certainty to the commercial operators from the perspective of investment return. There are two main approaches for the alternate access frameworks: the transitional approach and the 2-tier framework.

The main concept of the transitional approach is to segment the entire band to ensure availability of spectrum for different category if users. This approach allows PAL licensees to develop products, invest in networks, and introduce 3.5 GHz chipsets into the user devices, all without fear of interference [56]. At the same time it allows the GAA users to develop necessary capabilities to ensure proper functioning in the spectrum sharing environment [57, 58]. For Federal incumbents, the transitional approach offers more certain interference protection as the Commission introduces shared uses into the band [59]. It also allows spectrum use while the SAS undergoes further development and testing. With PAL and GAA users in separate frequency blocks, a much simpler SAS can be employed to prevent them causing harmful interference to incumbent operations. Thus the transitional approach can facilitate a trust environment between the IA and CBRS users and further the process of exclusion zone reduction. There are three major version of the transitional approach.

Two exclusive segments: PA exclusive and GAA exclusive [56, 59-61]

In this approach, the both the PA and GAA users get an exclusive band of their own and operate as a secondary user to the IA users in the band (Figure 3 (a)). The justification is to provide the PA users certainty for investment and infrastructure development. For GAA users it provides opportunity to develop the device ecosystem that can coexists with the IA users.

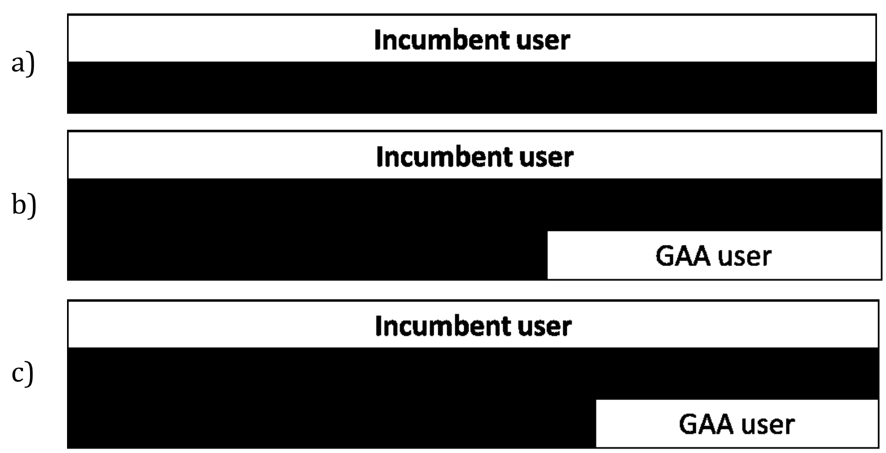

Figure 3: Transitional Approach: a) 2 segments exclusive approach, b) 2 segments exclusive-share approach, c) 3 segments exclusive/share approach

Two exclusive/shared segments: PA exclusive and PA-GAA share band [57, 58]

This approach also provides the PA users with an exclusive band for secondary operation. The other segment is used to develop the proposed 3-tier framework (Figure 3 (b)). Also this segment can be used to gradually develop the required SAS functionalities as proposed in the 3-tier framework.

Three exclusive/shared segments: PA exclusive, GAA exclusive, and PA-GAA share band [50, 54, 62-67]

The 3 segment approach provides the CBRS users with their exclusive bands and at the same time allocate a certain portion of the band for experiment with the Commission's proposed 3-tier framework (Figure 3 (c)). This approach allows the development of the SAS functionalities within this limited segment and at the same time allows GAA users to develop the device ecosystem suitable for coexistence with the IA users of the band.

Once an ecosystem begins to evolve for 3.5 GHz base stations and client devices, and scalable SAS technologies are designed, tested and refined, adjustments necessary to span the entire band and account for increasingly complex sharing scenarios will be far more achievable.

The other alternate framework proposed is based on the ASA/LSA access framework. The proponents of this approach argued that this approach would provide certainty to the investors, could take advantage of the existing technology and regulatory efforts, and would provide better protection to the IA users of the band [50, 68-70]. The ASA/LSA two tier framework allows commercial licensees to operate within the interstices of the frequency band where and when government users are not using it, and to quickly vacate the spectrum so incumbents can operate on a completely interference-free basis [50, 51]. Implementation of two tiers under this framework is completely transparent to the end user device. In Europe, ETSI is implementing the ASA two tiered framework, where it is referred to as LSA for Licensed Shared Access. So majority of the technical and regulatory works to enable a two-tier framework at the 3.5 GHz band is completed. On the ground of providing certainty of investment the supporter of the 2-tier framework urged that the commission should rely on conventional licensing mechanisms and adopt the 2-tier framework for the 3.5 GHz spectrum sharing system.

On the other hand, the proponents of the proposed 3-tier model advocated that the proposed dynamic spectrum sharing and management concept is implementable using existing technologies. According to them, the critics of the 3-tier framework have mistakenly assumed that a SAS cannot manage the interactions between PAL and GAA users while protecting incumbents [71, 72]. Based on the experience of the TVWS database operation, the existing geo-location database technology and spectrum management platforms are technically capable of handling a multitude of complex policies and rules that facilitate tiered access to spectrum and a secondary spectrum marketplace [73, 74].

For example, Spectrum Bridge claimed to have developed a frequency and spectrally agnostic spectrum management platform capable of supporting any band plan – fixed or dynamic [75]. The supporters of the proposed 3-tier framework believe that spectrum sharing in this band should be managed through an SAS and there are no technical obstacles to immediate implementation. In a way, the dynamic spectrum management approach would provide greater certainty and protection to all the users. Loss of any specific channel in any specific locations would not result in the loss of PAL rights due to federal or FSS operations [72, 76]. At the same time it would allow protection of federal IA and PA operations while enabling a seamless experience for end users of CBRS services [77]. In addition, the spectrum sensing technologies could play a key role in augmenting SASs to better enable cooperative and opportunistic access [78, 79]. According to the supporters of the 3-tier access framework, it would be a major step backward for the Commission to adopt a transitional band plan.

Majority of the commenters agreed in principle with the authorization proposal for the PA tier. The only concern they raised is about the mandatory registration of the CBSDs in order to operate in the shared band. The proposal does not clarify whether the end user devices fall under the CBSDs or not. The stakeholders aiming for the PA tier suggested that the end user devices should not be required to register with the SAS [80]. Instead the PA licensees should register the access points (eNB, femtocell, etc.) with the SAS describing the area of operation. This would allow the network operators to manage the end users and execute the network management plans, and would relieve SAS from micro-managing the network operation [58]. For the authorization of GAA devices, the Commission proposed a license-by-rule approach. Any party meeting the eligibility requirements would be authorized to operate a CBSD on a GAA basis without an individual station license. CBSDs used on a GAA basis must register with the SAS and comply with the requirements. Some of the advocates of the dynamic spectrum management approach asked the commission to adopt the unlicensed approach for the GAA devices based on the success story of the 2.4 GHz band [78, 81, 82]. According to them the GAA small cell devices should be unlicensed under the equipment authorization rules [78]. Others agreed with the Commission's proposed license-by-rule approach but requested that the authorization approach should have light regulatory touch [81, 83, 84]. In order to provide flexibility in GAA operations, the regulatory burden on CBSDs should be limited to those rules necessary to protect incumbents from harmful interference [79, 81].

R&O on Access Framework and the SAS Functionalities

The three-tier framework makes the entirety of the 3.5 GHz Band available for shared commercial use utilizing an SAS to coordinate operations between and among users in different tiers. An ESC may be used to detect transmissions from DoD radar systems and transmit that information to an SAS. The SAS will incorporate information from the Environmental Sensing Capability (ESC), which will be used to increase available spectrum in coastal areas, while continuing to protect incumbent Department of Defense (DoD) radar systems. The 3.5 GHZ R&O and Second R&O adopted the proposed three-tier authorization model to encourage innovation, and spur investment in the band. It was also decided that the 3650-3700 MHz band should be included in the Part 96 authorization regime and the 3650-3700 MHz band should be reserved for GAA users and Grandfathered Wireless Broadband Licensees. The proposed approach accounts for the needs of commercial users, priority users, and the general access users. At the same time, this approach provides the necessary opportunity for the development of the network and device ecosystem and regulatory structure capable of realizing dynamic spectrum sharing. The critical element of realizing the dynamic spectrum management regime is the implementation of a dynamic SAS. The SAS is required to be able to protect the interest of the incumbent and facilitate the dynamic access of the PA and GAA devices to the available spectrum.

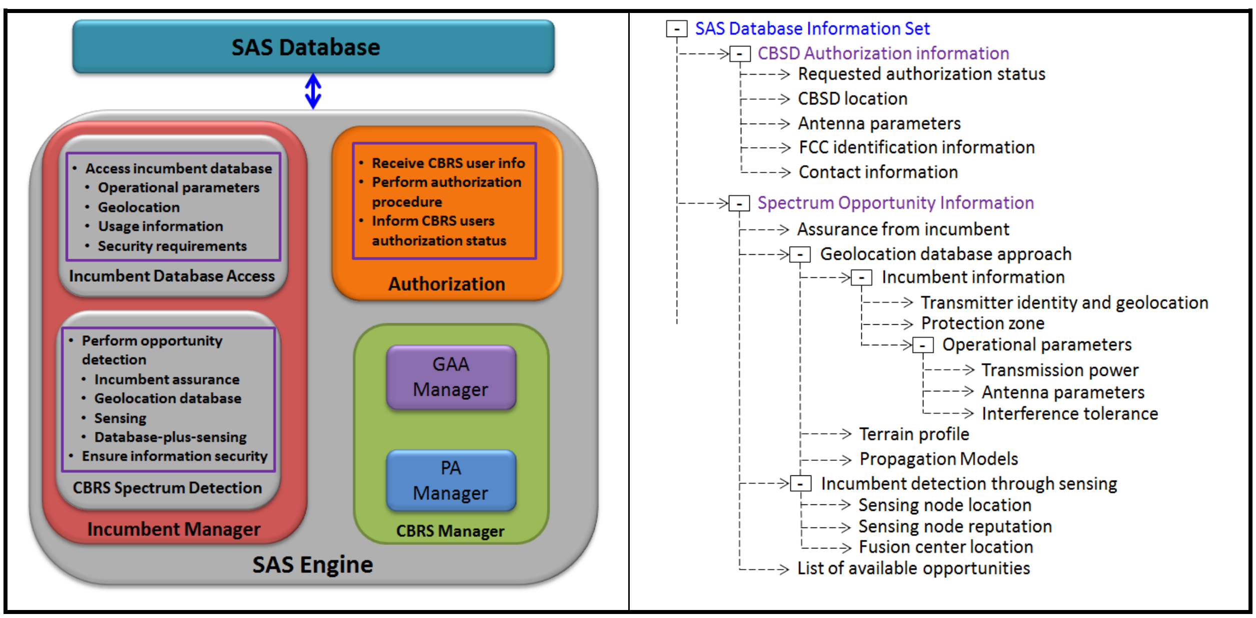

Figure 4: SAS composition and information set: General Access Framework

Following our approach of modular SAS composition, we propose separate SAS modules to manage different tier of users. At this stage our proposed SAS composition is presented in Figure 4. The proposed SAS has the following major modules: *Incumbent manager, CBRS manager, authorization module, Spectrum Opportunity Detection module,* and *the SAS database*. The *SAS engine* facilitates interaction among different modules of the SAS. The *CBRS manager* has two separate modules, *PA manager* and *GAA mana*ger, to facilitate the operation of the two tiers in the CBRS.

Incumbent Manager

The responsibility of the *Incumbent manager* is to ensure coordination between the SAS and the incumbent operations. This coordination is critical for successful operation of the CBRS while ensuring the desired operating environment for the incumbent users. At this stage the *Incumbent Manager* includes only the Incumbent database access module. The *database access* module fetches information based on the prior agreement with the incumbent. The nature of the accessed primary user usage information plays a significant role in generating the probabilistic assurance about the quality of the spectrum opportunities. The incumbent user may agree to provide its usage information such as duration of operation or only the operational parameters such as transmit power and location, antenna height, and protection contour, etc. The *Spectrum Opportunity Detection* module identifies the available spectrum for the CBRS users based on the information gathered by the database access module. If the SAS is provided with incumbent's operational parameters, it can either use the geolocation database, sensing technologies, or a database-plus-sensing approach to identify the spectrum opportunities. Thus the *Spectrum Opportunity Detection* module and the *Incumbent manager* module interact with each other and with the incumbent users in order to provide the CBRS users the opportunity to access the shared spectrum and at the same time ensure the desired interference environment for the primary user perspective.

Authorization Module

The *Authorization module* authorizes the CBRS users, both the primary user and the secondary users, and clears them for participating in the sharing of the incumbent users' spectrum. The *Authorization module* should have the capabilities of receiving information from the CBRS users, performing the authorization procedure, and informing the applications about their authorization status. The R&O adopted the authorization rules, as suggested by the cellular communication industry, such that the PA user's access points (PA-AP) should register with the SAS rather each of the end devices. This will provide the SAS with a central point of monitoring and communication to facilitate desired PA tier operations. The authorization rules for the GAA devices proposed in the FNPRM and Second FNPRM was also adopted by the 3.5 GHz R&O and the Second R&O. Information provided by the CBSDs for authorization purpose allows the SAS to monitor the CBSD operations and ensure that they are abiding the interference protection requirements of the incumbents. Table 4 presents the task list and required information for each of the SAS modules in Figure 4.

Table 4: General Framework: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
Authorization Module	• Receive CBRS user information • Perform authorization procedure • Inform CBRS users authorization status	• Requested authorization status • CBSD location • Antenna parameters • FCC identification information • Contact information	• CBSDs
		• CBRS requirements	• Regulatory authority
Incumbent Database Access	• Check the extent of Incumbent cooperation • Access Incumbent database to fetch • Operational parameters • Geolocation information • Usage information • Security requirements	• Incumbent-SAS agreement for information access	• Incumbent database access module
		• Information required from the Incumbent database	• Spectrum opportunity detection module
Spectrum Opportunity Detection	• Check available opportunity detection mechanisms • Perform opportunity detection • Incumbent assurance • Geolocation database • Incumbent detection through sensing • Sensing-plus-database • Generate list of available opportunities • Ensure required information privacy for the Incumbents	• Assurance from Incumbent • Incumbent information • Transmitter identity • Geolocation information • Transmission power • Antenna parameters • Interference tolerance	• Incumbent database access module
		• Terrain profile • Propagation models • Sensor information • Sensing node location • Sensing node reputation • Fusion center location	• SAS database

Allocation Proposal

Proposed Rules

The Commission proposed rules governing frequency assignments that would balance the needs of PA Licensees and GAA users. The allocation proposal for the 3.5 GHz band has four major aspects. First, it proposes to reserve a minimum of 50% of the 3.5 GHz Band in any given census tract for GAA use. After accounting for IA tier use, the remaining spectrum to be assigned as PALs. Second, any spectrum not assigned to PALs or not in actual use by PALs would be available for GAA on an opportunistic basis. Third, Contained Access (CA) users may request up to 20 MHz of GAA spectrum from the SAS to be reserved for CA Use inside a CA Facilities (CAFs). Fourth, the SAS dynamically assign and maintain PAL channels and GAA bandwidth within given geographic areas in real time. Under this approach of dynamic frequency assignment, there is no fixed spectral location for the PA or GAA allocations. Although PALs would be assigned with spectrum blocks of 10 MHz, there is no fixed channel size for GAA use and the GAA users would be permitted to operate on a range of frequencies within the GAA pool, as determined by the SAS.

Stakeholders Standpoint

Majority of the stakeholders agreed with the concept of the proposed GAA spectrum floor to ensure stability for 'unlicensed' or 'license by rule' applications [74]. Some of the commenters supported the proposal to reserve 50% of the available bandwidth for GAA use [85-89]. Others, especially supporters of the dynamic spectrum access approach demanded more aggressive reservation for the GAA users [79, 90, 91]. It was proposed that as a baseline a minimum of 50% of the available bandwidth should be made available for GAA use at any given time over the full 150 MHz band [92-96]. The exact partitioning of the band between the PA and GAA use would be determined dynamically, based on the need. Another proposal suggested to reserve the greater of 50 MHz or 50% of non-incumbent spectrum within each census tract for GAA use [81, 97]. New America Foundation proposed a dynamic approach in which the minimum GAA reservation would be defined as a proportional ratio based on the available spectrum in a given location or time after protecting incumbents, rather than a fixed bandwidth [98] and this relative allocation ratio should be flexible to modification over time.

Majority of the stakeholders also supported the "Use it or share it" approach where opportunistic GAA devices could function on unused portions of the PA tier [71, 74, 81, 88, 93-95, 98-102]. They claim that the same dynamic mechanisms proposed for CBSD-incumbent system sharing spectrum can also be applied to GAA-PA spectrum sharing [103, 104]. A dynamic SAS would determine allowable transmission parameters based on predicted and measured interference levels and interference protection thresholds. Whether a channel is active or idle would be determined by the SAS. SAS could differentiate between base stations or access points that are handling actual, real-world customer traffic and which base stations or access points are simply 'idling' and not serving real, end-user needs [90, 91]. Method for coexistence in the 3.5 GHz band may include 'listen-before-talk' capability for GAA devices [81], near-real-time notification from PAL [96], periodic reporting of traffic and measurements from CBSDs, and TTL concept, or evacuation commands from the SAS [92].

On the other hand, the stakeholders planning to operate in the PA tier, especially the wireless carriers opposed both the spectrum floor and opportunistic access of unused PAL spectrum provisions for the GAA users on the principle that rules should not set aside spectrum for a particular class of users [70, 105, 106]. They argued that reserving 50% of spectrum for GAA may not leave enough spectrum available for multiple PA Licensees and would violate the priority status of the PA tier users [53-55, 58, 107, 108]. According to them the initial reservation of 50% of the spectrum for GAA use, if adopted, should not remain static if the incumbent operations reduce the total amount of spectrum available for private sector uses [55]. It was also claimed that the proposed GAA spectrum floor would complicate global harmonization and implementation of the shared system and advanced techniques such as carrier aggregation [109]. The prospective PA tier users also suggested that opportunistic GAA use of PAL spectrum should not be allowed on spectrum where PAL facilities have been deployed in order to avoid potential harmful interference, even during a period when it is "unused" [55, 109, 110]. If the Commission ultimately includes the proposed opportunistic GAA access in the rule, these stake holders proposed that the determination of used spectrum should come directly from the PA Licensee [55]. The SAS should not have the responsibility to determine "actual use" because it will not know how the PAL license fits into a licensee's network management strategy [53]. For example, PA Licensee may dedicate a channel in all or a portion of its license area as a guard-band to protect its network from interference. In summary these commenters believes that further study is required before making "unused" PAL spectrum available for opportunistic GAA use [110].

The supporters of transitional or 2-tier access framework and other stakeholders from the wireless communication industry strongly opposed the proposal of dynamic frequency assignment [50, 56, 59-61, 68-70]. From the wireless carrier's perspective, PA Licensees require stable assignment of frequencies across the service area – not dynamically assigned spectrum – to maximize efficient use of reliable mobile broadband services [59, 63, 69]. Adopting a fixed frequency spectrum regime would promote investment and innovation in the band. So the spectrum in use under a PAL should not be available for dynamic assignment [60, 101]. They also disagreed with the proposal of no fixed spectral location for CBRS user's spectrum assignment and that the SAS would dynamically determine the assignment of the spectrum. They proposed that the SAS should not be responsible for dynamic PAL frequency assignments and the Commission should adopt fixed assignments for PALS [110]. The proposed use of dynamically-assigned 10 MHz channels for PAL licensees, rather than fixed channels, may raise potential technical issues regarding control channels, synchronization, OOBE, handover, etc. [65, 68, 74].

Majority of the commenters outside the cellular communication industry welcomed the Commission's proposal of dynamic spectrum assignment by the SAS in real time [71, 80, 81, 92]. The dynamic spectrum management approach would facilitate coexistence and interference protection among the various users [77, 90]. PA or GAA Users should not be entitled to a specific 10 MHz block and the SAS should have the flexibility to dynamically assign spectrum blocks at any time—even during a PAL period [72, 92]. SAS can take into account the actual size and shape of the adjoining emitter and receiver masks for devices at a given area and assign blocks to maximize efficient use of the spectrum [72, 81]. In order to realize dynamic spectrum assignment by SAS, the CBSDs should have the capability and obligation to report signal level measurements in their local environment to the SAS [93]. This will enable the SAS to validate its algorithms continuously, support all users, and assist the Commission in identifying reported sources of interference [71]. The champions of the dynamic spectrum management approach also welcomed the proposal of no fixed channel size for GAA users as this provide the opportunity for innovation and facilitates diverse use cases [71, 79]. The GAA users would be permitted to operate on a range of frequencies within the GAA pool, as determined by the SAS. The dynamic spectrum assignment by SAS would provide certainty in terms of spectrum availability [71, 81], maximize spectrum use [92, 95], and facilitate the coexistence of a diverse user class [77].

R&O on Allocation and the SAS Functionalities

The 3.5 GHZ R&O adopted allocation proposals largely consistent with the FNPRM proposals, as amended to reflect the NTIA Letter [46]. FCC also proposed to add a co-primary, non-federal fixed and mobile allocation to the band. The Commission also proposed to retain the federal allocation for airborne radar systems subject to the same type of approach used in the AWS-3 proceeding where the commercial operations accept interference from federal airborne systems. The non-federal co-primary fixed and mobile except aeronautical mobile allocations will allow for shared use of the band between Citizens Broadband Radio Service and incumbent federal Radiolocation and Aeronautical Radionavigation and non-federal FSS services.

Ensuring the availability of a stable and significant quantity of spectrum for both PA Licensees and GAA promises to foster innovation, encourage efficient use of the band, and create an environment conducive to a wide array of potential users and uses. The CBRS consists of two tiers—PA and GAA - both assigned in any given location and frequency by an SAS. PA operations receive protection from GAA operations. A PAL is defined as a non-renewable authorization to use a 10 MHz channel in a single census tract for three years. A maximum of 70 megahertz may be reserved for PALs in any given license area at any time and the remainder of the available frequencies should be made available for GAA use. PALs will be assigned via competitive bidding in up to 70 MHz of the 3550-3650 MHz portion of the band. One PA Licensee may hold up to 40 MHz of PALs in any given census tract at any given time. GAA use will be licensed by rule throughout the 150 MHz band. GAA users will be permitted to operate on any frequencies not assigned to PALs. GAA users will receive no interference protection from other CBRS users, including other GAA users, and must not interfere with higher tier operations.

A maximum of 70 MHz may be reserved for PALs in any given license area at any time and the remainder of the available frequencies should be made available for GAA use. PALs will be assigned via competitive bidding in up to 70 MHz of the 3550-3650 MHz portion of the band. One Priority Access Licensee may hold up to 40 MHz of PALs in any given census tract at any given time. GAA use will be licensed by rule throughout the 150 MHz band. GAA users will be permitted to operate on any frequencies not assigned to PALs. They are also allowed to access the spectrum opportunities that are assigned to the Priority Access Licensees but are not in 'use' at that particular instant. GAA users will receive no interference protection from other CBRS users, including other GAA users, and must not interfere with higher tier operations.

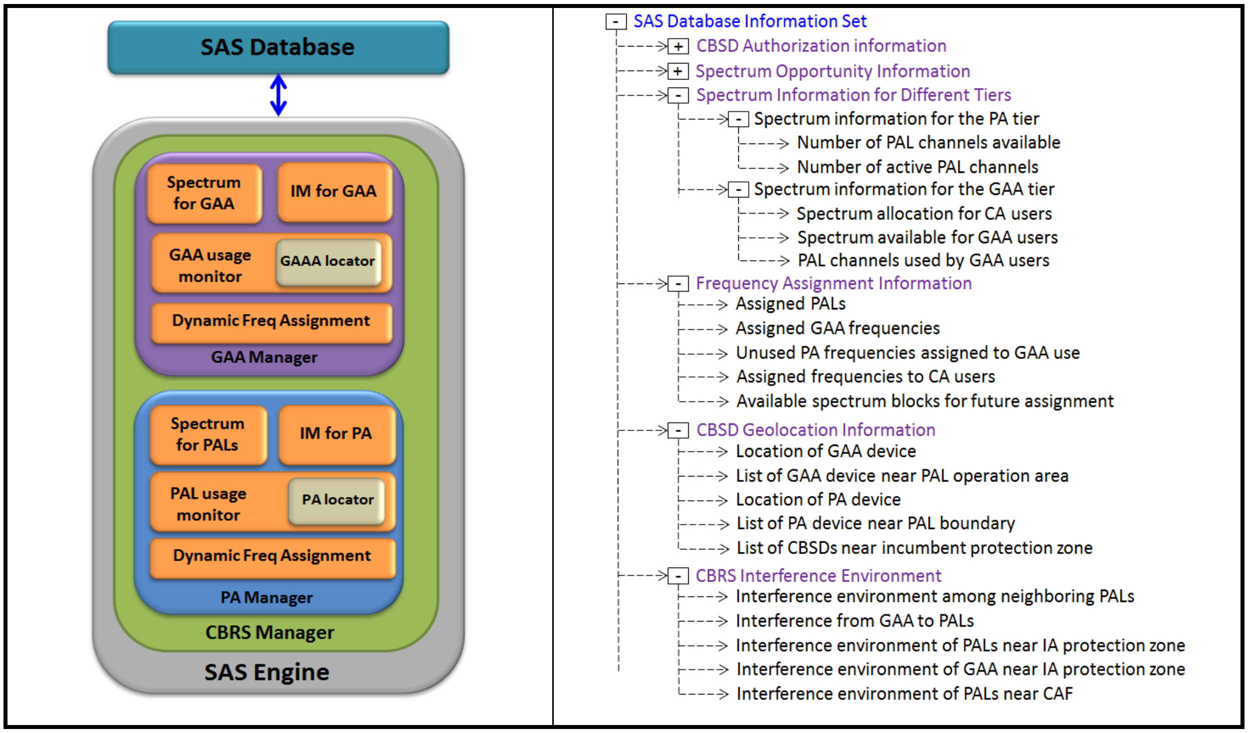

Figure 5: SAS composition & info set: allocation proposal & technical rules

The allocation proposal for the CBRS puts SAS as the governing entity for spectrum opportunity allocation among different tiers of users. By proposing no fixed channel size for GAA users, it provides the platform for dynamic spectrum management. It also provides incentive to innovative and involved dynamic GAA usage by reserving a spectrum pool. Also according to the rules, the CBSDs (both GAA and PA) has to have frequency agility to operate anywhere in the entire 3.5 GHz band and thus pushing the GAA systems towards a more dynamic usage of spectrum. To accommodate the allocation proposals, we introduce the *Spectrum for GAA, Spectrum for CA, Spectrum for PALs,* and *Dynamic Frequency Assignment (DFA) modules* (Figure 5). The *PAL usage monitor module* is also introduced in the *PA Manager* to ensure that the PA users operate within the proposed rules.

Priority Access (PA) Manager

The Priority Access manager ensures the available spectrum opportunities and dynamically assigns frequencies for Priority Access operation. The Priority Access manager needs to coordinate with both the Incumbent Access and the General Authorized Access manager in order to obtain the most recent spectrum availability information. The Priority Access spectrum availability module requires information about the number of available PAL channels, number of active PAL channels, spectrum allocations for General Authorized Access and CA users, and PAL channels used by the

General Authorized Access users. Based on this information, the Priority Access spectrum availability module prepares a list of PAL channels available for future assignment and also informs the General Authorized Access manager if any PAL channel that has been assigned to General Authorized Access users is to be claimed back. The PAL usage monitor module is responsible for determining the usage status of the PAL and ensures the availability of the unused PAL channels for GAA opportunistic use.

Table 5: CBRS Allocation: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
Spectrum for PA Tier	• Check available spectrum opportunities • Check allocations for the GAA tier • Check allocation for the CA users • Determine available spectrum opportunities for PA tier • Claim back PALs used by GAA based on PA demand	• Available spectrum opportunities	• Opportunity detection module (IA manager)
		• Allocation for GAA tier • Allocation for CA users	• Spectrum for GAA tier module
		• List of PALs to be claimed back	• Dynamic frequency assignment (PA tier) module
Dynamic Frequency Assignment (PA Tier)	• Check the available spectrum opportunity for PA tier • Receive spectrum demand from PA-APs • Efficient resource allocation • Prioritizing contiguous allocation if possible • Generating temporary list of available PALs for future allocation	• Available opportunity for PA tier	• Spectrum for PA tier module
		• Spectrum demand from PA users	• PA-APs
		• Use status of the assigned PALs	• PAL usage monitor module
PAL Usage Monitor	• Identify the PAL channels that are in active use • Generate list of unused PAL for opportunistic GAA use • Coordinate with Spectrum for GAA tier module	• List of Assigned PALs	• Dynamic frequency assignment (PA tier) module
		• List of PALs used by GAA tier	• Spectrum for GAA tier module

Spectrum for GAA Tier	• Check available spectrum opportunities • Check allocations for the CA users • Check allocation for the GAA tier • Get the list of unused PALs for GAA assignment • Determine available spectrum opportunities for GAA tier	• Available spectrum opportunities	• Opportunity detection module (IA manager)
		• Spectrum allocation for CA users	• Spectrum for CA module
		• List of unused PALs	• PAL usage monitor module
Spectrum for CA users	• Check available spectrum opportunities • Check allocations for the GAA tier • Check allocation for the CA users	• Available spectrum opportunities	• Opportunity detection module (IA manager)
		• Spectrum allocation for GAA tier	• Spectrum for GAA tier module
Dynamic Frequency Assignment (GAA Tier)	• Check the available spectrum opportunity for GAA tier • Receive spectrum demand from GAA users • Efficient resource allocation • Generating temporary list of available GAA spectrum for future allocation	• Available opportunity for GAA tier	• Spectrum for GAA tier module
		• Spectrum demand from PA users	• GAA users

The Dynamic Frequency Assignment (DFA) module of the PA tier ensures dynamic assignment of available PA spectrum with a best effort approach towards contiguous allocation. It coordinates with PA spectrum availability and interference management modules to know the available resource and interference context for frequency assignment (Figure 5). This module also receives the spectrum demand from the PA users along with associated QoS requirements and is responsible for reassigning PAL channels to address any unwanted interference event.

GAA Manager

The responsibilities and sub-modules of the GAA manager are somewhat similar to those of the PA manager. The capabilities of the GAA spectrum availability module include ensuring the GAA spectrum pool, accounting for the reserved CA spectrum, and ensuring availability of the unused PAL channels. This module coordinates with the spectrum availability modules of the IA and PA managers and generates a list of available frequencies for the GAA users. The DFA module of the GAA manager must have the capabilities of receiving the spectrum demands from the GAA users with associated QoS requirements, dynamic opportunity scheduling, and reassigning allocations as needed. As there is no fixed channel size for GAA use and the DFA module is required to have the capability of efficient resource allocation to maximize the spectrum efficiency and satisfying the QoS demands of the GAA users. The task list and the required information set for these modules are presented in Table 5.

Priority Access License: Units, Aggregation, and Assignment

Proposed Rules

In the NPRMs, PAL units are defined in terms of time, frequency, and geographic area in order to promote granular but administratively streamlined licensing approach. PALs will be authorized at the census tract level and geographic aggregation across license areas will be permitted. PALs will operate over 10 MHz unpaired channels with the ability to aggregate multiple (3) channels. The license term will be limited to one-year with no renewal, but entities will be allowed to aggregate up to five (5) consecutive years of licenses. PALs will be awarded through competitive bidding to resolve any mutually exclusive applications received for initial PALs. The frequency assignments governing rules are proposed to balance the needs of PA Licensees and GAA users. To foster a robust GAA ecosystem, a meaningful amount of the 3.5 GHz Band must be reserved for GAA use in any given geographic area. The Commission proposed to reserve for GAA use a minimum of 50 percent (50%) of the 3.5 GHz Band in any given census tract – after accounting for any frequencies used by Incumbent Access tier operators in the area – with the remainder to be assigned as PALs.

The Commission proposed to employ the general competitive bidding rules set forth in Part 1, Subpart Q to resolve any mutually exclusive applications received for initial PALs [27]. The Commission, on an annual basis, would open windows for applications for available PALs. To accommodate the ability of licensees to aggregate consecutive one-year terms, the Commission may offer multiple consecutive years of PAL rights simultaneously. At the close of such a window, the Commission would hold an auction to assign PALs where there are mutually exclusive applications pending. The existing bidding process options include sequential and simultaneous auctions, single and multiple round auctions, and auctions with combinatorial bidding. In the Broadcast Incentive

Auction NPRM the Commission proposed a rule that provides for the establishment of specific auction procedures governing bid collection, assignment of winning bids, and the determination of payment amounts in spectrum license auctions.[111] Such auctions may use one or more rounds of bidding and/or contingent stages of bidding; and may incorporate bids or offers that simply specify a price for an item, that indicate demand for an item at a specified price, or that are more complex. The Commission is also considering any revision in the existing payment rules to address unique aspects of the CBRS, such as the short license term for PALs, the potential for applicants to become winning bidders for licenses that do not become effective until a year or more after the initial PAL. Also the Commission is considering revision of the existing payment rule to ensure that a winning bidder may not game the results of an auction by bidding upon consecutive year PALs only to seek to selectively pay for some but not others of those bids at a later date. The Commission is also weighing the option if awarding bidding credits in the CBRS would be necessary to ensure the participation of small businesses in competitive bidding. To facilitate a secondary market for PALs, the commission is considering the extent to which existing secondary market rules (both for license transfers and for leases) might be appropriately modified with respect to the secondary market for PALs in the 3.5 GHz Band.

Stakeholders Standpoints

The Commission proposed the PAL units in accordance with its vision to promote granular but administratively streamlined licensing approach as an initial step toward promoting flexibility, fungibility and liquidity in the secondary market. The Commission defined the PAL units by defining the size of PAL in terms of geographic area, duration of license, and size of spectrum block. But the prospective PAL users, especially the cellular communication industry, opposed the proposal mentioning that extending license terms, adopting a renewal policy, expanding geographic size, and enhancing power levels will promote PAL participations [63].

The proposal of using census tract as PAL's geographic area of operation received mixed response. Some of the commenters supported the census tract license scheme mentioning that the proposed fine grid areas would clearly offer the most flexibility and reuse at this wavelength [78, 112, 113]. Coverage area of a 3.5 GHz femtocell is <1km2 which justifies the use of census tracts as a reasonable order of magnitude [73]. They also opposed modification of the proposed PAL geographic area. A more granular "pixels" or other smaller unit might be adequate for non-rural areas, but would be inappropriate for rural areas where the benefits of higher-power operations could be unnecessarily confined within smaller geographic areas [90].

The proposal of census tract as PAL's geographic area of operation was addressed by a variety of counter proposals. One of the major issues raised by the commenters is that the management of the 74000 census tracts may prove to be administratively burdensome [66]. It was also claimed that the census tract is a poor fit for small cell deployments as their edges "generally follow visible and identifiable features". These features often divide the very areas where it will make the most sense from a network coverage perspective to deploy access points [114]. The prospective PAL users, especially the cellular communication industry, supported license areas that are larger than the census tract [50, 66, 115]. Various larger geographic units were suggested for PAL such as the traditional mobile licenses area [66], county [69], metropolitan service area, etc. On the other hand the Utilities and CII industry members requested to tailor the geographic areas or the channel sizes to the needs of mission critical communications users [77, 88, 116] and opted for a smaller PAL unit in terms of geographic area. Proposed census tract and geographic aggregation approach may impose unnecessary constraints for utility Smart Grid networks [117]. On the other hand, adopting a more granular licensee area would reduce the likelihood that portions of PA spectrum will be used inefficiently [71]. The proponents of dynamic spectrum management asked for a more aggressive approach dynamic geographic unit for PAL. According to the dynamic geographic unit approach, the PAL areas should be based on interference protection needs and should correspond to actual network deployment [71]. This approach is claimed to have the added advantage of reducing the need for a separate category of CAF users.

Majority of the commenters agreed with the proposed 10 MHz channel size for PAL as it align with the existing standards [69, 84, 87, 90]. Some minor modifications were proposed such as allowing the 5 MHz [85] and 20 MHz [50, 69] blocks in addition to the proposed 10 MHz block. But the cellular communication industry members disagreed on the proposed spectrum cap of 30 MHz for channel aggregation. The wireless carriers strongly opposed the 30 MHz cap mentioning that this upper limit on holding PALs is proposed without any justification [54, 55, 60]. Stakeholders outside the cellular industry welcomed the proposal as a mechanism to avoid spectrum hoarding by a single entity [77, 82] and asked the Commission to enforce the spectral cap for any single licensee over a given area [84, 92]. In this regard the Utilities and CII industry members requested the Commission to allow Grandfathered systems in the 3.6 GHz band that certify use of more than 30 megahertz within a census tract to retain that spectrum under Priority Access licensing [84].

The strongest opposition to the proposed definition of the PAL unit was aimed towards the proposed one year term with no renewal expectancy [58-60, 106, 109]. The cellular industry indicated this as a major issue that would impose uncertainty and discourage investment. 10 or 15 year terms are the norm associated with wireless service licenses and they typically include an expectation of renewal [57]. A one year term even with the possibility for licensees to aggregate multiple consecutive PALs to obtain multi-year rights will be insufficient to provide the predictability and certainty needed for MNOs and other potential PA users of the spectrum to make investments in the band [66, 69]. In addition, the investors demand the certainty of continuous operation to ensure the return of their investment. The commenters urged the Commission to adopt a multi-year PAL licensing with preference or renewal expectancy for current licensees [50, 60, 69, 85, 115]. The members of the cellular industry provided some alternative proposals to encourage the investors. These proposals included adopting the traditional 10 year term with renewal expectancy [60], initial 2 year term with a one year renewal subject to build out requirements [112], a 3 year license term during the transition period [66, 69]. The cellular industry also supported the proposed aggregation up to 5 years [90, 118]. The supports of the transitional approach proposed an initial term of 3 years and a first renewal of 2 years. After the original 5 year license term, PA Licenses should be able to renew for additional 1 year terms so long as service is being provided in the licensed service area [60]. The dynamic spectrum access industry on the other hand opposed any proposal that allows a commercial party to obtain multi-year rights by aggregating consecutive PAL terms within the same geographic area [81].

In response to the proposed rules for the auction process, the commenters have three major standpoints. The Utilities and CII members opposed the auction of spectrum in the 3550-3700 MHz band because competitive bidding for PALs against the commercial carriers will greatly disadvantage users who do not generate direct revenue from their use of spectrum [88, 112, 117, 119]. They request the Commission to have special provision and present a number of counter proposals. These proposals included a simple lottery based system for multiple PAL applicants [112], discrete auctions for mission critical communications users [88], separate CII filing window [85], etc. In order to provide a level playing field and to allow the Utilities and CII entities to fairly participate, these entities requested the Commission to place spectrum holding limits upon commercial carriers [118] and provide bidding credits for the entities that would use the spectrum for "mission critical" communications system[105, 116, 118].

The members of the cellular industry responded to the proposed auction rule by cautioning the Commission that the untried dynamic auction approach creates considerable uncertainties [109] and the Commission should provide greater clarity in the auction rules [60]. According to them the proposed auction rules lack the predictability for infrastructure investment certainty and QoS, which typically require multi-year planning and deployment horizons and additional time thereafter to yield reasonable returns to long-term infrastructure investors [63]. The members of the cellular industry supported the proposed rule to allow package bidding for contiguous frequencies and contiguous service years [64]. On the other hand, the supporters of the dynamic spectrum management approach welcomed the proposed auction rules as this provides a mechanism for the introduction of new innovative uses of spectrum within recognized commercial time frame [78, 84]. They agreed that a dynamic SAS will be able to manage the dynamic spectrum auction process for the commercial PALs [83, 120] and requested the commission to consider permitting dynamic disaggregation and partitioning of the licenses as this may improve demand and value of the spectrum opportunities in the secondary market [68, 121]. Some commenters suggested that the licensees should be permitted to trade future PAL rights via secondary market transactions as this would relieve potential users from the burden of accurately predicting future demand [73]. The proposal of secondary market for allowing usage right to secondary users has the potential of promoting innovative, short-lived, and more dynamic use cases for the available spectrum opportunities and thus improve the overall spectrum usage efficiency.

R&O on Allocation and the SAS Functionalities

The Commission proposed the PAL units in accordance with its vision to promote granular but administratively streamlined licensing approach as an initial step toward promoting flexibility, fungibility and liquidity in the secondary market. The proposed rules for PAL units, aggregation, and assignment require a separate module, Auction center, to facilitate the assignment of licenses through competitive bidding. The Spectrum for PA module also needs to be able to accommodate the granular license units and aggregation based on the decision of the Auction center.

Dynamic disaggregation and partitioning will impose additional complexity and overheads. But at the same time going back to the traditional dedicated licensing will stall the effectiveness of the dynamic spectrum management approach. The use of census tract as the operational area of the PALs could potentially result into inefficient spectrum usage at the boundaries. This can be addressed by complementing the operational area with suitable interference environment conditions at the boundaries. In the 3.5 GHz R&Os [28, 32], a Priority Access License (PAL) is defined as a non-renewable authorization to use a 10 MHz channel in a single census tract for three (3) years. A Priority Access applicant may apply for up to two consecutive three-year terms for any given PAL available during the first application window, for a total of six years. A maximum of 70 MHz may be reserved for PALs in any given license area at any time and the remainder of the available frequencies should be made available for GAA use. PALs will be assigned via competitive bidding in up to 70 MHz of the 3550-3650 MHz portion of the band. One PA Licensee may hold up to 40 MHz of PALs in any given census tract at any given time. GAA use will be licensed by rule throughout the 150 MHz band. Both PA and GAA use will be assigned and coordinated by an SAS, which will also perform additional coordination functions as set forth in the rules. GAA users will be permitted to operate on any frequencies not assigned to PALs. GAA users will receive no interference protection from other CBRS users, including other GAA users, and must not interfere with higher tier operations. Table 6 presents the task list, required information set and the sources of the information to facilitate the proposed rules for PAL unit, aggregation, and assignment.

Table 6: PAL Unit, Aggregation, and Assignment: Task List and Info Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
Auction Center	• Receive applications from interested PAL users • Carry out the auction process • Inform the applicants the auction results • Forwards the assignment decisions to SAS modules	• Bidding information • Authorization information • Operational area • Aggregation information • Contact information of the applicants	• PAL applicants
		• Authorization information	• Authorization Center
Spectrum for PA users	• Check allocation for the PA users • Determine available PAL units for PA tier • Check the PAL aggregation information	• PAL assignment information • Aggregation information	• Auction Center
Dynamic Frequency Assignment (PA Tier)	• Dynamic assignment based on PAL unit and aggregation	• Available PAL channels • Operational area • Aggregate QoS demand	• Spectrum for PA users
PAL Usage monitor	• Monitor PAL user activity satisfy assignment conditions	• PAL assignment information	• Spectrum for PA users

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Technical Rules for CBSDs

Proposed Rules

The CBSD general requirement and the general radio requirements are proposed to ensure efficient spectrum use and coexistence and secure communication among different tiers of CBRS. The approaches required to achieve these objectives include proper authorization, determination of spectrum availability, management of interference environment, and dynamic assignment of available frequencies. To enable the SAS to authorize and effectively coordinate the use of shared spectrum in the 3.5 GHz Band, CBSDs must have certain administrative, operational, and reporting capabilities. These capabilities include registering with SAS by providing required administrative and operational information, Geolocation reporting capability, interoperability, interference reporting capability, and certain radio capabilities.

The Commission proposed that the CBSDs must be able to determine their geographic coordinates to an accuracy of ±50 meters horizontal and ±3 meters vertical. Further, a CBSD must reestablish its position and report changes to its position within 60 seconds to the SAS each time it is activated from a power-off condition. A CBSD must check its location at least once every 60 seconds while in operation and report to the SAS any location changes exceeding ±50 meters horizontal and ±3 meters elevation within 60 seconds of such location change.

To facilitate the proposed dynamic approach to frequency assignment, the Commission proposed that the CBSDs must be interoperable across all frequencies from 3550-3700 MHz. This would ensure that all CBSDS and End User Devices certified to operate in the band would be capable of sending and receiving information regardless of the frequencies assigned by the SAS. An interoperability requirement will also help to establish uniform certification requirements for both the GAA and the PAL equipment. Both these points are important to generate economies of scale and also to make sure that GAA equipment is manufactured to the same standards as the PAL equipment.

In order to address the real time interference issues, the Commission proposed that the CBSDs would report to the SAS if they experience interference that exceeds a threshold established by the SAS. To meet this requirement, CBSD devices would need to incorporate the ability to measure and report on their local signal level environment.

Stakeholders Standpoints

Majority of the commenters agreed that the location information would be important for the SAS to function properly. But a number of commenters pointed out that the existing technology cannot satisfy the Geolocation capability requirements [52, 53, 60, 101, 110]. According to them, the reporting requirements are impractical and onerous [53] and they are unware of any feasible technology to meet the horizontal and vertical accuracy requirements [60, 110]. Others mentioned that the existing technology may satisfy the horizontal accuracy requirement based on the ongoing proceeding on E911 location accuracy, but cannot provide geographic information to the SAS within ±3 meters elevation with sufficient accuracy [52]. Achieving the timing requirements for the proposed geolocation and reporting capability may also prove to be challenging as the wireless providers and manufacturers rely upon GPS technologies to provide position fixes [77]. On the other hand, the supporters of the dynamic spectrum management approach suggested that the proposed rules are unreasonable and unnecessary to protect incumbent operation [71, 72, 92]. According to them, the location accuracy should be a characteristic of each device and the SAS should be allowed to dynamically calculate worst-case interference based upon the location capabilities of the device [72].

Majority of the commenters supported the proposed rule for interoperability that the equipments certified to operate on the band, whether on a GAA or a PA basis, should be capable of dynamic frequency selection across the entire band based on an SAS channel assignment that could change depending on location, frequency or time [82, 87, 92, 114]. It was suggested that the interoperability requirement should not be imposed as a rule [101] and that the commercial PAL and GAA equipment manufacturers should be responsible for their own receiver performance design and harm interference threshold [79]. Some of the commenters also asked for clarification that the "Interoperability" relates only to operations across all relevant frequencies, but does not require devices to conform to any particular air interface standard [90]. The non-federal incumbents on the band suggested that the Legacy 3650-3700 MHz equipments should be excluded from the interoperability requirement [91].

Many technologies already support this capability to allow radio resource management within a network [103, 110]. The supporters of the dynamic spectrum management approach agreed that SAS should use the CBSD interference management reports to determine suitable assignments and to identify sources of interference [71, 92]. Some of the commenters disagreed with the proposal that allows SAS to adjust maximum EIRP of CBSDs to address any interference issue and believe that the SAS should mitigate interference by monitoring CBSD error rates and changing operational frequency [90]. Members of the cellular industry raised concern that such measurement information must be provided rapidly enough to mitigate the interference [60, 70]. Without rapid, actionable information from the SAS on interference issues, the PAL operators will not be able to react to the issue in time to manage interference and the SAS will not be able to manage the dynamic frequency assignments [101].

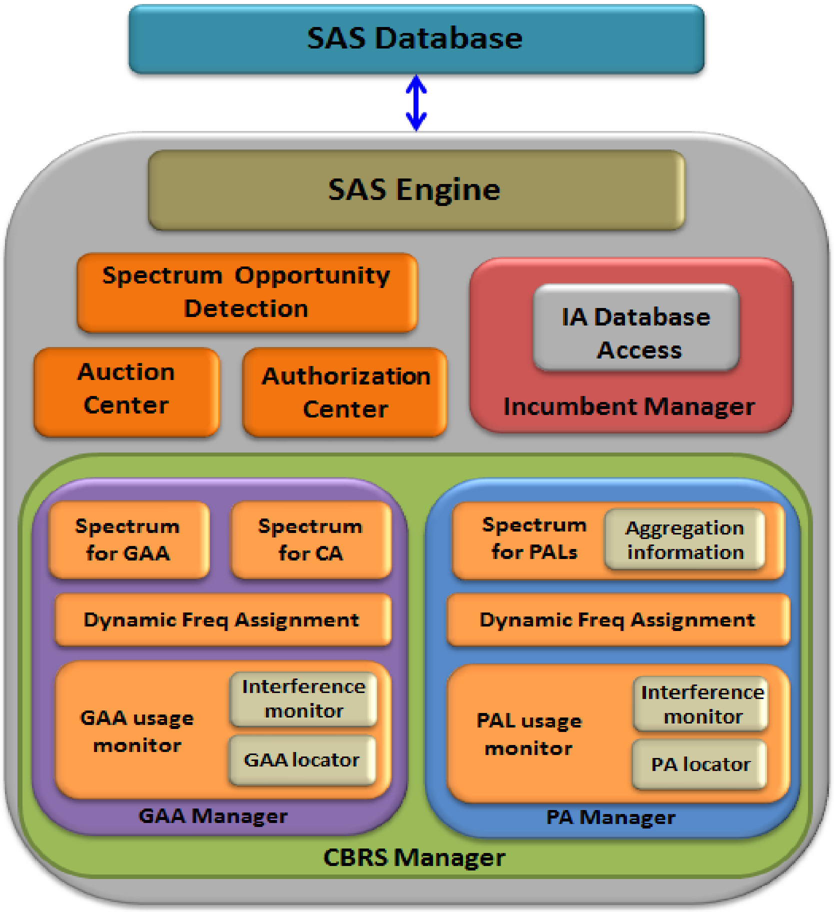


Figure 6: SAS Architecture: CBSD General Requirements

R&O on Allocation and the SAS Functionalities

The geolocation and interference reporting capability and interoperability of the CBSDs are the fundamental requirements for the dynamic spectrum management approach. CBSDS with these technical capabilities will enable SAS to efficiently execute the dynamic assignment of available spectrum and ensure coexistence among different tier of the CBRS. The critics of these proposed rules argued that the technical decisions made by the Commission must be guided by current technological realities, not by the potential of future capabilities that have not been shown to be feasible [60]. Compliance with certain of the Commission's technical rule proposals has not been proven to be technically feasible at this time. We won't be commenting on the feasibility of these capabilities as these general requirements are for CBSDs. In this report, we are discussing from the perspective of SAS. In this section we discuss the SAS modules and functionalities required to accommodate these CBSD capabilities. The SAS could use the geolocation and interference reporting capability to efficiently monitor the CBRS user's activities. The rules for interoperability for the CBSDs will allow the SAS to efficiently perform dynamic frequency assignment. Figure 6 shows the SAS composition that accommodates the proposed rules for CBSD general requirements and Table 7 presents the task list and required information for the corresponding modules.

Table 7: CBSD requirement: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
PAL Usage Monitor	• Receive the geolocation information of the PAL users • Receive the interference environment of the PAL operational area • Monitor that the PA users satisfying the operational restrictions	• Geolocation information with required vertical and horizontal accuracy • Interference environment	• PAL users
		• Agreed interference environment • Operational restrictions	• Regulatory Authority / Authorization Center
GAA Usage monitor	• Receive the geolocation information of the GAA users • Receive the interference environment of the GAA operational area • Monitor that the GAA users satisfying the operational restrictions	• Geolocation information with required vertical and horizontal accuracy • Interference environment	• GAA users
		• Agreed interference environment • Operational restrictions	• Regulatory Authority / Authorization Center
Spectrum for PA Tier	• Receive the geolocation and interference report • Identify the available spectrum opportunity for the PA users	• Geolocation information of PA users • Interference environment of PA users	• PAL usage monitor
Spectrum for GAA users	• Receive the geolocation and interference report • Identify the available spectrum opportunity for the GAA users	• Geolocation information of GAA users • Interference environment of GAA users	• GAA usage monitor

DFA (PA and GAA Tier)	• Use geolocation and interference reports for efficient frequency assignment	• Geolocation report • Interference reports	• PAL and GAA usage monitor
		• Updated spectrum availability based on geolocation and interference report	• Spectrum for PA tier • Spectrum for GAA tier

General Radio Requirements

Proposed Rules

The general radio requirements proposed for the CBSDs are targeted towards facilitating interference management and coexistence of different tier of the CBRS. The rule proposed a list of conducted and emitter power limits for different operational environment. The end user devices are allowed to a maximum EIRP of 23 dBm per 10 MHz. The baseline rule permits the CBSDs to a maximum conducted power of 24dBm/10MHz with additional 6 dB of antenna gain. For rural areas, the CBSDs may operate up to 30dBm/10MHz of conducted power with an additional 17 dB antenna gain. The proposed rule also specified maximum conducted power for fixed point-to-point systems to be 30dBm/10MHz with an additional antenna gain of 23 dB. It also proposed that the CBSDs should limit their operating power to the minimum necessary for successful operations and should include transmit power control capability and the capability to adjust maximum EIRP in response to instructions from an SAS.

Table 8: Conducted and Emitted Power Limits (Proposed in 3.5 GHz NPRMs)

		Max conducted O/P power (dBm/10MHz)	Max EIRP (dBm/10MHz)	Max conducted PSD (dBm/MHz)
End User Device	All	N/A	23	N/A
Category A CBSD	All	24	30	14
Category B CBSD	Non-Rural	24	40	14
Category B CBSD**	Rural	30	47	20

**** Category B CBSDs will only be authorized for use after an ESC is approved and commercially deployed consistent with sections 96.15 and 96.67 of the 3.5 GHz R&O [28]**

The general radio requirements also specified that the median signal strength of CBSD transmission at any location on the boundary of a co-channel PAL should not exceed -80 dBm as measured by a 0 dBi isotropic antenna in 10 MHz, unless the affected licensees or incumbents agree to a different field strength and communicate that to SAS. This requirement facilitates management of interference environment among co-channel PA users. For PA and GAA operations in the 3.5 GHz Band, the Commission proposed to apply the limit of 43+10log(P), which is equivalent to –13dBm/MHz, to all emissions outside of channel assignments and frequency authorizations by SAS in the 3.5 GHz Band. The Commission further proposed to apply a stringent limit of -40dBm/MHz with a transition gap of 30 MHz immediately outside the 3.5 GHz band. For CBSD emissions above 3680 MHz or below 3520 MHz, the power of any emissions at these frequencies should be attenuated below the transmitter power in watts by at least 70+10log(P) dB, which is equivalent to –40dBm/MHz.

The rule also specified the minimum level of interference tolerance expected from the CBSDs. PA Licensees must accept adjacent channel and in-band blocking interference up to a PSD level not to exceed -30dBm/10MHz with greater than 99% probability, unless the affected licensees agree to a higher or lower PSD limit and communicate with the terms of such agreement to the SAS. GAA operations are subject to the conditions that they should cause no harmful interference to IA Users or PA Licensees and claim no protection from interference received from IA Users or PA Licensees. PA and GAA Licensees must accept interference in authorized areas of operation from federal radar systems up to a peak field strength level of 180dBuV/m.

Stakeholders Standpoints

Majority of the stakeholders in their response to the NPRM requested the Commission to increase the power limit of the CBSDs. In the FNPRM, the Commission increased the power limits for different operational environments compared to that proposed in the NPRM. Even with this increment in the power limits, members of the cellular industry expressed their disagreement and asked for higher conducted and emitted power limits. Some of the incumbent operations also requested an increased power limit as the proposed limits dramatically reduces their operational power, constraints the minimal link budget, and impacts target applications, such as backhaul operation, Smart Grid WAN deployment, etc. [117, 122]. A number of commenters requested the Commission to authorize higher power levels for systems deployed in the rural areas [65, 98]. If the Commission would adopt the proposed power levels in the rule, it was suggested that the SAS should have discretion to permit higher power levels based on location of the CBSD and knowledge of the presence or absence of incumbents in the region [58]. The members of the cellular industry asked for higher power level and presented several counter proposals. Majority of the commenters suggested a maximum EIRP of either 25 dBm/10 MHz based on the 3GPP Technical Specification ("TS") 36.101 which provides for 2 dB tolerance [87, 107] or 36dBm/10MHz to match the power level of the uncontrolled Wi-Fi devices [53, 60, 70, 71]. One of the more aggressive proposals also suggested a CBSD baseline power level should be 40dBm/10MHz + 6 dBi antenna gain (46 dBm EIRP) for omnidirectional uses, and 40dBm/10MHz + 18 dBi antenna gain (58 dBm EIRP) for directional coverage for outdoor PAL usage [54]. Members of the cellular industry also cautioned the Commission that the total EIRP of the system, dependent on antenna beam-width and gain, shall not exceed the total EIRP specified for PTP deployments of 53 dBm to prevent harmful interference and minimize the area required for exclusion zones [60] and the GAA users should be limited to the proposed 24 dBm transmission power [53]. For small cell operations near coasts, it was suggested that allowing 47 dBm EIRP in rural locations near the coast lines could cause interference to incumbent systems and should not be allowed [50]. One of the commenters identified an anomaly that even with maximum EIRP of 47dBm/10MHz, a fixed end user device transmitting at only 23dBm/10MHz EIRP would not be able to reliably communicate back to the CBSD. And this would effectively reduce the link distance and reliability to the least common denominator of23 dBm/10 MHz EIRP [90]. It was suggested that for rural areas the Commission should modify proposed power levels so that the maximum conducted output power is 30dBm/10MHz with a maximum EIRP for end user devices of 47dBm/10MHz.

The rules require the CBSDs to comply with a -80dBm/10MHz signal level threshold anywhere along the census tract boundary. But a number of commenters argued that the small cell deployments would not be possible in those areas unless the operator obtains a license in each relevant census tract or negotiate coexistence conditions with each of its neighbors to provide relief from the -80 dBm boundary condition [114]. Majority of the commenters supported a more cooperative approach among the CBRS users and suggested that the PAL and GAA service providers may coordinate with each other to determine an acceptable RSS limit [79, 112]. It was also suggested that rather than using a one-size-fits-all specification (-80 dBm boundary condition), the Commission should allow multilevel interference framework with different regimes (areas, channel sets) for managing the allowed frequency reuse density to achieve different IoT targets [54, 55].

Members of the cellular industry expressed their disagreement on the proposed OOBE limits. According to them, the use of -40dBm/1MHz at a frequency offset of 30MHz, i.e., above 3680 MHz and below 3520 MHz would not comply with 3GPP TS 36.101 OOBE limits of -25dBm/1MHz for 10 MHz channels beyond a 10 MHz frequency offset for End User Devices [60, 70, 101, 106]. Commenters outside the cellular industry mostly agreed with the proposed OOBE limit and requested the Commission to refrain from adopting any limits more stringent than proposed in the rule [87, 112]. It was also suggested that the EIRP limits for point-to-point systems in rural areas should be allowed to remain the same if a smaller bandwidth is employed (an increase of the power spectral density to 23dBm/MHz for a 5 MHz channel) [112]. The supporters of the dynamic spectrum approach continued to argue for a more dynamic approach and suggested that appropriate OOBE limits for specific operating environment should be determined based on the need to protect specific operations at a given time, place, and frequency [71, 76, 100]. According to them this dynamic approach of determining OOBE limits will result in increased device performance without requiring stringent thresholds for all devices [72].

On the proposed rules for interference tolerance capabilities of the CBSDs, majority of the commenters suggested that the Commission should refrain from imposing mandatory receiver standards and should be set by standards organizations [87, 107, 108]. They requested the Commission to facilitate a multi-stakeholder approach to the development of relevant standards, including receiver standards [123]. Some of the commenters agreed with the proposed PSD limit of -30dBm/10MHz that CBSDs and end user devises operating on a PA basis must accept as it conforms with the 3GPP out-of-band blocking specifications for LTE, but opposed the proposal that End User Devices be capable of accepting interference up to a peak field strength level of 180dBμV/m mentioning that the proposed rule is extremely severe and is not currently achievable [87]. The supporters of the dynamic spectrum management approach believes that PA systems and devices should also be allowed to operate, on an informed basis, in regions where interference from incumbents may occur [92]. According to them, the LTE or Wi-Fi systems can both be adapted to mitigate possible interference from Incumbents, including high-powered radar signals.

R&O on Allocation and the SAS Functionalities

The rules for general radio requirements are proposed to facilitate the interference management and coexistence among different tiers of CBRS users and the Incumbent users. As the governing entity of CBRS, the SAS has to monitor that the CBRS users are operating within the proposed rules.

Table 9: Conducted and Emitted Power Limits (from 3.5 GHz R&O)

		Max EIRP (dBm/10MHz)	Max conducted PSD (dBm/MHz)
End User Device	All	23	N/A
Category A CBSD	Baseline	30	20
Category B CBSD	Rural areas	47	37
**** Category B CBSDs will only be authorized for use after an ESC is approved and commercially deployed consistent with sections 96.15 and 96.67 of the 3.5 GHz R&O [28]**			

From the perspective of SAS, these rules will facilitate SAS to effectively carry out the dynamic spectrum management approach by ensuring coexistence and favorable interference environment. As mentioned by the stakeholders, implementation of some of these operational capabilities in the CBSDs might be technically challenging. But looking from the SAS perspective, here we will discuss the required SAS functionalities that use these rules in order to facilitate desired coexistence.

The 3.5 GHz R&O and the Second R&O [28, 32] finalized the conducted and emitted power limits as presented in Table 9. It also finalized more stringent emission and interference limits than proposed in the NPRMs: i) -13 dBm/MHz from 0 to 10 megahertz from the SAS assigned channel edge, -25 dBm/MHz beyond 10 megahertz from the SAS assigned channel edge down to 3530 MHz and up to 3720 MHz, and iii) -40 dBm/MHz below 3530 MHz and above 3720 MHz. Category B CBSDs will only be authorized for use after an ESC is approved and commercially deployed consistent with sections 96.15 and 96.67 of the 3.5 GHz R&O [28]. Compliance with emission limits shall be demonstrated using either average (RMS)-detected or peak-detected power measurement techniques.

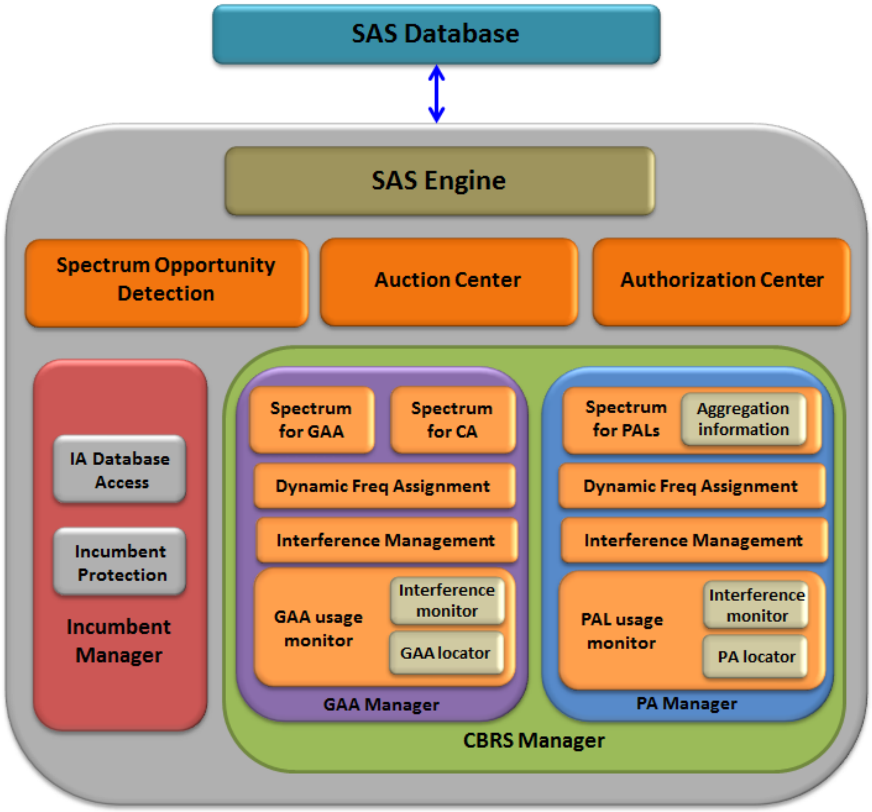


Figure 7: SAS Architecture: General Radio Requirements

The rules also include that for both PA and GAA users, CBSD transmissions must be managed such that the aggregate received signal strength for all locations within the PAL Protection Area of any co-channel PAL, shall not exceed an average (RMS) power level of -80 dBm in any direction when integrated over a 10 MHz reference bandwidth. Also the peak-to-average power ratio (PAPR) of any CBSD transmitter output power must not exceed 13 dB. The PA and GAA usage monitor modules must include the monitoring capabilities to ensure proper functioning of the CBSDs. They should be able to collect operational information from the PA-APs and the GAA devices. This information will also help the SAS to effectively carry out the dynamic frequency assignment among different tiers of the CBRS. These rules will also allow the Spectrum for PA and Spectrum for GAA modules to identify opportunities that conforms to the desired interference environment.

The Interference management modules of both the PA and GAA Manager can also receive the usage information from the usage monitor modules to ensure that the CBRS users are abiding by the rules. If any user is found to operating outside the permitted configuration, necessary steps will be taken to rectify the situation. Figure 7 shows the SAS composition and Table 10 presents the associated task list and required information set for the proposed CBSD radio requirements.

Table 10: General Radio Requirements: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
PAL Usage Monitor	• Monitor that the PA users satisfying the operational restrictions	• Interference environment	• PAL users
		• Agreed interference environment • Operational restrictions	• Regulatory Authority / Authorization Center
GAA Usage monitor	• Monitor that the GAA users satisfying the operational restrictions	• Interference environment	• GAA users
		• Agreed interference environment • Operational restrictions	• Regulatory Authority / Authorization Center
Interference Management for (PA and GAA Tier)	• Receive usage information from the spectrum usage monitor • Monitor that interference environment • Identify CBRS users causing undesired interference • Report unwanted interference events to the enforcing entity	• Usage information • Interference environment of PA users	• PAL and GAA usage monitor
		• Agreed interference environment • Operational restrictions	• Regulatory Authority / Authorization Center
DFA (PA and GAA Tier)	• Use the usage information for efficient frequency assignment	• Usage information • Interference reports	• PAL and GAA usage monitor
		• Updated spectrum availability based on interference report	• Spectrum for PA tier • Spectrum for GAA tier

PA Manager

The proposed technical rules enable the PA manager to efficiently determine the “use” status of PAL channels using the geolocation reports from the PA users. The PA locator sub-module should have the capability of receiving the geolocation reports and allowing the PAL usage monitor and IM module to use this information. The PA manager also uses this information to make sure that the PA user is operating within its designated operating area. The IM module of the PA manager ensures that the PA users is abiding by all the proposed radio requirements such as transmission power and OOBE limits and maintains a comfortable interference environment among the neighboring PA users.

GAA Manager

The GAA manager employs two new modules to accommodate the proposed technical rules. The GAA usage monitor module makes use of the GAA locator to observe whether the GAA devices are conforming to the allowed operational parameters. The GAA location sub-module should be able to receive the geolocation reports and ensure that the GAA devices are operating within the authorized area. The IM module of the GAA manager facilitates acceptable interference environment such that the GAA devices do not cause any harmful interference to the higher tier users. This module should have the capabilities of coordinating with the GAA usage monitor module and identifying the source of GAA interference based on the interference reports. If any unwanted interference event is identified, the IM module advices the GAA device to adjust its operating parameters or informs the enforcement entity to ensure desired interference environment.

Protection of the Federal Incumbent

Proposed Rules

The core concept of the proposed CBRS in the 3.5 GHz band is that the CBSDs must not cause harmful interference to and must accept harmful interference from federal users authorized to operate on the band [3]. The Federal incumbent in the 3550-3650 MHz band includes fixed and mobile high powered DoD radars using ground-based, shipboard, and airborne platforms, and Federal radiolocation service (RLS) and ground-based aeronautical Radionavigation service (ARNS) [27]. In the adjacent bands, the Federal incumbent includes high-powered ground and airborne military radars in the 3100-3500 MHz band and radiolocation service in the 3650-3700 MHz band. In the proposed rule, the Commission adopted the NTIA's proposed exclusion zones, approximately one to 60 km, coupled with frequency offsets of 40 or 50 MHz, to prevent incumbent operations and broadband wireless systems from causing interference to each other. For high-power ship-borne Naval radars this exclusion zone results in an over-land separation distances of several hundred kilometers. The CBSDs must comply with the geographic Exclusion Zones based on the parameters set forth in the Fast Track Report to ensure compatibility with federal operations and the SAS must ensure that CBSDs do not operate within Exclusion Zones. The SAS must immediately suspend operation of any CBSDs found to be causing harmful interference to Incumbent Users until such harmful interference can be resolved. In the NPRM, the Commission discussed about the possibility of reducing the proposed exclusion zones through effective SAS, advanced interference mitigation techniques, and through inclusion of small cell technical and operational parameters in the calculation of exclusion zones. The FNPRM contemplated additional uses of the band with varying maximum transmit power levels and antenna gains other than small cells and suggested that these use cases must be factored into the consideration of Exclusion Zones. The Commission also discussed the approach of dynamic coordinated access within the exclusion zone which allows authorized coordinated operations for GAA – and possibly PA – tier users inside the proposed exclusion zone.

Stakeholders Standpoints

The stakeholders from every interest group agreed that the Commission should significantly reduce the proposed exclusion zone which covers 60% of the U.S. population [58, 71, 81, 85, 107, 110, 112]. The commenters unanimously pointed out that the proposed exclusion zone effectively make the band unusable [53] and a reduced zone is a critical component to the acceptance of this band [59, 65, 103]. They also believe that the exclusion zones should be better managed based on “real world” protection requirements [90, 95]. The exclusion zones can be reduced by an order of magnitude by deploying small cells that operate with much lower transmit power than the typical cellular macro-cells that NTIA had assumed in the Fast Track Report [50]. The stakeholders mainly pointed out two major drawbacks of the proposed exclusion zone and thus must be reevaluated [81, 87]. The first drawback is that the analysis of the proposed static exclusion zone does not consider the technical and operational characteristics of small cell, which is the primary use case of interest for the 3.5 GHz band [58, 93]. The operational characteristics and existing technologies to tolerate significantly more interference than considered in the NTIA analysis result in an order of magnitude reduction in the exclusion zone [70, 79, 90]. The commenters urged that the Commission should recalculate the exclusion zones using the NTIA’s radar and propagation models but with operating parameters appropriate for LTE small cells and separation distances lower than 50km [70]. The second drawback of the exclusion zone analysis is that it considers the protection of CBRS operation while calculating the zones. The commenters pointed out that the Federal exclusion zones should protect federal incumbent users from PA and GAA users, and not vice versa [58, 60, 81, 93] as the secondary users neither require nor warrant protection from primary operations [58, 60]. The advanced technologies such as OFDM, eICIC, SON, FEC, and interleaving allows LTE, WiMAX, WiFi, and other similar systems to easily recover from the burst errors that result from pulses of radar energy that occupy only a short duration of the transmitted frame [59, 79]. It was also suggested that the Commission should draw exclusion zones solely to protect federal operations and not for protecting adjacent non-federal operations [58].

Some of the stakeholders carried out experiments to determine more appropriate exclusion zones [50, 70, 71]. Their findings indicate that the proposed exclusion zone assumed the worst case on a wholesale basis [71]. Based on the technical and service characteristics of small cell deployments and considering the advanced interference mitigation techniques employed by small cells, the static geographic exclusion zones are not necessary to protect the incumbent operations. A large number of commenters suggested that the DoD and SAS administrators should consider a more dynamic approach to exclusion zone by adopting interference protection as a criterion based on the "real world" incumbent use [58, 60, 79, 90]. The commenters also emphasized that exclusion zone could be based on the actual technical characteristics of the particular technology and network deployment of the PA licensee or the GAA user [71, 92]. The geographic exclusion zones should be time dependent, determined individually for each networks, and dynamically managed by SAS [92].

Some of the commenters suggested that the SAS should allow the CBSDs coordinated access with incumbent operations and to thereby convert the exclusion zones into coordination zone [53, 113]. Coordination zone approach would allow certain radio transmitters to be deployed within what would otherwise be the Exclusion Zone, subject to coordination with the Federal incumbent [109]. The supporters of dynamic spectrum management approach disagreed with the idea of coordination zone as this would be a time-consuming, mutually burdensome coordination process in which each user seeks permission from federal operators to access a static exclusion zone [71]. They suggested that the Commission should adopt a more dynamic spectrum sharing mechanism such as database-plus-sensing techniques for incumbent protection [79, 93, 103]. Even with stationary PU, due to variations in local propagation conditions, DSA based on sensing-plus-database more efficiently allocates spectrum among new users and existing incumbent systems than DSA where a database only enforces fixed geographic exclusion zones [79]. In this approach, the exclusion zones can be eliminated entirely with the implementation of DSA or similar sensing technologies into all end user devices in the 3.5 GHz band [93]. This can be accomplished with sensing at least two different ways; by deploying dedicated sensors in key locations (e.g., along the coast) or by leveraging the proposed CBSD interference reporting requirements [79].

R&O on Allocation and the SAS Functionalities

NTIA describes a phased approach to implementing protection criteria of federal operations, including the approval of an ESC to detect signals from federal radar systems. The ESC input would be used by the SAS to direct Priority Access licensees and GAA users to another portion of the 3.5 GHz Band or, if necessary, to cease transmissions to avoid potential interference to federal radar systems. In the first phase, as recommended by NTIA, geographic exclusion zones would be established along the coastlines and around designated ground-based radar locations. CBSDs with an EIRP up to 30 dBm as measured in a 10 MHz bandwidth would be authorized to operate outside of the Exclusion Zones during this phase but higher power operations would not be permitted. Approved SASs would manage CBRS users outside of the Exclusion Zones during this phase. Phase two would begin after an ESC that meets all of the requirements set forth by the Commission is approved and synchronized with at least one approved SAS. With the SAS and ESC in place, the Exclusion Zones for the incumbent users would be converted to Protection Zones. ESC deployment near the borders of protection zones (i.e., not nationwide) would protect radars from interference.

In the first phase, as recommended by NTIA, geographic exclusion zones would be established along the coastlines and around designated ground-based radar locations. CBSDs with an EIRP up to 30 dBm as measured in a 10 megahertz bandwidth would be authorized to operate outside of the Exclusion Zones during this phase but higher power operations would not be permitted.

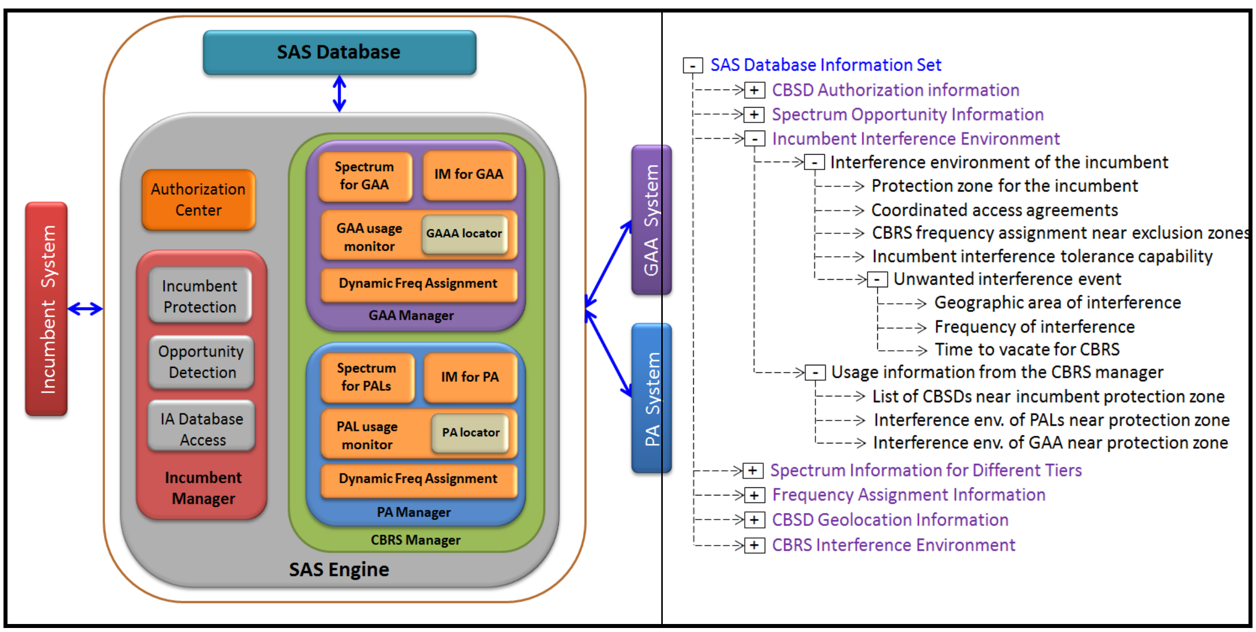


Figure 8: SAS Architecture: Protection of Federal Incumbent

Approved SASs would manage Citizens Broadband Radio Service users outside of the Exclusion Zones during this phase. Phase two would begin after an ESC that meets all of the requirements set forth by the Commission is approved and synchronized with at least one approved SAS. With the SAS and ESC in place, the Exclusion Zones for the coastal areas and the ground-based radars would be converted to Protection Zones. ESC deployment near the borders of protection zones (i.e., not nationwide) would protect radars from interference.

As a consequence of ESC deployment in phase two, the Exclusion Zones will be converted to Protection Zones. Citizens Broadband Radio Service operations in the 3550-3650 MHz band will be permitted within Protection Zones, including major coastal cities, except when the ESC reports federal use in the area. Availability of an ESC will also allow use of Category B CBSDs in the 3550-3650 MHz band portion, provided that the relevant system parameters required to protect the federal Incumbent User at these higher levels are determined and implemented through the ESC approval process. After the ESC and SAS are approved, spectrum availability will be determined and conveyed automatically, promoting efficient use of the band and ensuring that federal Incumbent Users are protected.

Protection of the Federal Incumbent operations from the CBRS users is the core condition for sharing the spectrum. As indicated by the stakeholders and also acknowledged by the Commission, the static geographical exclusion zone proposed in the FNPRM will be reconsidered based on operational characteristics of small cells. We believe that SAS can play an important role to provide sufficient protection to the Incumbent operations. The Federal Incumbent Protection module can use the interference environment information from the Interference Monitor modules of the PA and GAA Manager and desired interference environment information from the IA Database Access module. Based on this information the SAS will be able to identify the area of operation for the CBRS users. Some of the stakeholders proposed that the protection of incumbent operation should be based on the interference environment of the involved systems. This puts the SAS in charge of deciding the coordination zone and at the same time ensures required protection to the incumbent operations. Figure 8 presents the SAS composition that includes module for Federal incumbent operation protection. The task list and the required information set are presented in Table 11.

Table 11: Protection of the Federal Incumbents: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
• **Federal Incumbent Protection**	• Access required protection criteria from the incumbent operation • Receive incumbent satisfaction report • Coordinate with the usage monitor modules of the PA and GAA Managers • Inform Interference Management modules of the GA and PAA Manager of any unwanted interference environment	• Incumbent protection criteria • Incumbent satisfaction report	• Incumbent users
		• Interference environment of the PA and GAA users	• Usage monitor modules of the PA and GAA Managers
• **Usage Monitor** • **(GAA and PA Manager)**	• Coordinate with the Incumbent Protection module	• Interference environment of the PA and GAA users	• PA-APs and GAA users
• **Interference Management (GAA and PA Manager)**	• Coordinate with the Incumbent Protection module • Coordinate with the Usage Monitor modules of the PA and GAA users • Take necessary actions to restore desirable interference environment	• Unwanted interference environment for the Incumbent operation	• Incumbent Protection module
		• CBRS interference environment	• Usage Monitor modules (PA and GAA Manager)

Incumbent Manager

The primary objective of the Incumbent manager is to maintain coordination with the incumbent operations. To facilitate this task, this module must have the capability to access information about the incumbent's interference environment such as the interference tolerance capability of the incumbent. If any interference event is identified, the database access module can gather information about the spectral and geographical location of the source and acceptable "time to vacate" parameter.

The Incumbent Protection module should be capable of coordinating with the database access module and GAA and PA usage monitoring module. It should also have the capability of informing the IM module of the PA and GAA managers if the incumbent suffers from any unwanted interference.

Inclusion of the 3.65GHz Band in the CBRS

The 3.5 GHZ FNPRM proposed to include the 3650-3700 MHZ (3.65 GHZ) band in the CBRS and offered a 5 year Grandfather status to the incumbent operations. The 3.5 GHz R&O agreed with the NPRM proposal and finalized the rule that the 3650-3700 MHz (3.65 GHz) band should be included in the Part 96 authorization regime. It also decided that the 3650-3700 MHz band should be reserved for GAA users and Grandfathered Wireless Broadband Licensees.

As expected, the commercial operations of the 3.65 GHz Band are not willing to welcome a novel and untested technical and regulatory framework into the band of their operations. The 3.65 GHz band incumbents, especially the Utilities and CII users, present reasonable objections that the proposed rule will add uncertainty and disrupt the operation of many incumbents in the band. Their disagreement with the proposed inclusion of the 3.65 GHz band comes from the fact that the technical rules and granular licensing approach are suitable for small cell operations. The incumbent users are hesitant to compete with the financial might of the wireless commercial operators. Also the 5 year transition period is not substantial for Grandfathered systems to fully recoup the capital expenditure. Requiring incumbents to bring equipment into compliance with the rules for the 3.5 GHz Band over an inadequate transition period of 5 year would be cost-prohibitive. If the Commission finally decides to uphold the proposed rules, the Utilities and CII users requests the Commission to adopt an alternate transition framework under which 3.65 GHz band users have the option, but not the obligation, to migrate to the CBRS rules. Majority of the stakeholders, other than the Utilities and CII users, agree to extend the proposed framework for authorizing access to CBS spectrum to the 3.65 GHz band as this provides the opportunity to enjoy a contiguous 150 MHz band with uniform technical rules. Including this 50 MHz band within the framework will also harmonize the spectrum use in the U.S. with other ITU Regions: 3650-3700 MHz is within 3GPP Band 43 [124].

Protection of the Non-Federal Incumbents

Proposed Rules

The FNPRM proposed rules for the protection of the non-Federal incumbents in the 3.5 GHz band. The non-Federal incumbents in the band include non-Federal radiolocation service (on a secondary basis) and the Fixed Satellite Service (FSS) earth stations for receive only, space-to-earth operations and feeder links. The Commission has so far licensed FSS earth stations on 37 locations. The Rule proposed that the existing stations would be included in the Incumbent Use tier and afforded protection from lower-tier operations in the proposed CBRS [27]. The CBSDs shall not cause harmful interference to the FSS earth stations listed in NPRM and the protection criteria shall only apply to FSS earth stations that are in actual use. These operational restrictions shall be enforced by the SAS and the FSS earth station licensees must inform SAS Administrators of their operational status annually. CBSDs may operate within areas that may cause harmful interference to FSS earth stations listed in the NPRM provided that the licensee of the FSS earth station and an SAS Administrator mutually agree on such operation and the terms of any such agreement are provided to SAS and can be enforced by the SAS. The NPRM also discusses the possibility of minimizing/eliminating geographic protection areas around FSS earth stations by incorporating detailed information on "Look angles" of FSS earth stations, emission characteristics of CBSDs and end user devices, detailed regional topographical information, and other relevant variables.

The FNPRM also discussed the possible impact of the proposed CBRS on the adjacent band incumbent operations. In the 3.65 GHz band, the non-Federal incumbents include Utilities and CII entities, Wireless Internet Service Providers (WISPs), and FSS operation (on a non-exclusive basis). In order to provide protection of the incumbents in the 3.65 GHz band, the proposed Part96 rules include stricter-than-normal out of band emission limits for CBSDs/user devices and a spectrum access framework utilizing a dynamic SAS. The NPRM also suggested to use Equivalent Power Flax Density (EPFD) to measure the sum of the power flux densities produced at a geostationary satellite system receive Earth station by CBSD and end user devices in the area of that earth station. The EPFD would be calculated to take into account the off-axis discrimination of the Earth station receiving antenna assumed to be pointing in its nominal direction. Also the "Look angle" of FSS earth stations would have a significant impact on the potential for interference from CBSDs, particularly those located at moderate angles (e.g., >15°) from the axis of the FSS earth station main lobe.

Stakeholders Standpoints

The non-Federal incumbents of the 3.5 GHz band cautiously responded to the proposed CBRS and requested the Commission to ensure the protection of the incumbent operations [125-127]. The satellite Industry Association urged the Commission that the proposed rule must ensure that existing and future primary FSS networks are protected from unacceptable interference [125]. They believe that the small cell policies must provide flexibility for future satellite operations [128]. If the Commission succeeds in developing a framework that allows such co-existence, that framework should be fully capable of accommodating future earth station deployment as well. Small cell policies must also incorporate protections for primary FSS operations. PALs should not be issued in areas surrounding FSS earth stations as the Commission cannot grant "priority" access to spectrum in areas where primary FSS operations would be adversely affected [93]. Rather they request the Commission to define zones surrounding earth station sites where no PALs would be issued. SIA proposes a 150-km radius for these areas as a starting point [126]. They also opposes permitting localized critical access use within the 150 km areas surrounding primary FSS earth stations as the CI services would receive disruptive interference that could be prevented only by imposing unacceptable burdens on primary FSS networks [125].

The proposed rules for CBRS technical standards must ensure protection of the FSS operations. The Commission should adopt a sufficiently stringent OOBE limit to protect adjacent-band operations from harmful interference [126, 127]. The proposed OOBE limit (-13dB) is insufficient to protect spectrally-adjacent weather radar systems, but the proposed OOBE limit of -40dBm/MHz at 3520 MHz would fail to adequately protect S-band weather radar systems. So the Commission should adopt an OOBE limit at 3520 MHz more stringent than -50dBm/MHz. In absence of a more stringent OOBE limit, the Rule needs to create minimal exclusion zones around each radar site. With an OOBE limit of -50dBm/MHz at 3520 MHz, the necessary exclusion zone would only need to be approximately 1,500 meters and with an OOBE limit of -40 dBm/MHz at 3520 MHz would require an exclusion zone of only 5 kilometers [127]. The members of the non-Federal incumbents in the 3.5 GHz band believes that a dynamic and robust SAS with proven capabilities and security measures will be able to provide necessary protection to the incumbent operations [125]. The SAS will need the ability to calculate the aggregate interference environment into each earth station from existing small cells, to reassign frequencies for one or more small cells operating near a specific earth station, and must be equipped with enforceable information security and integrity measures.

The supporters of the dynamic spectrum management approach requested the Commission to enable SAS to provide sufficient protection to incumbent satellite operations while maximizing areas available for wireless broadband [71, 72, 79, 92]. SASs can reasonably protect FSS earth stations from harmful interference using only minimal geographic protection zones—or eliminate those zones entirely – by using real world information to protect incumbent satellite earth stations [71, 92]. SASs will be capable of not only including information about the emissions characteristics of CBSDs, but also the OOBE performance [72, 79], and the protective effects of terrain and other factors to create "real-world" protection zones [90]. The cellular Industry welcomed the suggestion that the CBRS users, especially the PA Licensees, be allowed to negotiate with individual FSS earth station licensees for smaller exclusion zones [70, 90]. Wi-Fi Alliance pointed out that the FSS earth stations currently operating on a secondary basis should not be afforded primary status within the CBRS framework [95].

The non-federal incumbents in the 3.65 GHz band believe that the Interference mitigation measures suggested in the FNPRM are far from adequate and request the Commission to provide necessary interference protection in the 3.65 GHz band [114, 129, 130]. Any undesirable technical characteristics, such as OOB and spurious emissions, undue spectral density, and excessive output power in combination with transmitting antenna directional gain, resulting from any new operations in the 3.5 GHz band should be appropriately limited [114]. For C-band-delivered services, adjacent band interference is equally as important as the in-band interference potential is to incumbents from 3.65 GHz band [129].

Figure 9: SAS Architecture: Protection for the Non-Federal Incumbents

Besides a more restrictive spectral emissions mask or reduced power levels, the incumbents of the 3.65 GHz band propose two options for protecting incumbent C-band operations: i) Establish protection by rule – essentially requiring no harmful interference to C-band through a mandatory separation distance of 9.5 km and ii) protection through a dynamic SAS database [130, 131]. They also proposed to position the GAA operations away from the C-Band with sufficient distance separation as GAA use can't be kept separated geographically from C-band earth stations [130]. The appropriate device obligations, such as emission masks, lower power of GAA devices, and indoor use restriction for GAA, should consider "Look angle" of the earth stations [129].

On the other hand, the dynamic spectrum management supporters believe that SAS will be able to provide sufficient protection to the C-Band satellite operations [71, 72]. The capabilities of SAS to provide this protection may include determination of the aggregate total of the OOBE of all relevant CBSDs, ensuring that the OOBE and the aggregate adjacent band emissions are within the interference threshold limits of the FSS operation, etc. [71]. According to them coordination techniques and SAS-based spectral and physical separation can protect of grandfathered earth stations between 3.6 and 3.65 GHz [72, 92].

R&O on Allocation and the SAS Functionalities

The FNPRM provides the required protection to the non-Federal incumbent operations by offering the Grandfather status for a limited period of time. During this period, the non-Federal incumbents will enjoy interference protection from PA and GAA tier users. In addition to the proposed rules for protection, the non-Federal incumbents demand more stringent protection provisions. But in accordance with the dynamic spectrum management approach, SAS will be capable of not only including information about the emissions characteristics of CBSDs, but also the OOBE performance, and the protective effects of terrain and other factors to create "real-world" protection zones. Figure 9 presents the SAS composition that includes the Non-Federal Incumbent Protection module. The protection module for the non-Federal incumbent operations can receive usage information from the PA and GAA Managers and ensures the desired operational environment for the operations. Number of non-Federal incumbent operation within any specific locality is small. So the SAS governing the CBRS for that locality could customize the protection mechanisms according to the requirements and operational characteristics of the system involved. This approach will allow the SAS to locally optimize the spectrum usage and at the same time provide required protection for the non-Federal incumbent operations. Table 12 presents the task list and the required information for the Non-Federal Incumbent Protection module to provide necessary protection for the non-Federal incumbent operations.

Table 12: Protection of the Non-Federal Incumbents: Task List and Information Set for SAS Modules

Module	Task list	Required Information	
		Information Set	Information Source
• **Non-Federal Incumbent Protection**	• Receive desired protection criteria specific to individual non-Federal incumbent operations • Monitor the operation of PA and GAA users • Identify undesired interference scenario and report to the Interference Management modules of the PA and GAA Managers	• Desired interference environment • Agreed protection criterion	• Non-Federal Incumbents
		• Interference environment information	• Usage Monitor modules of the PA and GAA Managers
• **Dynamic Frequency Assignment (PA and GAA Manager)**	• Coordinate with the Non-Federal Incumbent Protection module • Incorporate incumbent protection criterions in the resource allocation process	• Desired interference environment • Agreed protection criterion	• Non-Federal Incumbents
• **Usage Monitor (PA and GAA Manager)**	• Ensure that the operational restrictions are satisfied by the CBRS users in close proximity of non-Federal incumbent operations	• Desired interference environment • Agreed protection criterion	• Non-Federal Incumbents
• **Interference Management (PA and GAA Manager)**	• Coordinate with the Non-Federal Incumbent Protection module • Take necessary actions to restore desired interference environment	• Desired interference environment • Agreed protection criterion	• Non-Federal Incumbents
		• Unwanted interference event caused by the CBRS users	• Non-Federal Incumbent Protection module

SAS Architecture and Responsibilities

The most critical step towards realizing the dynamic spectrum management approach is the implementation of a dynamic SAS. The SAS should have the ability to protect the incumbent and facilitate the dynamic access of the PA and GAA devices to the available spectrum. The survey of the stakeholder's comments on different aspect of CBRS revealed a number of important SAS functionalities required to facilitate the dynamic spectrum management approach. For each of these aspects, we identified required SAS modules and related task list and required information set. Each of the modules can play important role to address a number of different aspects of the CBRS. In this section we will focus on each of the SAS modules to discuss the responsibility and core technical capabilities of the modules. In this section we present the requirements of the SAS to carry out the desired functionalities considering the inputs of the interest groups and outline a potential SAS architecture. In this example SAS architecture, we trust the PA operator to perform the frequency assignment of the end users and interference resolution of the PA tier. The SAS would include the PA operator's inputs to determine the PAL "use status".

SAS Requirements

The survey of the comments revealed four major interest groups: the non-federal incumbents, the Utilities and CII, the cellular industry, and the advocates of the DSM approach. The incumbents and the Utilities and CII members are mainly concerned about ensuring comfortable interference environment for their operations. As expected, the strongest opposition against the proposed DSM approach came from the cellular industry. The survey also indicated that the cellular industry would find them in a more favorable position if some of their more justified concerns, such as determination of the PAL "use" status, resolution of any interference scenario, and frequency assignment for the end users, are addressed. Although the supporters of the dynamic approach argue for a more aggressive role of the dynamic SAS to manage the spectrum usage, the FCC can accommodate the above mention concerns of the cellular industry without compromising its vision of dynamic spectrum management. For resolving any unwanted interference issue, the SAS can instruct with the PA access points to adjust their operating parameters. Also the SAS can avoid micro-management by dynamically allocating the PALs to the PA service providers and leaving the frequency assignment at the end-user level to the PA operator. The SAS can also include the PA user's input to determine the PAL "use" status. These simple modifications in the proposed rules will allow the PA operators more control over their operations and at the same time SAS will be able to manage the dynamic spectrum sharing system more efficiently.

In order to efficiently execute the functionalities, the SAS must be able to coordinate with the incumbent and CRRS operations. SAS has to be able to protect Priority Access Licensees from interference caused by other PALs and from General Authorized Access Users, including the calculation and enforcement of PAL Protection Areas. Also it has to be able to receive reports of interference and requests for additional protection from Incumbent Access users and promptly address interference issues. Both Dynamic Frequency Assignment and Interference Management functionalities will require the SAS to access the incumbent database to gather information about its spectrum usage. Depending on the information provided by the incumbent, the SAS may require to have the capability of using a geolocation database with terrain information and/or detecting the incumbent operation through sensing. Here we present a list of SAS responsibilities (this is not a comprehensive list):

1. Enforce all policies and procedures developed by the SAS Administrator consistent with the 3.5 GHz R&Os.
2. Determine and assign available spectrum opportunities to the CBSDs at their location.
3. Determine the maximum permissible transmission power that the CBSD can operate according to the 3.5 GHz R&O.
4. Register and authenticate the CBSDs.
5. Enforce the Exclusion Zones and Protection Zones with the help of the Environmental Sensing Capability (ESC) system.
6. Communicate with the ESC to obtain information about federal Incumbent User transmissions and instruct CBSDs to move to another frequency range or cease transmissions.
7. Ensure that CBSDs operate in geographic areas and within the maximum power levels required to protect federal Incumbent Users from harmful interference.
8. Ensure that CBSDs protect non-federal Incumbent Users from harmful interference.
9. Protect Priority Access Licensees from interference caused by other PALs and from GAA Users.
10. Facilitate coordination between GAA users operating Category B CBSDs.
11. Resolve conflicting uses of the band while maintaining a stable radio frequency environment.
12. Ensure secure and reliable transmission of information between the SAS and CBSDs.
13. Protect Grandfathered Wireless Broadband Licensees according to the 3.5 GHz R&Os.

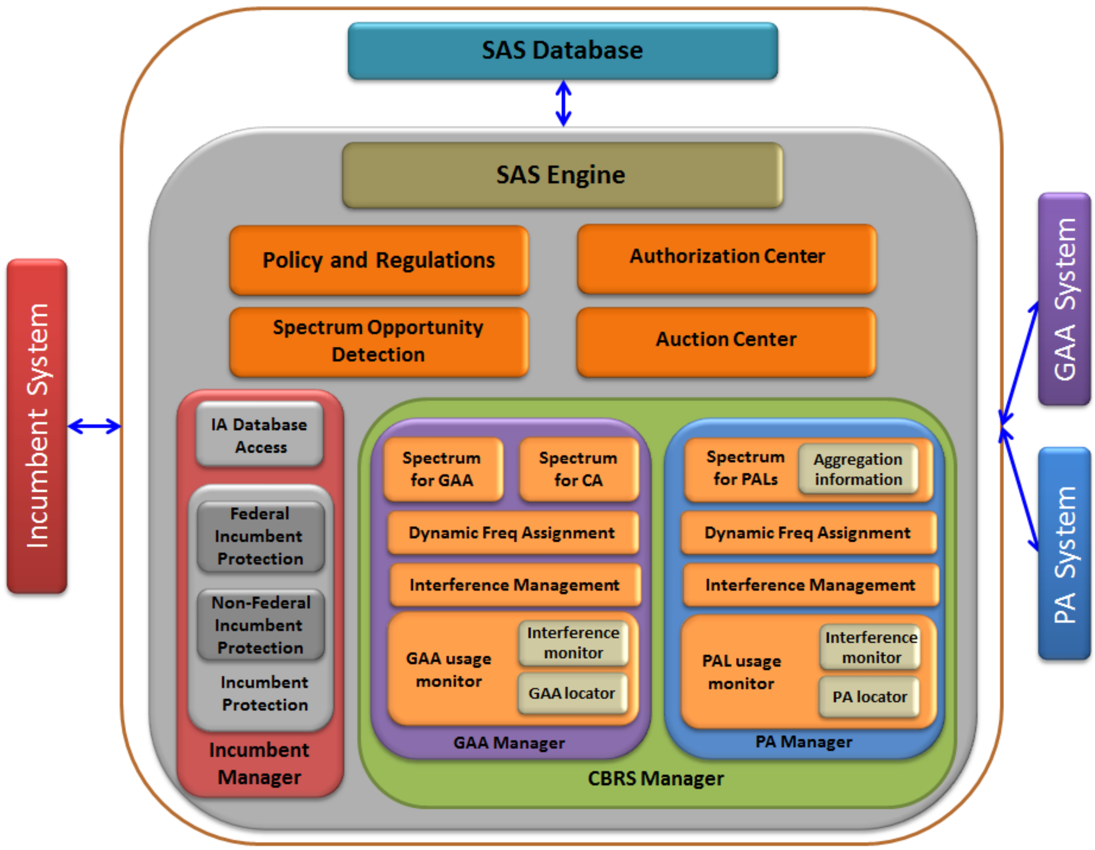


Figure 10: SAS Composition for Citizen Broadband Radio Service

The SAS also needs to coordinate with the CBRS operations such as authorizing the CBSDs, gathering CBSD information including geolocation, interference environment, and radio parameters, and spectrum demand with associated QoS requirements. The SAS should be able to dynamically allocate spectrum to different tiers of the CBRS, and detect and resolve any unwanted interference event.

SAS Architecture

Incumbent Manager

The primary objective of the Incumbent Manager is to ensure coordination between the SAS and the incumbent operations. SAS is required to coordinate the CBRS operation with the incumbent operations to ensure protection of the incumbent operations, availability of the spectrum opportunity information, and privacy of the incumbent usage information. In order to acquire accurate and updated information on spectrum availability, the SAS is required to access the incumbent database. The modules introduced to help the Incumbent Manager to carry out its responsibilities include IA Database Access, and Federal and Non-Federal Incumbent Protection modules. In the following we briefly discuss the responsibilities of these sub-modules in order to achieve the technical and administrative objectives of the Incumbent Manager.

IA Database Access

The IA Database Access module helps the SAS to access incumbent's spectrum usage and interference environment information. The nature and amount of information that the IA Database Access module acquire and forward to the SAS depends on the agreed level of primary-secondary cooperation. The access module facilitates two major SAS functionalities based on the available information. These functionalities are: i) spectrum opportunity detection, and ii) ensuring desired interference environment. There has to be a prior agreement between the CBRS and the IA user about the extent of incumbent's cooperation. The incumbent may agree to provide its usage information such as spectrum location and duration of opportunities or only the operational parameters such as transmit power and location, antenna parameters, tolerable interference limit, and protection contour. Based on the agreement, the SAS knows the nature of available information and decides about the method for identifying spectrum opportunities. The IA Database Access module can also provide information about the desired interference environment of the incumbent operation to the SAS. Another important aspect of IA Database Access module is to ensure desired privacy of the incumbent operation information. The IA user may not want to expose its usage information to the CBRS users. The IA Database Access module must have the capability to forward the operational information of the incumbents in such a way that reduces the likelihood of unwanted exposure.

The IA Database Access module plays important role in the primary-secondary cooperation framework. In order to take advantage of the agreed level of cooperation, it is imperative that the IA Database Access module successfully carry out the responsibilities assigned to it. The above discussion indicates two major responsibilities for the IA Database Access sub-module of the Incumbent Manager module as presented in Figure 10:

1. Access operational information of the incumbent, in accordance with the agreement of cooperation, to facilitate identification of spectrum opportunity and protection of incumbent operation.
2. Ensure desired privacy for the sensitive information of the incumbent operation to reduce likelihood of unwanted exposure.

Table 13: IA Database Access: Functionalities and Technical Challenges

<table>
<tr><th rowspan="2">Functionalities</th><th rowspan="2">Task list</th><th colspan="2">Required Information</th><th rowspan="2">Technical Requirements</th></tr>
<tr><th>Information Set</th><th>Source</th></tr>
<tr><td rowspan="2">• Access IA Database</td><td rowspan="2">• Check the extent of Incumbent cooperation
• Access Incumbent database to fetch
• Operational parameters
• Geolocation information
• Usage information
• Interference environment requirements
• Security requirements
• Periodically update the information</td><td>• Incumbent-SAS agreement for information access</td><td>• Policy and Regulations module</td><td rowspan="2">• Fast, reliable and secure communication with the IA database
• Information update procedure</td></tr>
<tr><td>• Information required from the Incumbent database</td><td>• Spectrum opportunity detection module</td></tr>
<tr><td rowspan="2">• Ensure Incumbent Information Privacy</td><td rowspan="2">• Check the incumbent privacy requirements
• Apply abstraction mechanisms to minimize likelihood of unwanted exposure</td><td>• Incumbent privacy requirements</td><td>• Policy and Regulations module</td><td rowspan="2">• Information abstraction mechanisms
• Secure communication among SAS and CBRS</td></tr>
<tr><td>• Information required for efficient operations</td><td>• Dynamic Frequency Assignment module</td></tr>
</table>

Federal/Non-Federal Incumbent Protection

Protection of the Federal and non-Federal incumbent operations from the CBRS users is the core condition for sharing the spectrum. The same interference protection mechanisms can be used for both the Federal and non-Federal incumbent operations. The application of these mechanisms can be different depending on the policy decisions associated with the Federal and non-Federal incumbents. The Commission needs to decide whether the protection will be provided through static exclusion zones or through dynamic coordination among the involved parties based on tolerable interference threshold. As indicated by the stakeholders and also acknowledged by the Commission, the static geographical exclusion zone proposed in the FNPRM will be reconsidered based on operational characteristics of small cells. The non-Federal incumbents that are enjoying Grandfather Status will receive same protection as the Federal incumbents. The number of non-Federal incumbent operation within any specific locality is small. So the SAS governing the CBRS for that locality could customize the protection mechanisms according to the requirements and operational characteristics of the system involved. This approach will allow the SAS to locally optimize the spectrum usage and at the same time provide required protection for the non-Federal incumbent operations. Although this protection for the non-Federal incumbent operation will be provided for a limited duration. Within this duration all these operations are expected to become accommodated with the CBRS framework.

The Incumbent protection module has to coordinate with the Priority Access and General Authorized Access Managers to ensure that the CBRS users are not violating the operational restrictions and maintaining desired interference environment. If the coordination zone approach is adopted, the Incumbent protection module is required to ensure desired interference environment for the incumbent operation. The Incumbent Protection module can use the interference environment information from the Interference Monitor modules of the Priority Access and General Authorized Access Manager and desired interference environment information from the IA Database Access module. To facilitate this task, this module must have the capability to access information about the incumbent's interference environment such as the interference tolerance capability of the incumbent. It should also have the capability of informing the Interference Management module of the Priority Access and General Authorized Access managers if the incumbent suffers from any unwanted interference. If any interference event is identified, the IA Database Access module can gather information about the spectral and geographical location of the source and acceptable "time to vacate" parameter.

The major responsibilities of the Incumbent Protection module include (Figure 10):

1. Coordinating with the Policy and Regulation module to determine the protection approach (exclusion zone or coordination zone)
2. Access information about the operational restrictions of the CBRS users and desired interference environment of the incumbent user
3. Get incumbent satisfaction report on existing interference environment
4. Identify unwanted interference event
5. Report and request necessary actions to restore desired interference environment

Table 14: Incumbent Protection: Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Determine incumbent protection approach**	• Coordinate with the Policy and Regulations module • Determine protection approaches for Federal and non-Federal incumbents • Get information on pre-agreed interference environment	• Incumbent protection approach (exclusion zone or coordination) • Pre-agreed interference environment • Area of operation with interference threshold	• Policy and Regulations module	• Fast, reliable and secure communication • Information update procedure
• **Access information on interference based protection** • **Identify unwanted interference events**	• Access the incumbent protection requirements	• Interference tolerance capability • "Time to vacate" parameters • Location, transmit power, antenna parameters	• IA Database Access module	• Fast, reliable and secure communication • Information update procedure • Determination of unwanted interference events
	• Access information on the interference environment of the CBRS	• Location, operational area, transmit power, antenna parameters	• Interference Management module (PA and GAA Manager)	
	• Access information on incumbent satisfaction report	• Unexpected interference environment	• IA Database Access module	

	• Access contextual information	• Propagation model • Terrain profile • Technology/standard used by the involved parties (LTE, Wi-Fi, etc.)	• SAS Database	
• **Report and request action to restore desired interference environment**	• Identify source/location of the interference event • Report to the Interference Management modules of the PA and GAA Manager	• Unexpected interference environment	• IA Database Access module	• Interference source identification procedure • Enforcement procedures
		• PA and GAA usage report	• Usage Monitor module (PA and GAA Manager)	

Spectrum Opportunity Detection

The responsibility and required technical capabilities of the Spectrum Opportunity Detection module depends on the incumbent usage information accessible by the IA Database Access module. The available spectrum opportunities can be identified in two different ways. First, the incumbent may provide some modified version of its spectrum usage that can be used to identify spectrum opportunities. Second, the incumbent only provides its operational parameters based on which the SAS tries to identify the opportunities. If the SAS is provided with incumbent's operational parameters, there are three main approaches for identifying spectrum opportunities. These are: i) Spectrum sensing approach, ii) Geolocation database approach, and iii) Hybrid database-plus-sensing approach.

The Spectrum Opportunity Detection module needs to be aware of the extent of incumbent's cooperation. In accordance with the cooperation agreement, the opportunity detection module can receive related information through the IA Database Access module. If the incumbent agrees to provide information about its spectrum usage and available spectrum opportunities, then the role of the Spectrum Opportunity Detection module becomes insignificant. But the incumbent may not be willing to provide direct information about its spectrum usage to avoid unwanted exposure of sensitive operational information. So the SAS must have some mechanism and capability to impose additional layer of abstraction such that the likelihood of unwanted exposure is minimized. On the other hand, if the incumbent only agrees to provide its operational information such as geolocation, antenna parameters, power levels, desired protection contours, etc., then the SAS must have the technical capabilities to identify spectrum opportunities based on this information. In this case spectrum sensing, geolocation database, or a hybrid approach of database-plus-sensing can be used.

Table 15: Spectrum Opportunity Detection: Functionalities and Challenges

<table>
<tr><th rowspan="2">Functionalities</th><th rowspan="2">Task list</th><th colspan="2">Required Information</th><th rowspan="2">Technical Requirements</th></tr>
<tr><th>Information Set</th><th>Source</th></tr>
<tr><td rowspan="2">• Check the extent of incumbent cooperation
• Decide on the opportunity detection mechanism</td><td rowspan="2">• Access cooperation agreement information
• Determine the nature of information to be accessed
• Determine the detection procedure</td><td>• Accessible incumbent information</td><td>• IA Database Access module</td><td rowspan="2">• Fast, reliable and secure communication
• Determining the best detection option for a particular scenario</td></tr>
<tr><td>• Available detection capabilities</td><td>• SAS Database</td></tr>
<tr><td rowspan="2">• Detection using incumbent's usage information</td><td rowspan="2">• Access incumbent's usage information
• Apply abstraction mechanism
• Forward the opportunity information to Spectrum for PA and GAA modules
• Update opportunity information</td><td>• Opportunity location on the time-frequency grid
• Duration of availability
• Interference tolerance capability of the incumbent</td><td>• IA Database Access module</td><td rowspan="2">• Determining required form of incumbent usage information
• Information abstraction mechanism
• Opportunity information update mechanism</td></tr>
<tr><td>• Available abstraction mechanisms</td><td>• SAS database</td></tr>
</table>

<table>
<tr>
<td rowspan="3">Detection using incumbent’s operational parameters</td>
<td rowspan="3">Access incumbent’s operational parameters
Determine suitable detection approach
Employ spectrum opportunity detection technique
Continuously monitor spectrum to identify return of incumbent</td>
<td>Incumbent information for Geolocation database approach:
Transmitter identity and geolocation
Protection contour
Transmission power
Antenna parameters
Interference tolerance capability</td>
<td>IA Database Access module</td>
<td rowspan="3">Opportunity detection through geolocation database
Opportunity detection through spectrum sensing
Opportunity information update mechanism
Continuous monitoring to detect incumbent return</td>
</tr>
<tr>
<td>Spectrum sensing approach
Sensing node location
Sensing node reputation
Fusion center location
Sensing technique</td>
<td>SAS Database</td>
</tr>
<tr>
<td>Terrain profile
Propagation model
Operational restrictions for the CBRS users</td>
<td>SAS Database</td>
</tr>
</table>

The Spectrum Opportunity Detection module can access the operational parameters of the CBRS users from the Policy and Regulations module and use this information along with the available spectrum information to identify specific spectrum opportunities for the PA and GAA users. The major responsibilities of the Spectrum Opportunity Detection module include:

1. Coordinating with the Policy and Regulation module to determine the extent of incumbent cooperation
2. Decide the mechanism for opportunity detection
3. For opportunity detection using incumbent’s usage information
4. Access incumbent usage information
5. Determine the form of information required
6. Apply abstraction mechanisms to minimize the likelihood of information exposure
7. For opportunity detection through incumbent’s operational information

8. Access incumbent's operational parameters
9. Decide the detection approach
10. Apply the detection procedure and identify spectrum opportunities
11. Update the spectrum opportunity information
12. Periodic update about the status of the spectrum opportunities
13. Update through incumbent's interruption

Authorization Center

The Authorization Center module proposed in the SAS architecture facilitates SAS's control over the CBRS operation. As mentioned earlier, we agree with the cellular communication industry that the PA user's access points (PA-AP) should register with the SAS rather each of the end devices. This will provide the SAS a central point of monitoring and communication to facilitate desired PA tier operations. We also support the proposed authorization rules for the GAA devices. Information provided by the CBSDs for authorization purpose allows the SAS to monitor the CBSD operations and ensure that they are abiding the interference protection requirements of the incumbent users of the spectrum sharing system.

In order to get authorization from the SAS, CBSDs are required to provide operational and technical parameters such as requested authorization status, CBSD location, operational area, antenna parameters, etc. This set of information allows the SAS to monitor the CBSD operations and ensure that they are abiding the interference protection requirements of the incumbents. The Authorization module should have the capabilities of receiving information from the CBRS users, performing the authorization procedure, and informing the applicants about their authorization status. The Authorization Center also need to access auction results from the Auction Center and use that information in the authorization process. In order to possess the most updated auction results, the Authorization Center needs to periodically coordinate with the Auction center to access the auction decisions.

The major responsibilities of the Authorization Center module include:

1. Receive operational information of the Citizen Broadband Radio Service (CBRS) users required by the authorization rules
2. Receive auction results from the Auction Center module
3. Perform the authorization procedure
4. Inform the applicants about their authorization status

Priority Access Manager

The PA Manager is responsible for the operations of the PA tier in the shared spectrum. To facilitate the desired coexistence of the PA users, the primary responsibility of the PA Manager is to ensure that the PA users satisfy the operational restrictions outlined in the proposed CBRS. It must be able to monitor the operations of the PA users and based on that employ interference management mechanisms to ensure desired interference environment. The PA manager also has the responsibility to ensure the available spectrum opportunities for the PA tier and perform efficient and dynamic assignment of these opportunities. The sub-modules of the PA Manager shown in Figure 10 include the Spectrum for PALs, Dynamic Frequency Assignment, PAL Usage Monitor, and Interference Management.

Table 16: Authorization Center: Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Perform the authorization procedure**	• Receive operational information of the CBRS users required by authorization rules • Receive auction results from the Auction Center module • Review and decide the status of the applications • Inform applicants of their authorization status	• Requested authorization status • CBSD location • Area of operation • Antenna parameters • FCC identification information • Contact information	• CBRS users	• Fast, reliable and secure communication • Secure and efficient authorization procedure
		• Result of the auction procedure • PAL aggregation information	• Auction Center	

The major responsibilities of the Spectrum for PALs module include:

1. Ensure available spectrum opportunities for the PA tier users
2. Efficient and dynamic assignment of the spectrum opportunities among the PA users
3. Monitoring the PA tier operations to ensure that the users satisfy the operational restrictions

4. Ensure a desirable interference environment using available interference management mechanisms

Spectrum for PALs

The Spectrum for PALs module is responsible for ensuring the available spectrum opportunities for the PA tier users. The module needs to coordinate with the IA and GAA Manager modules to obtain the spectrum availability information. The PA spectrum availability module requires information about the number of available PAL channels, number of active PAL channels, spectrum allocations for GAA and CA users, and PAL channels used by the GAA users. Based on this information, the PA spectrum availability module prepares a list of PAL channels available for future assignment and also informs the GAA manager if it wants claim back any PAL channels that has been assigned to GAA users.

Table 17: Spectrum for PALs: Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Ensure available spectrum opportunities for the PA users**	• Check available spectrum opportunities • Check allocations for the GAA tier • Check allocation for the CA users • Determine available spectrum opportunities for PA tier • Check auction results for the PA users • Check the PAL aggregation information	• Available spectrum opportuniti es	• Opportunit y detection module (IA manager)	• Fast, reliable and secure communication • Determination of PAL units based on • available spectrum opportunities • allocation proposal • Update frequency and mechanism based on • Geolocation report • Interference report
		• Allocation for GAA tier • Allocation for CA users	• Spectrum for GAA tier module	
		• List of PALs to be claimed back	• Dynamic frequency assignment (PA tier) module	

	• Determine available PAL units based on auction results • Receive the geolocation and interference report • Update available PAL list based on geolocation and interference report • Claim back PALs used by GAA tier based on PA demand	• PAL assignment information • Aggregation information	• Auction Center	• Spectrum availability • PAL claim back procedure
		• Geolocation information of PA users • Interference environment of PA users	• PAL usage monitor	

Dynamic Frequency Assignment (PA Manager)

The Dynamic Frequency Assignment module of the PA Manager is responsible for efficient and dynamic assignment of the available spectrum opportunities to the PA users. Dynamic and efficient assignment of PALs is one of the most important and challenging technical capability that the SAS must have to facilitate the proposed dynamic spectrum management approach.

Table 18: Dynamic Frequency Assignment (PA): Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Dynamic and efficient assignment of the spectrum opportunities**	• Check the available spectrum opportunity for PA tier • Receive spectrum demand from PA-APs • Coordinate with the Non-Federal Incumbent Protection module	• Available opportunity for PA tier • Available PAL channels • Operational area • Updated spectrum availability based on geolocation and interference report	• Spectrum for PA tier module	• Fast, reliable and secure communicatio n • Efficient and dynamic resource allocation algorithms • Fast resource reassignment mechanism based on incumbent

	• Efficient resource allocation based on • PAL assignment and aggregation information • CBSD geolocation and interference reports • CBSD operational parameters • Protection criteria and desired interference environment of the Federal and non-Federal incumbents • Prioritizing contiguous allocation if possible • Generating temporary list of available PALs for future allocation	• Spectrum demand from PA users	• PA-APs	satisfaction reports
		• Use status of the assigned PALs • Geolocation report • Interference reports • Usage information	• PAL usage monitor module	
		• Desired interference environment • Agreed protection criterion	• Federal Incumbent s	
		• Desired interference environment • Agreed protection criterion	• Non-Federal Incumbent s	

The Dynamic Frequency Assignment module should coordinate with the Spectrum for PALs module to get information about the available spectrum opportunities for the PA tier users. The module should be able to receive the spectrum demands from the PA tier access points (PA-APs) and the usage reports of the PA users including geolocation and interference report from the PAL Usage Monitor module. Based on this information the module should be able to dynamically assign spectrum opportunities to maximize spectrum usage. While performing the frequency assignment procedure, the module should take a best effort approach towards contiguous spectrum assignment. The Dynamic Frequency Assignment module should also coordinate with the incumbent operations to react according to their interference environment satisfaction report. The module may also generate list of probable spectrum opportunities (PALs) for future assignment procedures.

PAL Usage Monitor

The PAL Usage Monitor module helps the Interference Management module of the PA Manager to ensure the desired interference environment. The module monitors the PA user operation and collects information about its operational parameters. The PAL Usage Monitor module gathers information to facilitate two important aspects of the PA operations: determining the usage status of the PAL channels and ensuring desired protection to the incumbent. The usage monitor receives the geolocation and interference reports from the PA tier users and uses this information to determine the location and interference environment of the PA users. It monitors the PA operational parameters, such as power levels, out-of-band emissions, etc., to ensure that they are within the allowed limits. The module also collects information about the "use" status of the PALs from the PA-APs.

Interference Management (PA Manager)

The Interference Management module of the PA Manager is responsible for managing the PA user operations to ensure the desired interference environment among the CBRS users and between the PA tier users and the incumbent operations. The Interference Management module of the PA Manager ensures that the GAA users satisfy the priority status of the PA tier. It also coordinates neighboring PA operations such that the interference environment along the census tract boundary is comfortable.

Table 19: PAL Usage Monitor: Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Identification of violation of assignment condition** • **Identification of violation of operational restrictions**	• Monitor that the PAL user activity satisfies assignment conditions • Receive the geolocation information of the PAL users • Monitor that the PA users	• Geolocation information with required vertical and horizontal accuracy • Interference environment	• PAL users • PA-APs	• Fast, reliable and secure communication • Determination of the assigned PALs • Determination of the active PALs
		• Operational restrictions	• Policy and Regulations module	

	are satisfying the operational restrictions	• Assignment conditions	• Authorization Center	• Identify any violation of the assignment conditions • Identify any violation of the operational restrictions • Identify any violation of agreed interference environment
• **Identification of unwanted interference event** • **Report unwanted events to the Interference Management module**	• Receive the interference environment of the PAL operational area • Coordinate with the Incumbent Protection module • Report interference events to the Interference Management module of the PA Manager	• Desired interference environment • Agreed protection criterion	• Policy and Regulations • Incumbent Manager	
		• CBSD interference reports	• PAL users	
		• Incumbent satisfaction report	• Incumbent Manager	
• **Identification of the "Use" Status of the PALs**	• Identify the PAL channels that are in active use • Generate list of unused PAL for opportunistic GAA use	• List of Assigned PALs	• Dynamic frequency assignment (PA tier) module	
		• List of PALs used by GAA tier	• Spectrum for GAA tier module	
		• PAL availability information	• Spectrum for PA users	

The Interference Management module coordinates with the PA access points and helps them to adjust their operational parameters to maintain a desired interference environment. The module also reports any unwanted GAA interference issue to the GAA Manager so that the PA users may enjoy their priority status. The Interference Management module ensures that the PA tier users are abiding by all the proposed radio requirements such as transmission power and OOBE limits and maintains a comfortable interference environment among the neighboring PA users. This module also coordinates with the Incumbent Protection module to ensure desired interference environment for the incumbent operations. The Incumbent protection module may report any unwanted interference event to the Interference Management module of the PA Manager and request necessary actions to address the issue.

General Authorized Access Manager

The GAA operation is at the center of the proposed dynamic spectrum sharing and management approach. The GAA Manager must make all information necessary to effectively coordinate operations between and among CBSDs available to other SAS Administrators. The responsibilities and sub-modules of the GAA Manager are somewhat similar to those of the PA Manager. In addition to the tasks described for the PA Manager module, the GAA Manager has to ensure the spectrum pool for the GAA users, spectrum allocation for the CA users, and interference protection to higher tiers of the framework. The GAA Manager is responsible for the operations of the GAA users in the shared spectrum. To facilitate the desired coexistence of the GAA users, the primary responsibility of the GAA Manager is to ensure that the GAA users satisfy the operational restrictions outlined in the proposed CBRS. It must be able to monitor the operations of the GAA users and based on that employ interference management mechanisms to ensure desired interference environment. Upon request from the Commission, the GAA Manager must confirm that CBSDs in a given geographic area and frequency band have been shut down or moved to another available frequency range in response to information received from the ESC. The GAA manager also has the responsibility to ensure the available spectrum opportunities for the GAA users and perform efficient and dynamic assignment of these opportunities.

Table 20: Interference Management (PA Manager): Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Interference management of the CBRS users**	• Receive usage information from the spectrum usage monitor • Monitor the interference environment • Identify CBRS users causing undesired interference	• Usage information • Interference environment of PA users	• PAL usage monitor	• Fast, reliable and secure communicatio n • Identification of the source of interference • Interference mitigation and
		• Agreed interference environment • Operational restrictions	• Policy and Regulations • Authorizati on Center	

	• Take actions to restore desired interference environment			management mechanisms
• **Facilitate protection of the incumbent operations**	• Coordinate with the Incumbent Protection module • Coordinate with the Usage Monitor modules of the PA and GAA users • Take necessary actions to restore desirable interference environment	• Unwanted interference environment for the Incumbent operation	• Incumbent Protection module	
		• Desired interference environment • Agreed protection criterion	• Policy and Regulations • IA Database Access	
		• CBRS interference environment	• Usage Monitor modules (PA Manager)	

The sub-modules of the GAA Manager shown in Figure 10 include the Spectrum for GAA, Dynamic Frequency Assignment, GAA Usage Monitor, and Interference Management. The major responsibilities of the Spectrum for PALs module include:

1. Ensure available spectrum opportunities for the GAA users
2. Efficient and dynamic assignment of the spectrum opportunities among the GAA users
3. Monitoring the GAA tier operations to ensure that the users satisfy the operational restrictions
4. Ensure a desirable interference environment using available interference management mechanisms

Spectrum for GAA/CA Users

The capabilities of the GAA spectrum availability module include ensuring the GAA spectrum pool, accounting for the reserved CA spectrum, and ensuring availability of the unused PAL channels. This module needs to coordinate with the Spectrum Opportunity Detection module to receive information about the available spectrum opportunities and the PA Manager to receive information about assigned PALS. Based on this information the Spectrum for GAA module determines the available spectrum opportunities for the GAA users. In addition to that the module needs to coordinate with the Usage Monitor module of the PA manager to identify unused PALs to ensure their availability as GAA spectrum. This module also needs to have the capability to frequently update the spectrum availability information to facilitate desired coexistence among different tiers of the CBRS.

Table 21: Spectrum for GAA: Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Ensure available spectrum opportunities for the GAA users**	• Check available spectrum opportunities • Check allocations for the PA tier • Check allocations for the CA users • Determine allocation for the GAA users • Get the list of unused PALs for GAA assignment • Determine available spectrum opportunities for GAA tier	• Spectrum allocation for CA users	• Spectrum for CA module	• Fast, reliable and secure communication • Determination of GAA spectrum • Update frequency and mechanism based on • Geolocation report • Interference report • Spectrum availability • Determination of the spectrum reserved for the CA users
		• Spectrum allocation for PA tier	• Spectrum for PALs module	
		• List of unused PALs	• PAL usage monitor module	
• **Update available opportunity information**	• Receive the geolocation and interference report • Receive PAL claim back requests from PA Manager • Update available spectrum opportunity for the GAA users	• Geolocation information of GAA users • Interference environment of GAA users	• GAA usage monitor	
		• PAL claim back requests	• Spectrum for PALs module	

• **Ensure the spectrum reservation for the CA users**	• Check available spectrum opportunities • Check allocations for the GAA tier • Check allocation for the CA users	• Available spectrum opportunities	• Opportunity detection module (IA manager)	
		• Spectrum allocation for GAA tier	• Spectrum for GAA tier module	

Dynamic Frequency Management (GAA Manager)

The Dynamic Frequency Assignment module of the GAA Manager is responsible for efficient and dynamic assignment of the available spectrum opportunities to the GAA users. The functionalities of this module differ from that of the PA Manager because the allocation proposal does not specify any fixed channel size for the GAA users. This module receives the spectrum demands from the GAA users with associated QoS requirements and dynamically schedules the available opportunities based on the interference environment in the GAA area of operations. The Dynamic Frequency Assignment module of the GAA Manager must have the capabilities of receiving the spectrum demands from the GAA users with associated QoS requirements, dynamic opportunity scheduling, and reassigning allocations as needed. This module also needs to coordinate with the Spectrum for GAA module to receive updated information for the available GAA spectrum in the GAA spectrum pool. The GAA spectrum pool consists of the remaining spectrum chunk after assigning the IA tier requirement, assigning 70 MHz of spectrum to the PA tier, and also the PA spectrum opportunities that are not currently in “use” by the PA tier users. Also the spectrum opportunity assignment can be from anywhere in the 3.5 GHz band. There is no fixed channel size for GAA use and the Dynamic Spectrum Assignment module is required to have the capability of efficient resource allocation to maximize the spectrum efficiency and satisfying the QoS demands of the GAA users.

Table 22: Dynamic Spectrum Assignment (GAA Tier): Functionalities and Technical Challenges

Functionalities	Task list	Required Information: Information Set	Required Information: Source	Technical Requirements
• **Dynamic and efficient assignment of available GAA spectrum**	• Check available spectrum for GAA tier • Receive spectrum demand from GAA users • Coordinate with the Incumbent Protection module • Efficient resource allocation • Available GAA spectrum • CBSD geolocation and interference reports • CBSD operational parameters • Protection criteria and desired interference environment of the incumbents • Generating temporary list of available GAA spectrum for future allocation	• Available opportunity for GAA tier • Operational area • Updated spectrum availability based on geolocation and interference report	• Spectrum for GAA module	• Fast, reliable and secure communication • Efficient and dynamic resource allocation algorithms • Account for no fixed channel size for GAA users • Fast resource reassignment mechanism based on incumbent satisfaction reports
		• Spectrum demand from GAA users	• GAA users	
		• Geolocation report • Interference reports • Usage information	• GAA usage monitor	
		• Desired interference environment • Agreed protection criterion	• Federal/Non-Federal Incumbents • Incumbent protection module	

GAA Usage Monitor

The responsibilities of the GAA Usage Monitor are more challenging as the module has to monitor operations of each of the GAA devices. The GAA Usage Monitor module makes use of the GAA locator to observe whether the GAA devices are conforming to the allowed operational parameters. The GAA location sub-module should be able to receive the geolocation reports and ensure that the GAA devices are operating within the authorized area. This module also monitors the interference report from the GAA devices and facilitates the operation of the Interference Management module of the GAA Manager.

Table 23: GAA Usage Monitor: Functionalities and Technical Challenges

<table>
<tr><th rowspan="2">Functionalities</th><th rowspan="2">Task list</th><th colspan="2">Required Information</th><th rowspan="2">Technical Requirements</th></tr>
<tr><th>Information Set</th><th>Source</th></tr>
<tr><td rowspan="3">• Identification of violation of assignment condition
• Identification of violation of operational restrictions</td><td rowspan="3">• Monitor that the GAA user activity satisfies assignment conditions
• Receive the geolocation information of the GAA users
• Monitor that the GAA users are satisfying the operational restrictions</td><td>• Geolocation information with required vertical and horizontal accuracy
• Interference environment</td><td>• GAA users</td><td rowspan="6">• Fast, reliable and secure communication
• Identify any violation of the assignment conditions
• Identify any violation of the operational restrictions
• Identify any violation of agreed interference environment</td></tr>
<tr><td>• Operational restrictions</td><td>• Policy and Regulations module</td></tr>
<tr><td>• Assignment conditions</td><td>• Authorization Center</td></tr>
<tr><td rowspan="3">• Identification of unwanted interference event
• Report unwanted events to the Interference Management module</td><td rowspan="3">• Receive the geolocation information of the GAA users
• Receive the interference environment of the GAA operational area
• Coordinate with the Incumbent Protection module
• Report interference to the Interference Management module of the GAA Manager</td><td>• Desired interference environment
• Agreed protection criterion</td><td>• Policy and Regulations
• Incumbent Protection module</td></tr>
<tr><td>• CBSD interference reports</td><td>• GAA users</td></tr>
<tr><td>• Incumbent satisfaction reports</td><td>• Incumbent Manager</td></tr>
</table>

Interference Management (GAA Manager)

The Interference Management module of the GAA Manager facilitates acceptable interference environment such that the GAA devices do not cause any harmful interference to the higher tier users. To facilitate the desired coexistence of the GAA users, the primary responsibility of the Interference Management (GAA Manager) module is to ensure that the GAA users satisfy the operational restrictions outlined in the proposed CBRS. It must be able to monitor the operations of the GAA users and based on that employ interference management mechanisms to ensure desired interference environment. This module makes use of the observations of the GAA Usage Monitor module and ensures that the GAA devices do not cause harmful interference to the IA or PA tier users. This module should have the capabilities of coordinating with the GAA Usage Monitor module and identifying the source of GAA interference based on the interference reports. If any unwanted interference event is identified, the Interference Manager module advices the GAA device to adjust its operating parameters or informs the enforcement entity to ensure desired interference environment. Upon request from the Commission, the Interference Management (GAA Manager) module must ensure that CBSDs in a given geographic area and frequency band have been shut down or moved to another available frequency range in response to information received from the ESC.

Table 24: Interference Management (GAA Tier): Functionalities and Technical Challenges

Functionalities	Task list	Required Information		Technical Requirements
		Information Set	Source	
• **Interference management of the CBRS users**	• Receive usage information from the spectrum usage monitor • Monitor the CBRS interference environment • Identify CBRS users causing undesired interference • Report unwanted interference events to the enforcing entity	• Usage information • Interference environment of GAA users	• GAA usage monitor	• Fast, reliable and secure communication • Identification of unwanted interference events • Identification of the source of interference • Interference mitigation and management mechanisms
		• Agreed interference environment • Operational restrictions	• Policy and Regulations • Authorization Center	

• **Facilitate protection of the incumbent operations**	• Coordinate with the Incumbent Protection module • Coordinate with the Usage Monitor modules of the PA and GAA users • Take necessary actions to restore desirable interference environment	• Unwanted interference environment for the Incumbent operation	• Incumbent Protection module	
		• Desired interference environment • Agreed protection criterion	• Policy and Regulations • IA Database Access	
		• CBRS interference environment	• GAA Usage Monitor	

SAS Engine, Policy and Regulations, Auction Center

The SAS Engine works as the central controller for the proposed SAS modules and facilitates orderly coordination among these modules to carry out their functionalities. Most of the SAS modules depend on other modules to receive required information in order to carry out their functionalities. The Policy and Regulations module coordinate with the regulatory authority to provide the updated policy decisions and regulations in order to ensure desired CBRS operations. This module stores information about the CBSD's general and radio requirements, nature and terms of interference environment agreements, nature and extent of corrective measures to restore desired interference environment, authorization requirements, etc. The Auction Center module facilitates the assignment of PA licenses (PALs) through competitive bidding. This module will also decide on possible PAL aggregation by the successful bidders. The Auction Center receives the applications from the interested PAL users. The PAL applicants include all the required information in the application including authorization information, operational area, bidding information, requested spectrum information, aggregation information, etc. The Auction Center coordinates with the Policy and Regulations module and the Authorization Center module to cross-check the information provided by the PAL applicants. Then the module performs the auction procedure among the valid applications and informs the PA and GA Managers and the applications about the auction results.

SAS Database

The SAS Database serves as the information repository of the proposed dynamic SAS. The SAS database gathers all the information required by the above mentioned modules to perform the SAS functionalities. SAS determines and assign available spectrum opportunities to the CBSDs at their location along with the maximum permissible transmission power required to protect federal Incumbent Users from harmful interference. SAS database must also help in register and authenticate the CBSDs. It must have information to ensure protection zones with the help of the Environmental Sensing Capability (ESC) system in order to protect both Federal and non-federal Incumbent Users from harmful interference. The SAS database also helps to resolve conflicting uses of the band while maintaining a stable radio frequency environment. The set of information presented here serves as an initial framework for the SAS database. The SAS database gathers information on CBSD's operational parameters, interference environments, and spectrum usage and availability information for each of the CBRS tiers. Table 25 presents the information sets in the SAS Database to facilitate the above mentioned functionalities of the dynamic SAS.

Table 25: SAS Database Information Set

Type of Information	Information Set
CBSD Authorization Information	• Requested authorization status • CBSD location • Area of operation • Antenna parameters • FCC identification information • Contact information

Policy and Regulations Information	• CBSD operational restrictions
	• Interference environment agreement guideline
	• Interference protections guidelines for incumbent operations
	  ▪ Exclusion zone / Coordination zone
	  ▪ Grandfather status information
	  ▪ Allowed operational parameters
	• Corrective measures to address undesired interference environment
	• Authorization and auction procedures

Incumbent Database Access Information		• Incumbent-SAS cooperation agreement • List of accessible information on incumbent operation • List of sensitive information required for CBRS operation • List of required information to complement the Environmental Sensing Capability (ESC) system

Incumbent Privacy Information		• Incumbent privacy requirements
		• Allowed information for CBRS use
		• Privacy sensitive information handling
		  ▪ Obfuscation mechanisms
		  ▪ Requirements for sharing

Spectrum Opportunity Information	Assurance from the incumbent	• List of available spectrum opportunities • Duration of available spectrum opportunities • Probability of PU return over the opportunity duration • Channel quality of the available spectrum opportunities • Previous success rate of opportunistic use • Allowable transmission power

	Geolocation database approach	• Incumbent information
		  ▪ transmitter identity and geolocation
		  ▪ Protection contour
		  ▪ Transmission power
		  ▪ Antenna parameters
		  ▪ Interference tolerance capability
		• Terrain profile
		• Propagation model

	Incumbent detection through sensing	• Sensing node location
		• Sensing node reputation
		• Fusion center location
		• Fusion algorithms and performance expectation
		• ESC reporting policy on channel monitoring
		  ▪ Sensing data reporting
		  ▪ Sensing decision reporting
		  ▪ Collaborative fusion decision reporting

Spectrum Information for CBRS	PA Tier	• Available spectrum opportunity for PA tier • Number of PAL channels available • Number of active PAL channels
	GAA Tiers	• Spectrum allocation for CA users • Spectrum available for GAA users • PAL channels used by GAA users
Frequency Assignment Information		• Assigned PALs • Assigned GAA frequencies • Unused PA frequencies assigned for GAA use • Assigned frequencies to CA users • Available spectrum for future assignment

CBRS Interference Environment		• Interference environment among neighboring PALs
		• Interference from GAA to PALs
		• Interference environment
		  ▪ PALs near IA protection zones
		  ▪ GAA near IA protection zones
		  ▪ PALs near CAF

Incumbent Interference Environment	Interference environment of the incumbent	• Protection zones for the incumbent
		• Coordinated access agreements
		• CBRS frequency assignment near protection zones
		• Incumbent interference tolerant capability
		• Unwanted interference event
		  ▪ Geographic area of interference
		  ▪ Frequency of interference
		  ▪ Time to vacate for CBRS
		  ▪ Suggested radio parameters for CBRS

	CBRS usage information	• List of CBSDs near incumbent protection zone • Interference environment of PALs near the protection zone • Interference environment of the GAA near the protection zone

Summary of the Section

In this era of technology, spectrum plays a significant role to ensure the continued growth and innovation in every aspect of our life. It is an essential tool for connecting communities. Access to adequate spectrum has the power to maximize our collective potential. With global data traffic expected to go through an unprecedented increase, it is imperative that we find creative and flexible ways to maximize this valuable and finite resource, so that we may continue to unleash the possibilities of tomorrow. The Citizens Broadband Radio Service is a unique spectrum sharing regime that incentivizes the dynamism in the management and utilization of spectrum opportunities. This new service leverages innovative new sharing rules and technologies to create a 150 MHz band of contiguous spectrum to help meet the Nation's wireless broadband needs, including 100 MHz previously unavailable for commercial use. It establishes a three-tier framework for making the entirety of the 3.5 GHz band available for shared commercial use, while putting in place protections for the band's incumbents. With Spectrum Access Systems taking on the complicated and vital role of frequency coordination, the three tiers: Incumbent Access users, Priority Access Licensees and General Authorized Access users, will soon be able to cohabitate in the band and maximize spectrum efficiency. The rules adopted by the 3.5 GHz R&Os make the 3.5 GHz Band hospitable to a wide variety of users, deployment models, and business cases, including some solutions which are not adequately served by our conventional licensed or unlicensed rules. Carriers can avail themselves of "success-based" license acquisition, deploying small cells on a GAA basis where they need additional capacity and paying for the surety of license protection only in targeted locations where they find a demonstrable need for more interference protection. Real estate owners can deploy neutral host systems in high-traffic venues, allowing for cost-effective network sharing among multiple wireless providers and their customers. Manufacturers, utilities, and other large industries can construct private wireless broadband networks to automate processes that require some measure of interference protection and yet are not appropriately outsourced to a commercial cellular network. Smart grid, rural broadband, small cell backhaul, and other point-to-multipoint networks can potentially access three times more bandwidth than was available under the previous 3650-3700 MHz band rules. All of these applications could share common wireless technologies, providing economies of scale and facilitating intensive use of the spectrum.

The FCC proposed rules for the CBRS and stakeholder's feedback, and analysis of the functionalities of different SAS modules point us to a number of important technical issues. These technical challenges are required to be addressed to facilitate a dynamic SAS and hence successful operation of the proposed CBRS. In order to facilitate dynamic spectrum access and sharing, the SAS needs to be able to interact with incumbent database and CBRS users in a reliable manner. Dynamic spectrum sharing also calls for fast information exchange to ensure fast adaptability with the operating environment. The system also requires secure and efficient user authorization and spectrum opportunity assignment (auction) procedure. Another important technical issue is developing information abstraction mechanisms that provide necessary information privacy to the incumbent operations. The efficient and accurate detection of spectrum opportunity is another important technical challenge that is required to be addressed. Based on the extent of incumbent's cooperation and context of operation, the SAS should have different technical capability to detect spectrum opportunities. The efficiency of a spectrum sharing system is highly dependent on the performance of a dynamic spectrum opportunity allocation mechanism. The technical challenge in this regard involve development of efficient, fast, and dynamic allocation algorithms that takes into account all the different aspects of spectrum availability, duration of spectrum opportunity, interference environment, and information privacy of the incumbent operations. In order to provide the desired interference environment for all the involved parties, identification of any violation of the spectrum assignment conditions, operational restrictions, and agreed interference environment is very important. The SAS should have the technical capability to identify the violation and the source of the violation and should be able to take necessary corrective measures to restore desired operational environment. Finally, the information update procedure of the dynamic spectrum management approach poses another important technical challenge. Effective operation of the dynamic spectrum sharing system requires up-to-date information from the incumbent database, spectrum opportunity detectors, policy and regulations entity, and CBRS users to adapt to the changes of the environment.

Addressing all of the above mentioned technical challenges is important for successful implementation of the FCC's dynamic spectrum management approach. In response to the proposed rules for CBRS, the stakeholders raised three important questions. For the incumbent operations, important considerations include protection from interference due to CBRS operations and privacy of the sensitive operational information. From the PA tier user's perspective, the most important considerations are certainty of spectrum occupancy in the short and long run, suitable interference environment, and efficient resource allocation mechanisms. Dynamic and efficient resource allocation and maintaining agreed interference environment are the important considerations from the perspective of the GAA users. If we try to prioritize these technical challenges based on the comments of the stakeholders from different tiers of the CBRS, the most important challenges would be ensuring certainty of spectrum availability in dynamic spectrum opportunity allocation and maintaining desired interference environment. Ensuring desired level of information privacy is also one of the top priorities from the perspective of the incumbent operations.

In this chapter, we discussed the efforts towards a dynamic spectrum sharing system in the U.S. context and look forward to initiate a more focused analysis of the required SAS composition and functionalities to support the dynamic management of the 3.5 GHz band. We also analyzed the position of the Commission on different aspect of the CBRS through the 3.5 GHz R&O and the Second R&O in order to address this hesitation of the critics of the proposed 3-tier system. We presented a brief summary of a survey of the stakeholder's comments in response to the 3.5 GHz FNPRM. The stakeholders responded to different aspects of the FNPRM from their industry perspective. We looked at these responses from the perspective of a dynamic SAS capable of facilitating the dynamic spectrum management approach. Our analysis yielded a number of important issues which are required to be addressed for successful operation of the proposed CBRS. We identified the required functionalities, technical capabilities, and composition of the SAS to support the dynamic spectrum management approach envisioned in the CBRS. The successful implementation of the dynamic spectrum management approach will significantly improve the spectrum usage efficiency and influence the management approach of other spectrum bands. This calls for a coordinated effort from the government, industry, and academia to expedite the development of the dynamic SAS and move forward towards the dynamic spectrum management regime. We hope the discussion presented in this chapter will help the readers understand the policy and regulatory aspects of the spectrum sharing initiatives and will initiate further awareness and more informed discussions and research towards an efficient dynamic spectrum sharing system.

Chapter 3

Generation of Probabilistic Assurance for Spectrum Opportunities

Chapter 3: Generation of Probabilistic Assurances for Spectrum Opportunities

Introduction

Advances in wireless networks and technologies require easily accessible spectrum where wireless devices can establish stable data communication. Ever increasing bandwidth demand for wireless devices has motivated the regulatory bodies and research communities to explore innovative strategies and techniques that can offer improved radio spectrum utilization without adversely affecting existing incumbent users. Conventional spectrum management policies use static spectrum assignment to prevent interference. Due to spatial and temporal variation of spectrum utilization by the incumbent users, also known as Primary Users, static allocation of wireless bandwidth is observed to be spectrally inefficient. Therefore, dynamic sharing of wireless spectrum seems to be the panacea for higher spectral efficiency.

In order to overcome spectrum scarcity, dynamic spectrum access based spectrum sharing has come up as the most promising solution [132-134]. Dynamic spectrum access allows fast deployment of wireless technologies by reusing the under-utilized pre-allocated spectrum channels, all with minimal impact on existing primary users. Successful deployment of dynamic spectrum access based spectrum sharing requires secondary users to guarantee minimal interference to primary users. However, existing proposals take a reactive sense-and-avoid approach to impulsively reconfigure spectrum usage based solely on the latest observations [134-136]. This can result in frequent disruptions to operations of both primary and secondary users. Secondary users reconfigure spectrum usages only after detecting changes in spectrum availability following some action by a primary user. Devices monitor spectrum channels through individual or collaborative sensing [135, 137-141]. When detecting a change in spectrum utilization, e.g. a primary user appears, secondary users pause existing transmissions, relinquish the band and seek other opportunities to resume communications [142]. Reconfiguration is reactive in nature and is based solely on the latest observations. Such passive ‘‘sense and react’’ approach results in frequent disruptions to communications of both primary and secondary users. Specifically, periodic sensing and adaptation cannot guarantee interference free environment for primary user operations. As a result, primary users can experience short-term interference to transmissions before being detected by neighboring secondary users. Similarly, secondary users suffer from unexpected interruptions to communications, making it extremely difficult to satisfy application requirements. They have no expectations of future spectrum availability to help coordinate spectrum access or schedule transmissions.

Enabled with opportunistic spectrum sharing capability, cognitive radio [39, 143, 144] has emerged as a technology for dynamic spectrum access based spectrum sharing. A primary role of a cognitive radio is to detect primary user's unused spectrum and opportunistically allocate them among requesting secondary users based on availability over time and space. This, in turn, is conducive to increasing the spectral efficiency and the channel capacity. Cognitive radio technology has been proposed to promise maximal spectrum utilization, and it allows opportunistic users to access the spectrum that has been assigned away but not been fully used by the primary users [145-147]. Spectrum occupancy prediction provides cognitive radio secondary users with proactive ability to exploit spectrum opportunities. In order to avail the opportunistic access into the spectrum opportunities, the secondary users must have the cognitive ability, and the reconfigurability, to identify and exploit instantaneous availability of these opportunities. Spectrum prediction broadly targets channel availability, i.e., prediction of the channel status as idle or busy, and duty cycle, i.e., prediction of the average fraction of time the primary user is occupying the channel [148]. Channel monitoring is a very important activity that is used by the cognitive radio to understand the spectrum occupancy of primary user. A cognitive radio user develops a spectrum pool consisting of all the spectrum opportunities in a range of spectrum and chooses the optimum one for its future usage. Channel capacity can be increased by using proper spectrum sharing policy. Spectrum prediction in cognitive radio networks is a challenging problem that involves several sub topics such as channel status prediction, primary user activity prediction, radio environment prediction, and transmission rate prediction [149]. In cognitive radio networks, since secondary users are sensing and observing the spectrum all the time, they can learn the usage pattern of the spectrum and use such information to predict the future status of the spectrum.

An example of primary user operation with specific usage pattern is radar systems [150]. Radars could be a good candidate for the primary systems in spectrum sharing also due to the fact that they operate over a large amount of spectrum. For example, in the US over 1.7 GHz of spectrum from 225 MHz to 3.7 GHz involves radar and/or radionavigation infrastructure, and around 1.1 GHz of this 1.7 GHz is used by fixed land-based radars in non-military applications [151, 152]. Currently, there are some bands in which radars are protected from harmful interference by granting them exclusive rights to operate in a given area and frequency band, and other bands (e.g., at 5 GHz) in which radars share spectrum with unlicensed devices that can transmit only if they are so far from any radar that the radar is undetectable [153]. Both of these are 'White Space' approaches to primary-secondary sharing, where secondary wireless systems are allowed to operate in frequency bands and geographic regions that are found to be entirely unused by any primary system. In contrast, with the 'Gray Space' [154] sharing approach, a secondary device is allowed to transmit near a radar, but only when and with a transmit power that will not cause harmful interference. The maximum transmit power of secondary devices changes over time, based on the behavior of the primary system. In the context of spectrum sharing dynamic power control is used to allow systems under different administrative control to share spectrum in a primary-secondary arrangement [155]. Examples of these radars include applications in weather operating in 2.7-3.0 GHz, Air Traffic Control (ATC) in 2.7-2.9 GHz, and other surveillance in 0.42-0.45 GHz and 2.7-3.5 GHz [155]. With a rotating main beam, the radar antenna gain seen by the fixed secondary device varies, hence, there will be periods of time when the link loss (including antenna gains and path loss) between the device and the radar is high enough so that the device can transmit successfully, without causing harmful interference to the radar. This sharing can be either cooperative (through explicit coordination between the secondary device and the primary system) or coexistent (without coordination) [150].

Dynamic spectrum access schemes can help unlicensed users (secondary users) to access licensed channels without interference to primary users. To achieve this purpose, secondary users need to first sense the channels to detect which channels are not used by primary users, and then choose the available channels to access. In practice there are some problems when the number of channels is large. It becomes hard to choose which channels to sense and which channel to access. Because spectrum sensing costs time and energy, so it's not possible to sense too many channels every time. That's why channel usage prediction is introduced. With channel usage prediction, secondary users can reduce the cost of dynamic spectrum access by only sensing the channels with highest probability to be available. Another significant challenge lies in the fact that the wireless spectrum is nonstationary, which means its background probability model is varying. Therefore the prediction error is not avoidable. Also the dynamic spectrum access schemes have to deal with the fact that all spectrum opportunities are not generated equally. The diverse behavior of different primary users in various spectrum bands affects a cognitive radio's ability to exploit spectrum opportunities. In a heavily used spectrum environment, the availability of unutilized, uncluttered, and easily accessible white space spectrum is unlikely. In 'White Space' spectrum sharing, secondary users avoid interference with incumbents by utilizing portions of the spectrum that remain unoccupied for fairly significant periods of time. On the other hand, when cognitive radios opportunistically access the gray spaces, which may be intermittently occupied or occupied by low-power interferers, require a degree of interference tolerance. If the cognitive radio can learn how the other users are exploiting the spectrum, then it can make a more informed attempt to exploit the opportunity. For channels where the activity of the primary users is varying much over time, instantaneous sensing information might become obsolete in the near future, causing frequent service disruptions for secondary users since they have to refrain from transmissions and search for new available channels. Frequent channel switching causes delays and reduces throughput. In addition, interference is produced towards primary users. Therefore, the channel selection algorithm should take into account the cost or probability of such future change in channel availability when selecting a channel. The Opportunistic users may employ techniques that allow cognitive radios to familiarize themselves with an unknown spectrum environment, recognizing specific, moderately utilized spectrum bands that present an opportunity to be exploited using learning-enhanced dynamic spectrum access techniques. A cognitive radio should have the ability to learn from past experiences to improve future performance compared to the case where only instantaneous information is taken into account. This implies the need of prediction algorithms to predict the future from past observations. Predictive channel occupancy has the potential to enhance the efficiency of spectrum utilization.

Probabilistic Assurance for Spectrum Opportunity Availability and Duration

In this chapter we discuss the impact of cooperation between the incumbent user and the opportunistic secondary user on the nature of cooperation. The discussion leads us to identify the desired forms and level of cooperation according to the use cases and applications. We also present the generation of these cooperation metrics using different level of primary-secondary cooperation. In this submission, we address the generation of the Spectrum Opportunity Duration Assurance (SODA) metric; the probabilistic assurance about the availability and duration of spectrum opportunities using primary-secondary cooperation. To realize opportunistic spectrum access, spectrum monitoring techniques (such as spectrum sensing) are applied to identify the presence of spectrum opportunities. The secondary users, limited by their available resources and technical abilities, sequentially sense the channels until a spectrum opportunity is detected. The sequential monitoring results in significant consumption of energy, time and spectrum resources for opportunity identification. This motivates the idea for an intelligent predictive method so that secondary users can learn from the past channel utilization. The past channel utilization information can be useful for the secondary user operations in two ways: i) predicting the likelihood of availability to reduce the number of sensing events and thus reduce the amount of resources (time and spectrum) consumed in spectrum monitoring and ii) predicting the probability of an spectrum opportunity being available for certain duration and thus improve resource allocation and interference avoidance mechanisms. The spectrum opportunity duration significantly influences the quality of service (QoS) predictability of a shared spectrum [156]. By statistically representing the availability the reporting load can be significantly reduced. It also allows improved accuracy if spectrum usage data reporting is delayed due to network latency or is otherwise unavailable. In the existing approaches, the secondary user or a dedicated sensor network (Environmental Sensing Capability, ESC, proposed in the 3.5 GHz Second FNPRM [28]) is responsible for predicting the availability and duration of spectrum opportunities. The majority of the solutions proposed in the literature for modeling the availability and duration of spectrum opportunities involve Hidden Markov Model approaches. The problem with the Hidden Markov Model approach is that the state transition depends only on the current state but does not consider the dwell time of the current state. In order to predict the opportunity duration, we need to consider the time for which the primary user stays in a particular state. To address this issue and predict the dwell time distribution of the states, prediction algorithms using Non-Stationary Hidden Markov Model have been proposed recently in the literature in the context of spectrum sharing. As expected the Non-Stationary Hidden Markov Model approaches offer better prediction accuracy compared to the Hidden Markov Model approaches. But the primary criticism of the Non-Stationary Hidden Markov Model approaches is the significant increase in computational complexities. The computational complexity involved in Non-Stationary Hidden Markov Model approaches makes them infeasible to efficiently predict the availability and duration of spectrum opportunities in real time use cases.

We propose to introduce primary user cooperation into the prediction algorithms in order to observe the impact of primary-secondary cooperation on the prediction accuracy and computational complexity of the prediction algorithms. The additional information available through primary-secondary cooperation would include the operational parameters of the primary user system, reference mean and variance of observations (database approach), maximum state duration, model parameter initialization, identification of the Similar Activity Phases, tentative plan of future usage, etc. The Incumbent SAS, having access to this information and previous observations, performs the Non-Stationary Hidden Markov Model approach to re-estimate the model parameters and forward it to the Secondary SAS. The Secondary SAS uses the re-estimated model parameters to run the prediction algorithm in real time using the current channel monitoring results received from the ESC and/or the secondary users. The Spectrum Opportunity Duration Assurance (SODA) values determined for each of the shared channels helps the spectrum sharing systems to achieve the availability and duration information about spectrum opportunities. Thus the secondary user resource management system and/or the SAS become enabled to perform intelligent dynamic spectrum access to improve the spectrum sharing experience of both the primary and secondary users.

Related Work

Spectrum prediction in cognitive radio networks is a challenging problem that involves several sub-topics such as channel status prediction, primary user activity prediction, radio environment prediction, and transmission rate prediction [149, 157, 158]. Majority of the spectrum occupancy models presented in literature are focused on occupancy patterns of the primary user. Spectrum prediction broadly targets channel availability, i.e., prediction of the channel status as idle or busy, and duty cycle, i.e., prediction of the average fraction of time the primary user is occupying the channel [148]. In cognitive radio networks, since secondary users are sensing and observing the spectrum all the time, they can learn the usage pattern of the spectrum and use such information to predict the future status of the spectrum. Various sensing techniques, including energy detection [159-161], matched filter detection [162-164] and cyclostationary detection [160, 161, 165], etc., have been proposed for local spectrum sensing at a single cognitive radio user. Performances of these technologies are influenced by the quality of received signals which may be severely degraded due to multipath fading and shadowing. In [149], autoregressive moving average model (ARMA) is employed to predict the power of television (TV) signals in time domain. Auto Regressive models have been widely used to predict channel state transitions over fading channels [166, 167]. In [168], channel occupancy status is converted into binary form and autoregression model is used for predicting the binary channel status. The paper used artificially generated Global System for Mobile (GSM) signals for testing the performance of the prediction scheme. In [169], an autoregressive channel prediction model was proposed for cognitive radio systems to estimate spectrum opportunities. The model adopts a second-order autoregressive process and a Kalman filter. The parameters of the auto-regressive model are computed using the Yule-walker algorithm [167]. When these parameters were gained, the state of spectrum opportunity can be predicted via a Kalman filter. A Bayes risk criterion for spectrum opportunity detection was also proposed by considering interference temperature and channel idle probability. Using theoretical analysis and simulations, the authors claimed that cognitive radio systems based on this scheme can greatly reduce the number of collisions between incumbent and opportunistic users.

Conventional spectrum sensing schemes typically assume that cognitive radio users perform spectral band usage monitoring independently from block to block. Most cognitive devices might not be able to sense all the targeted channels concurrently. If secondary users need to sequentially sense through all the channels before a decision is made, significant amount of the scarce spectrum resources can be wasted in performing spectrum sensing. In [170], the authors extensively discussed this matter and have proven that the throughput increases with having a prediction on primary users' activity. The authors in [171] proposed a novel sequence spectrum sensing scheme by utilizing the statistics of the licensed activities. They also presented a suboptimal weighted average energy detection scheme adopting the Neyman-Pearson criterion where the weighting coefficients of the current block vary with detection results of the previous blocks. Several prediction methods such as binary time series analysis and Hidden Markov Model, have been used to provide predicted information to secondary users' "next-step decision" [158, 168]. A Multilayer Perception based approach for spectrum prediction was presented in [172]. Beta distribution is considered in [173] to represent the channel occupancy pattern of primary user and it is validated in [174]. Based on the statistical characteristics of the licensed band occupancy [175, 176], a probability-based periodic spectrum sensing scheme only during communication of cognitive radio users is investigated [177]. The wireless spectrum is non-stationary, which means its background probabilistic model is varying all the time, making the error of prediction unavoidable. Therefore, to improve the performance of dynamic spectrum access by leveraging spectrum usage prediction, the prediction error must be considered. The authors in [178] proposed a new prediction assisted dynamic spectrum access scheme, which learns the distribution model of prediction error online, and consider it when making choices. The study also suggests that the distribution of prediction error can be well approximated by Beta distribution. They claim that the prediction error-aware dynamic spectrum access scheme outperforms the prediction based dynamic spectrum access schemes which are not aware of prediction errors.

The ability to accurately estimate spectrum hole at next instant is critical for cognitive radio to realize channel access. A spectrum sensing scheme uses received signals to detect channel states, and it virtually predicts channel states in the near future simply using previous detected channel states [179-183]. The work in [159] explores the configuration of an energy detector in order to enable an accurate estimation of the real occupancy rate of a primary channel, thus providing dynamic spectrum access based cognitive radio systems with accurate statistical information of primary channels that can be used effectively in spectrum and radio resource management decisions. In [184], an algorithm based on support vector regression and empirical mode decomposition for frequency spectrum prediction in frequency monitor system is introduced. In [185], an interference time ratio that represents the fraction of a primary user's burst interfered by secondary transmission is proposed to control the transmission probability for secondary users, which is predicted using conditional probability. The idea of predictive dynamic spectrum access is introduced in [186], which aims at the distribution of the time length that a channel is idle. Cooperative fusion of secondary user's decisions has been studied extensively to address diverse optimization problems, particularly in spectrum sensing for dynamic spectrum access based spectrum sharing systems. A multitude of decision fusion techniques such as hard fusion and soft combining were used for temporal and spatial fusion of local node decisions [187]. In [182], cooperative spectrum sensing adapting distributed detection theory was investigated. The performance of a linear decision combiner in a cooperative setting for primary user detection in cognitive radio was presented in [41]. For spectrum occupancy prediction, a handful of papers investigated cooperative fusion using Hidden Markov Model based predictors. The authors in [188] implemented cluster formation, and coalition based game theory for multi-primary, multi-secondary user environment.

To flexibly allocate channel resources over a wide bandwidth, cognitive radio systems commonly employ multi-carrier modulation (MCM) based techniques, such as orthogonal frequency division multiplexing (OFDM) [143, 189] and filtered multitone modulation (FMT) [190]. The foremost task of a cognitive radio based on multicarrier modulation scheme is to sense the spectrum instantaneously. Generally, matched filter detection method is applied for pre-known primary user signals; while energy detection method can be used for unknown primary user signals [19, 139]. Maximum likelihood detection (MLD) method for unknown primary user signals has also been studied in [19, 191, 192]. Most time-domain approaches become inappropriate for MCM based cognitive radio systems due to the requirement of spectrum sensing. For MCM based cognitive radio systems, the spectrum sensing process detects the presence and locations of primary users' signals in the frequency domain, expressed by a spectrum hole vector (SHV) [190] or binary allocation vector (BAV) [189]. In order to accurately allocate unused channels to secondary users without generating excessive interference to primary users, an MCMCR system needs to predict the channel status information (CSI) at every next instant. Due to the advantage of simple prediction process, Markovian chain model has been suggested for communication channel prediction [193] and user access requests prediction on the Internet [194], etc. However, insufficient work has been done on the prediction of the subcarriers status information for MCM based cognitive radio systems. In [195], a maximum likelihood detection model is developed to detect the presence and locations of primary user signals in the frequency domain. Performance of the detection model, including the optimal detection region, detection probability and false alarm probability, is analyzed. A one-order two-state Markovian chain model is proposed to predict channel status information. In particular, a novel subcarrier allocation scheme for MCM based cognitive radio systems is proposed, taking into account the confidence of channel estimation, quality of services (QoS) of secondary user and throughput.

Only a few previous studies have addressed spectrum sharing with a rotating radar. Marcus qualitatively discussed the possibility in [8]; Wang et al. [9], and later Rahman and Karlsson [10], analyzed coexistent sharing quantitatively, but only when a device is far enough that its transmissions will not cause harmful interference even in the radar's main beam, as occurs in 5 GHz band. The authors in [155] explores opportunistic primary-secondary spectrum sharing when the primary is a rotating radar. They consider the case where an orthogonal frequency division multiple access (OFDMA) based secondary system operates in non-contiguous cells, as might occur with a broadband hotspot service or a cellular system that uses spectrum shared with radar to supplement its dedicated spectrum. The authors claim that by evaluating quality of service, it is found that spectrum shared with radar could be used efficiently for applications such as non-interactive video on demand, peer-to-peer file sharing, file transfers, automatic meter reading, and web browsing, but not for applications such as real-time transfers of small files and VoIP.

The authors in [196] proposed a method to classify traffic patterns of primary channels in cognitive radio systems and apply different prediction rules to different types of traffic. This allows a more accurate prediction of the idle times of primary channels. An intelligent channel selection scheme is used to find the channels with the longest idle times for secondary use based on the prediction results. The proposed scheme was tested with Pareto and exponentially distributed stochastic traffic and with deterministic traffic. The authors claim that the predictive method using past information improves the throughput of the system compared to a system based on instantaneous idle time information. A multiuser automatic modulation classification for cognitive radios using distributed sensing in multipath fading channel was presented in [40]. In [195], a spectrum opportunity vector was presented modeled as a Markov process model. The authors in [197] proposed a topology-transparent scheme for opportunistic and cooperative spectrum access for opportunistic users. An entropy based prediction method was introduced in [198]. Authors looked for the correlated channels to optimize the sensing strategy. In [196], the authors applied maximum likelihood to predict the length of idle period of each channel. By selecting the channel with the longest predicted idle time, they achieved a reduction in the number of channel switching needed. The author in [199] employ techniques that allow cognitive radios to familiarize themselves with an unknown spectrum environment, recognizing specific, moderately utilized spectrum bands or gray space opportunities in global system for mobile communications (GSM), digital-enhanced cordless telecommunications (DECT), and 2.4-GHz industrial, scientific and medical (ISM) bands that present an opportunity to be exploited using learning-enhanced dynamic spectrum access (DSA) techniques. A learning technique for cognitive radios that will allow prediction of spectral vacancy called predictive dynamic spectrum access (PDSA) was presented in [186]. The goal of PDSA is to gather statistical information about a primary user in an effort to predict when the channel will be idle. This allows to better plan secondary use of the spectrum without the cooperation of the primary user. The authors in [186] explore two approaches to PDSA. The first uses cyclostationary detection on the primary users' channel access pattern to determine expected channel idle times. These techniques are simulated with both Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) networks. The second briefly examines the use of Hidden Markov Models for use in PDSA. Several machine learning techniques have been adopted including neural network, time regression, and space vector machines [149, 200, 201]. The authors in [202] applied an artificial neural network based prediction method to reduce the number of channel sensing needed to perform. The accuracy of the Artificial Neural Network algorithm was compared with the accuracy of Hidden Markov Model in [172].

In general, modeling of spectrum occupancy is done by measuring the received signal powers and estimating the status of primary users using different kinds of spectrum sensing techniques [203, 204]. Such formulations are inaccurate since the primary users' true status cannot be obtained from some noisy and incomplete observations. Since the true states (occupancy by primary users in reality) of a sub-band are never known (i.e., hidden) to the cognitive radio, in [158, 205-207] the authors have extended their idea of improvising Hidden Markov model in spectrum sensing. Bayesian estimation based prediction, and Hidden Markov Model in particular, have received wide attention as viable solution for the spectrum occupancy prediction problem. In [208], the authors define a simple approach based on Bayesian theorem to predict spectrum occupancy status of primary user, from its spectrum occupancy pattern. They formulated the prediction requirement as a Bayesian problem and the solution is obtained through the Bayesian approach. The solution utilizes the conditional probability of busy/idle previous states to predict the probability of next busy state. A general probabilistic framework for traffic modeling and prediction with Bayesian inference were presented in [209], in which the transition probabilities between each pair of entry and exit states are modeled by a semi-Markov chain, and the traveling time durations between states are modeled by an exponential distribution.

Clancy [186] was the first to use an Hidden Markov Model, similar to that used in speech processing [210], to model the channel occupancy as a function of time. Ghosh et al. collected spectrum measurement (collected in the paging band: 928-948 MHz) and used the data to analyze the primary users' behaviors to validate the existence of Markov chain for sub-band utilization by primary users [211]. Furthermore, since the detection of idle sub-bands by a cognitive radio is prone to errors, the paper probabilistically model the errors and formulate a spectrum sensing paradigm as a Hidden Markov model that predicts the true states of a sub-band. In [158], the authors modeled each channel as a Poisson distribution, and used an Hidden Markov Model to predict the availability of a channel. The Hidden Markov Model was trained with Baum-Welsh algorithm [212] predicting the presence of primary users to avoid transmission collision. Hidden Markov Model is used to predict the usage behavior of a frequency band based on channel usage patterns in [158], to decide whether or not to move to another frequency band. A channel status predictor using Hidden Markov Model based pattern recognition is proposed in [207]. Single-user prediction of channel state is proposed in [157] to minimize the negative impact of response delays caused by hardware platforms. A modified Hidden Markov Model based single secondary user prediction is proposed and examined against real world Wi-Fi signals. Thao et al. [213] used bivariate HMM for spectrum sensing optimization. K-step ahead prediction was studied in [214] using Non-Stationary Hidden Markov Model. Different aspects related to the training for the Hidden Markov Model based systems are studied in [215], while [216, 217] exploited modified Hidden Markov Model to optimize secondary user's throughput. Goldsmith et al. [218], studied the information capacity of finite state Markov process. Earlier work by Mushkin et al. [219] focused on the posteriori estimation of Gilbert-Elliot Channel. Both works provided recursive numerical estimation of the posteriori probability of channel state, given a set of observations. The authors in [220] addressed the issue of prediction error performance of Hidden Markov Model, in relation to spectrum sensing errors, and primary user activity patterns. They extended their work in [221] and presented an investigative analysis of the Hidden Markov Model based prediction, and simulated the performance of mean prediction error against the model parameters in terms of channel sensing errors, and channel occupancy transitions. They also presented hard fusion based cooperative spectrum prediction, and the potential for better accuracy compared to local spectrum prediction. In [222], the authors consider how two secondary users should interact to maximize their total throughput by modeling the occupancy of the primary users as discrete-time Markov chains, then they obtain the optimal dynamic coordination policy using a partially observable Markov decision process (POMDP) solver. In [223], the authors propose a reinforcement learning based scheme to improve detection of primary user. The scheme can learn the underlying characteristic of primary user's spectrum usage by assuming that the detection of primary user is a Markov decision process. Although Hidden Markov Model offer good prediction accuracy with reasonable computational complexity, the problem with a Hidden Markov Model based prediction scheme is that the primary users' behavior patterns cannot be well exhibited by a Hidden Markov Model. The limitation comes from the memoryless property of Hidden Markov Model which makes the transition to the next state independent of the duration of stay at the present state. Nguyen et al. proposed a hidden bivariate Markov model to characterize the transmission behavior of a PU

[213]. For a hidden bivariate Markov model, the channel state and the PU's time spent dwelling on a state are assumed to be independent. The authors in [215] proposed a non-stationary Hidden Markov Model, in which the time-varying property of PU behavior is realized and a primary users' variations in spectrum occupancy across time is modeled. An expectation maximization (EM) based algorithm, which extends the traditional Baum-Welch algorithm [224], is developed to estimate the parameters of an Non-Stationary Hidden Markov Model. The authors in [45] proposed a method to statistically assure spectrum availability using Hidden Markov Models and Non-Stationary Hidden Markov Models to estimate the activity of the spectrum.

In this section we address the generation of probabilistic assurances about the availability and duration of spectrum opportunities for different cooperation levels of the primary-secondary cooperation framework. The SAS plays a central role in our proposed probabilistic assurance generator. It serves as a middle entity to facilitate the interaction between the primary user and secondary user operations. The SAS is capable of accessing the primary user usage statistics and process the information to improve the probabilistic assurance generator's performance. One interesting aspect of using cooperation in determining the probabilistic assurance is that we are more interested about the "Local True State" rather than the "Actual True State" of the primary users operations at the transmission antenna of the primary user. Even if we have access to the transmission status of the primary user operation, we need to translate that to the local primary user operational state to improve the spectrum sharing experience. In order to characterize the wireless propagation environment we assume a log-distance path loss with shadowing model [225]. Let d denote the distance from the primary user transmitter to the secondary user node. The log-distance path loss with shadowing can be calculated by

$$PL(d) = \left[PL(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)\right] + X_g$$
$$PL(d): total\ path\ lossat\ a\ distance\ d\ (dB)$$
$$PL(d_0): path\ loss\ at\ a\ reference\ distance\ d_0$$
$$\gamma: the\ path\ loss\ exponent$$
$$X_g: random\ shadowing\ effects$$

(1)

The path loss exponent, γ, varies for different propagation environments. The random variable, X_g, is assumed to be normal with zero (0) mean and variance, σ_g^2. Let us assume that the received signal strength at the SU node follows:

$$\{Y, t = 0, 1, 2, \dots\} \sim \mathcal{N}(P_T - PL(d), \sigma^2)$$

where P_T is the transmit power of the PU operation. In order to estimate the local true states of the primary user operation, we need to determine a threshold value that accurately identifies the ON/OFF status of the primary user transmitter. Due to the non-stationary nature of the wireless channels, determination of an appropriate threshold is a non-trivial problem and often results in erroneous predictions. In this work, we propose to make use of primary user cooperation by using statistics of the primary user operations to supplement channel monitoring in order to predict the primary user operation status. Even with the cooperation in the form of usage statistics, we need the local observation sequence to predict the local true states of the primary user operation. In our proposed approach, the SAS plays the central role to bridge the primary user cooperation and channel monitoring results to improve the prediction accuracy. We define the Spectrum Opportunity Duration Opportunity (SODA) as follows:

SODA is a probabilistic assurance about each of the idle primary user channels stating that the channel in consideration will be available for secondary user access for certain duration of time with the probability SODA.

Table 26: Level of cooperation considered

Cooperation Level	Methods
0	No cooperation, HMM
1	No cooperation, NS-HMM
2	NS-HMM with random segmentation
3	NS-HMM with similar activity phase identification
4	NS-HMM with similar activity phase identification and initial model parameter estimation

The cooperation framework consists of five levels, specified by Table 26. For Level 0, the primary and secondary user operations act on their own and the channel monitoring results are processed through a Hidden Markov Model or Non-Stationary Hidden Markov Model approach in order to generate the probabilistic assurances. The problem with the Hidden Markov Model approach is that it does not consider the duration of stay in a particular state while determining the state transition probabilities. The Non-Stationary Hidden Markov Model approaches address this issue and provides better prediction accuracy compared to the Hidden Markov Model approaches. But, the Non-Stationary Hidden Markov Model approaches result in significant increase in the computational complexity of the prediction algorithms.

The SAS framework proposed to incorporate the SODA approach is presented in Figure 11. In this work we will be using the Non-Stationary Hidden Markov Model approach for calculating the SODA values as this offers better prediction accuracy compared to the Hidden Markov Model approaches. The SODA calculation is done in two phases. In phase 1, the Incumbent SAS estimates the Non-Stationary Hidden Markov Model parameters based on previously stored training data and usage statistics of the primary user operations. In the second phase, the Secondary SAS receives these estimated model parameters and use them on the current channel monitoring results to predict the primary user operation's usage status. This approach entrusts the Incumbent SAS to estimate the model parameters offline and allows the Secondary SAS to perform prediction algorithms with relatively low computational complexity.

Responsibility of the Incumbent SAS (I-SAS)

The Incumbent SAS is responsible for communicating with the primary user database to access the usage information. The SODA calculation using the Non-Stationary Hidden Markov Model approach involves two phases. In the Phsae-1, previously stored observation sequence is used to train the model and estimate the model parameters. In the absence of primary user cooperation, the estimation of the model parameters begins with random initialization. The learning method (e.g. the Baum-Welch algorithm) starts from an initial model with randomly-chosen parameters, and iteratively updates the model parameters until convergence.

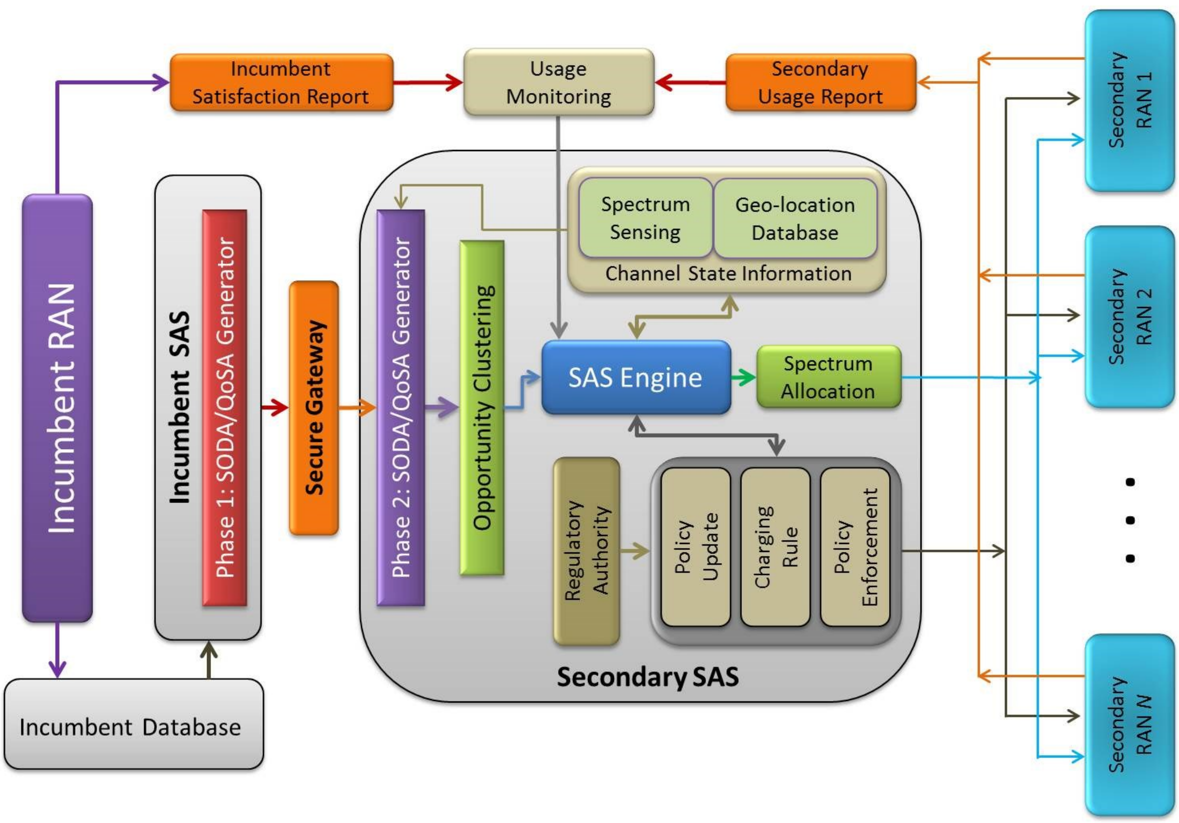


Figure 11: SAS framework for the proposed SODA approach

Thus, there is the risk of falling into local optima and low convergence speed because of the randomness of initial parameters [226]. The starting point of the training phase significantly impacts the estimated model parameters. This provides us with a potential opportunity to improve the prediction accuracy using primary user cooperation. The Incumbent SAS can generate a more suitable starting point for the training phase and thus improve the reliability of the SODA values. Another interesting primary user cooperation could be the *Similar Activity Phase Identification* information. If the primary user operation's usage can be segmented based on the intensity of the activity, it will help the Incumbent SAS to determine more appropriate initial model parameters. For this preliminary analysis, we propose to segment the training sequence in three (3) groups: 'Light activity', 'Moderate activity', and 'High activity'. With the help of *Similar Activity Phase Identification* information, the Incumbent SAS can select appropriate training sequence to perform the model parameter estimation routine. The primary criticism against the Non-Stationary Hidden Markov Model approach is the increase in computational complexity. The computational complexity of the Non-Stationary Hidden Markov Model is $O\big(T(M^2 + MK + MD + KD^3)\big)$ [227] compared to $O(2M^2T + M + K)$ of a Hidden Markov Model based approach [228], where M is the number of states, K is the emission alphabet size, D is the maximum state duration, and T is the length of the sequence. From the perspective of primary user operation ($M = 2$) and channel monitoring decisions ($K = 2$), the increase in computational complexity for the Non-Stationary Hidden Markov Model approach is mainly due to the maximum state duration (D). Without primary user cooperation, the Non-Stationary Hidden Markov Model approaches assume a large D to incorporate the state dwell time in the prediction algorithms. The Incumbent SAS can access this information from the incumbent database and provide the Non-Stationary Hidden Markov Model with a D value which is a much better approximation of the actual maximum state duration.

We also propose to ignore the low values of state durations as these spectrum opportunities will result in frequent channel switching from the perspective of the secondary user operations. Based on the minimum quality of service (QoS) requirement of the SU operations, we can decide on the minimum state duration for which an idle channel will be considered as a spectrum opportunity. The Incumbent SAS can access the primary user database to determine the probability of state durations from that lower threshold. While training the model parameters, we will preprocess the data such that the state transitions with smaller state duration are considered as continuance of a state. This approximation will result in degradation in the prediction performance as we are intentionally ignoring information. But we are interested to observe the reduction in complexity if the performance degradation is within a tolerable limit. As can be seen in Figure 11, the responsibilities of Incumbent SAS also include providing the incumbent satisfaction report in order to ensure a desired interference environment for the primary user operation.

Responsibility of the Secondary SAS (S-SAS)

The Secondary SAS is responsible to perform the Phase-2 of the Non-Stationary Hidden Markov Model based SODA generation. The Secondary SAS receives the estimated model parameters from the Incumbent SAS and use these parameters on the current channel monitoring results to identify the local true state of the primary user operations. The channel monitoring system that provides the channel state information may include both spectrum sensing and geo-location database approach. The Secondary SAS uses this information as the observation sequence in the Non-Stationary Hidden Markov Model based prediction algorithms. As the training and model parameter estimation is done offline by the Incumbent SAS, the Secondary SAS applies the estimated model parameters to the real time observation sequence and determine the probabilistic assurance about the availability and duration of the spectrum opportunities.

As can be seen from Figure 11, the Secondary SAS is also responsible for spectrum allocation, secondary user operation's usage monitoring, and policy enforcement.

Impact of Cooperation on Probabilistic Assurance Determination

Let $s_1, s_2, \dots, s_M$ be the states of a Non-Stationary Hidden Markov Model with initial state distribution $\pi: \{\pi_m\}$ and the transition probability matrix $A: \{a_{mn}\}$. Let q_t be the state of the semi-Markov chain at time $t, t = 1, 2, .., T$ and o_t the observable output with the conditional probability of emission

$$b_m(v_k) \triangleq P(o_t = v_k | \, q_t = s_m)$$

(2)

where $\{v_k\}$ is a set of K distinct values that may be assumed by the observation o_t (with $B: \{b_m(v_k)\}$). We also assume that the duration of a given state is a discrete random variable taking values d with probability $p_m(d)$ with $P: \{p_m\}$, where $d \in \{1, 2, \dots, D\}$. So for this work, we describe the Non-Stationary Hidden Markov Model with $\lambda = \{\pi, A, B, P\}$. For the Non-Stationary Hidden Markov Model calculation of forward-backward algorithm and parameter estimation we follow the work presented by Yu and Hisashi in [229]. Let τ_t denote the remaining sojourn (or residual life) time of the current state q_t. Then, if the pair process (q_t, τ_t) takes on value (s_m, d) at, say, time t_0, the semi-Markov chain will remain in the current state s_m until time $t_0 + d - 1$ and transit to another state at time $t_0 + d$, where $d \geq 1$. Let us define a variable,

$$\alpha_{t|x}(m, d) \triangleq \Pr(q_t = s_m, \tau_t = d \mid o_1^x)$$

where $x = t - 1, t, or\ T$. The above quantity is termed the 'predicted', 'filtered', or 'smoothed' probabilities of (q_t, τ_t), depending on whether the observation sequence is $o_1^{t-1}, o_1^t, or\ o_1^T$. Summing over every possible duration, we get the marginal distribution of q_t,

$$\gamma_{t|x}(m) \triangleq \sum_d \alpha_{t|x}(m, d)$$

(3)

We also define the ratio of the filtered probability $\alpha_{t|t}(m, d)$ over the predicted one $\alpha_{t|t-1}(m, d)$, for any d, by

$$b_m^*(o_t) \triangleq \frac{\alpha_{t|t}(m, d)}{\alpha_{t|t-1}(m, d)} = \frac{b_m(o_t)}{P(o_t | o_1^{t-1})}$$

(4)

Also the one step (from $t - 1$ to t) observation prediction probability $\Pr(o_t | o_1^{t-1})$ can be calculated as

$$P(o_t | o_1^{t-1}) = \sum_{m,d} \alpha_{t|t-1}(m, d) b_m(o_t)$$

$$= \sum_m \gamma_{t|t-1}(m) b_m(o_t)$$

(5)

The forward recursion formula can be written as

$$\alpha_{t|t-1}(m,d) = S_{t-1}(m) p_m(d) + b_m^*(o_{t-1}) \alpha_{t-1|t-2}(m,d+1)$$
$$with$$
$$\alpha_{1|0}(m,d) = \pi_m p_m(d)$$
$$S_t(m) \triangleq \Pr(q_{t+1} = s_m, \tau_t = 1 \mid o_1^t) = \sum_n \mathcal{E}_t(n) a_{nm}$$
$$\mathcal{E}_t(n) \triangleq \Pr(q_t = s_m, \tau_t = 1 \mid o_1^t) = \alpha_{t|t-1}(m,1) b_m^*(o_t)$$

(6)

Here $\mathcal{E}_t(m)$ represents the conditional probability of a state ending at t given o_1^t and $S_t(m)$ represents that of a state starting at $t + 1$ given o_1^t. The backward recursion formula is given by,

$$\beta_t(m,d) = \begin{cases} S_{t+1}^*(m) b_m^*(o_t), & d = 1 \\ \beta_{t+1}(m,d-1) b_m^*(o_t) & d > 1 \end{cases}$$
$$with$$
$$\beta_T(m,d) = b_m^*(o_T)$$
$$S_t^*(m) \triangleq \frac{\Pr(o_t^T \mid q_t = s_m, \tau_{t-1} = 1)}{\Pr(o_t^T \mid o_1^{t-1})} = \sum_n a_{mn} \mathcal{E}_t^*(n)$$
$$\mathcal{E}_t^*(m) \triangleq \frac{\Pr(o_t^T \mid q_t = s_m, \tau_{t-1} = 1)}{\Pr(o_t^T \mid o_1^{t-1})} = \sum_d p_m(d) \beta_t(m,d)$$

(7)

Now we can summarize the forward-backward algorithm using variables $\alpha_{t|t-1}(m,d)$ and $\beta_t(m,d)$ as given in Algorithm 1.1 and 1.2.

Algorithm 1.1: Forward Recursion
Initialization

- Randomly initialize the model parameters: $\lambda = \{\pi, A, B, P\}$
- For $t = 1$, calculate

1. Forward variable $\{\alpha_{1|0}(m,d), \forall m, d\}$ using Eq.(6)
2. One step observation probability: $\Pr(o_1 \mid o_1^0) = \Pr(o_1) = \sum_{m,d} \alpha_{1|0}(m,d) b_m(o_1)$
3. Normalized emission probabilities: $\{b_m^*(o_1), \forall m\} = \frac{b_m(o_t)}{Pr(o_1)}$

4. Probability of the state starting at t: $\{\mathcal{E}_1(m), \forall m\} = \alpha_{1|0}(m,1) b_m^*(o_1)$
5. Probability of the state ending at $t+1$: $\{S_1(m), \forall m\} = \sum_n \mathcal{E}_1(n) a_{nm}$

For the rest of the observation sequence

- Starting from $t = 2 \; to \; T-1$

1. Forward variable $\{\alpha_{t|t-1}(m,d), \forall m, d, t\}$ using Eq.(6)
2. One step observation probability: $\{\Pr(o_t \mid o_1^{t-1}), \forall t\}$ using Eq.(5) and Eq.(4)
3. Normalized emission probabilities: $\{b_m^*(o_t), \forall m, t\}$ using Eq.(4)
4. Probability of the state starting at t: $\{\mathcal{E}_t(m), \forall m\}$ using Eq.(6)
5. Probability of the state ending at $t+1$: $\{S_t(m), \forall m\} = \sum_n \mathcal{E}_t(n) a_{nm}$

- Save $\{\alpha_{t|t-1}(m,d), \forall m, d, t\}$ and $\{\Pr(o_t \mid o_1^{t-1}), \forall t\}$ for backward calculation

Algorithm 1.2: Backward Recursion

Initialization

- Use the saved $\{\alpha_{t|t-1}(m,d), \forall m, d\}$ and $\{\Pr(o_t \mid o_1^{t-1}), \forall t\}$ values from the forward recursion calculation
- For $t = 1$, calculate
- Backward variable $\{\beta_T(m,d), \forall m, d\}$ using Eq.(7)
- $\mathcal{E}_T^*(m) = \sum_d p_m(d) \, \beta_T(m,d)$
- $S_T^*(m) = \mathcal{E}_{T-1}^*(m) \sum_n a_{mn} \mathcal{E}_T^*(n)$

For the rest of the observation sequence

- Starting from $t = 2 \; to \; T-1$, calculate,

1. Backward variable, $\{\beta_t(m,d), \forall m, d, t\}$ using Eq.(7)
2. Accumulate $\{\gamma_{t|T}(m), \forall m, t\}$: $\gamma_{t|T}(m) = \gamma_{t+1|T}(m) + \mathcal{E}_t(m) S_{t+1}^*(m) - S_t(m) \mathcal{E}_{t+1}^*(m)$
3. Estimate the emission probability: $\hat{b}_m(v_k = o_t) = \hat{b}_m(v_k = o_t) + \gamma_{t|T}(m)$ using Eq.(4)
4. $\{\mathcal{E}_t^*(m), \forall m, t\}$ and $\{S_t^*(m), \forall m, t\}$ using Eq.(7)

- Use, $\{\beta_t(m,d), \forall m, d, t\}$, $\{\mathcal{E}_t^*(m), \forall m, t\}$ and $\{S_t^*(m), \forall m, t\}$ to re-estimate the model parameters for each observation symbol

The random initialization of the model parameters $\lambda = \{\pi, A, B, P\}$ and the probabilities calculated in the FB recursion algorithm are used in the re-estimation of the model parameters for every observation sequence of length T.

$$\hat{\pi}_m = \frac{\pi_m \mathcal{E}_1^*(m)}{N_\pi}, \qquad \hat{a}_{mn} = \sum_{t=2}^{T} \frac{\mathcal{E}_{t-1}(m) a_{mn} \mathcal{E}_t^*(n)}{N_a},$$

$$\hat{b}_m(v_k) = \sum_{t=1}^{T} \frac{\gamma_{t|T}(m)\delta(o_t, v_k)}{N_b}, \qquad \hat{p}_m(d) = \sum_{t=2}^{T} \frac{S_{t-1}(m) p_m(d) \beta_t(m,d)}{N_p}$$

$$where, \quad \delta(o_t, v_k) = \begin{cases} 1, & o_t = v_k \\ 0, & otherwise \end{cases}$$

$$N_\pi : such\ that \sum_m \hat{\pi}_m = 1, \qquad N_b : such\ that \sum_m \hat{b}_m(v_k) = 1$$

$$N_a : such\ that \sum_n \hat{a}_{mn} = 1, \qquad N_p : such\ that \sum_d \hat{p}_m(d) = 1$$

(8)

Based on the re-estimated model parameters $\lambda = \{\pi, A, B, P\}$ received from the Incumbent SAS, the Secondary SAS uses the current channel monitoring results as the observation sequence and determine the probabilistic assurance about the availability and duration of the spectrum opportunities. The Non-Stationary Hidden Markov Model based SODA calculation presented so far does not consider any cooperation between the primary user and secondary user operations. The computation complexity of the Non-Stationary Hidden Markov Model based prediction approach primarily depends on the maximum state duration for fixed number of states (ON or OFF) and observation alphabet size (present or absent). So the impact of having prior information about the maximum state duration on the computation complexity is straight forward compared to assuming a random large value as the maximum state duration. In the following we present the initial results on the impact of primary user cooperation in terms of usage statistics on the prediction accuracy and computational complexity of the Non-Stationary Hidden Markov Model based prediction approach. The block diagram of the SODA calculation procedure is given in Figure 12.

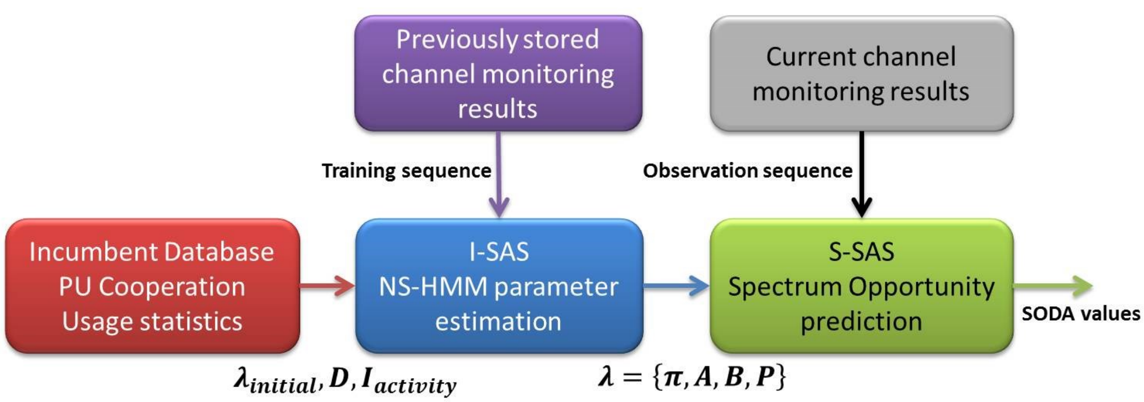


Figure 12: The 2-Phase SODA calculation procedure with Incumbent SAS and Secondary SAS

The traditional Non-Stationary Hidden Markov Model learning method begins with randomly chosen initial model parameters, and iteratively updates the model parameters until convergence. Thus, there is the risk of falling into local optima and low convergence speed because of the randomness of initial parameters. The underlying assumption of using primary user cooperation is that the segmentation of the observed signal allows us to identify quite accurately the operational aspects of the reference model. From the previously stored local true states of the primary user operations, we propose to segment the primary user activities based on the intensity of use.

The primary user operation's usage data is partitioned into three (3) segments: 'Light activity', 'Moderate activity', and 'High activity'. Figure 13 shows the received signal strengths (RSS) of the Blacksburg Police Department Dispatch operations measured on September 13th 2014 [230]. Based on the average RSS values, we partitioned the time between the midnight to 3 AM and 9 PM to midnight as moderate activity, 3 AM to noon as low activity, and noon to 9 PM as high activity. If the activity phases belonging to the same state are grouped correctly, they can offer us good insight into the behavior of the states, i.e. the observation and transition probabilities as well as the duration distribution.

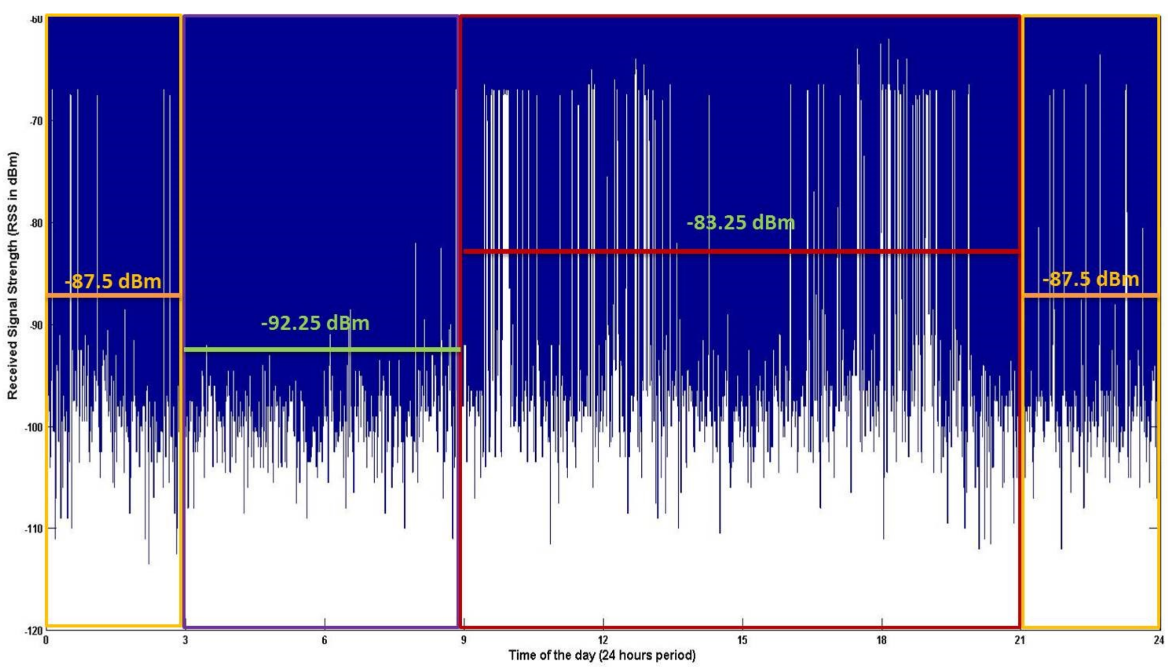


Figure 13: Similar Activity Phase Identification for primary user Operations

In this work, we estimate the model parameter probabilities based on the observed frequencies of the previously stored local true states of the primary user operation. Parameters of a Non-Stationary Hidden Markov Model can be calculated by simply counting the occurrence of the observed signal and the hidden states. Let ϕ_{ij} represents the transition from the state $S_i\ to\ S_j$; ψ_{ij} represent the event in which the system is at state S_i and emit the symbol v_j; and φ_{ij} represents the event in which the system is at state S_i and stays there for a duration of $j\ time\ units$. The indicator functions $I_{\phi_{ij}}$, $I_{\psi_{ij}}$, and $I_{\varphi_{ij}}$ are defined as,

$$I_{\phi_{ij}} = \begin{cases} 1, & if\ \phi_{ij}\ is\ true \\ 0, & otherwise \end{cases}, \quad I_{\psi_{ij}} = \begin{cases} 1, & if\ \varphi_{ij}\ is\ true \\ 0, & otherwise \end{cases}, \quad I_{\varphi_{ij}} = \begin{cases} 1, & if\ \varphi_{ij}\ is\ true \\ 0, & otherwise \end{cases} \tag{9}$$

The Baum-Welch algorithm also uses the same techniques for parameter re-estimation using other probability values. Let us assume that at the beginning of the system observation, $\pi_{m_{ini}}$ represents the frequency at state S_m, $\phi_{mn_{ini}}$ be the initial transition probability from state S_m to state S_n, $\psi_{m_{ini}}(v_k)$ be the initial emission probability of the symbol v_k at state S_m, and $\varphi_{m_{ini}}(d)$ be the initial duration probability at state S_m. Also let us define a counting variable x that takes the necessary range such that $\{x: 1 \leq x \leq max\,number\ of\ occurance\}$ according to the event in consideration. The initial estimates of the Non-Stationary Hidden Markov Model parameters can be calculated as follows:

$$\begin{aligned}
\pi_{m_{ini}} &= frequency\ at\ state\ s_m\ at\ t = 1 \\
\phi_{mn_{ini}} &= \frac{Number\ of\ transition\ from\ s_m to\ s_n}{Number\ for\ transition\ from\ s_m} \\
&= \frac{\sum_x I_{\phi_{mn}}{}^{(x)}}{\sum_x \sum_{n=1}^{N} I_{\phi_{mn}}{}^{(x)}} \\
\psi_{m_{ini}}(v_k) &= \frac{Number\ of\ emmision\ of\ v_k\ at\ s_m}{Number\ of\ time\ at\ s_m} \\
&= \frac{\sum_x I_{\psi_{mk}}{}^{(x)}}{\sum_x \sum_{n=1}^{N} I_{\phi_{nm}}{}^{(x)}} \\
\varphi_{m_{ini}}(d) &= \frac{Number\ of\ occurance\ of\, s_m with\ duration\ d}{number\ of\ transition\ to\ s_m} \\
&= \frac{\sum_x I_{\varphi_{md}}{}^{(x)}}{\sum_x \sum_{n=1}^{N} I_{\phi_{nm}}{}^{(x)}}
\end{aligned} \tag{10}$$

The initial estimate of the model parameters will be updated over time to improve the reliability and appropriateness of the estimated values. In this report, we provide the preliminary results on incorporating the primary user cooperation in terms of initial model parameters and *Similar Activity Phase Identification* information. We try to predict the spectrum opportunities using Markov Model approaches with and without the availability of primary user cooperation. As mentioned before the Incumbent SAS uses the measurement data from September 13th, 2015, presented in [230], to estimate the model parameters and the Secondary SAS uses the estimated model parameters on the measurement data of September 20th, 2015 to predict the availability and duration of the spectrum opportunities. In the absence of primary user cooperation, we use both the Hidden Markov Model and Non-Stationary Hidden Markov Model based prediction approaches to estimate the availability and duration of spectrum opportunities. In this scenario, we assume that a single entity is performing the entire prediction operation and thus results in high computational complexity. With the SAS framework proposed in this work, the Incumbent SAS performs the model parameter estimation procedure offline based on the previously stored local true states of the primary user operations. Thus the real time computational load for the Secondary SAS is reduced only to predicting the availability and duration of the spectrum opportunities based on the current channel monitoring results.

Table 27: Impact of PU cooperation on Spectrum Opportunity Prediction Accuracy

Means of Cooperation	Prediction accuracy
No Cooperation: Hidden Markov Model	74%
No Cooperation: Non-Stationary Hidden Markov Model	83%
Non-Stationary Hidden Markov Model with random segmentation	84%
Non-Stationary Hidden Markov Model with Similar Activity Phase Identification	89%
Non-Stationary Hidden Markov Model with Similar Activity Phase Identification and initial model parameter estimation	96%

Table 27 presents the prediction accuracy for five (5) different approaches observed in this work. Without primary user cooperation the Hidden Markov Model based approach provides 74% of accuracy while using Non-Stationary Hidden Markov Model based approach results in 83% of prediction accuracy. We observe the impact three (3) different approaches on the proposed SODA calculation procedure. In the first approach, Non-Stationary Hidden Markov Model with random segmentation, the Incumbent SAS performs the parameter estimation using the previously stored local true states of primary user operation. The Incumbent SAS randomly partition the training sequence into equal segment of symbols and estimate the model parameters for that duration of the day. This approach provides better prediction accuracy compared to the one where we use the channel monitoring results of the whole day as one training sequence. As we segment the training sequence randomly, if fails to capture the similarity in primary user activity and thus the parameter estimation falls short to provide significant improvement compared to Non-Stationary Hidden Markov Model based approach without random segmentation. Next, the Incumbent SAS looks into the channel monitoring results to identify similar activity phases (as shown in Figure 13) and use this information to generate separate model parameters for each of these activity phases. Using the *Similar Activity Phase Identification* information reasonably improves the prediction performance. The prediction accuracy of 89% shown in Table 27, represents the average accuracy achieved for all the three activity phases (Light, Moderate, and High activity phases).

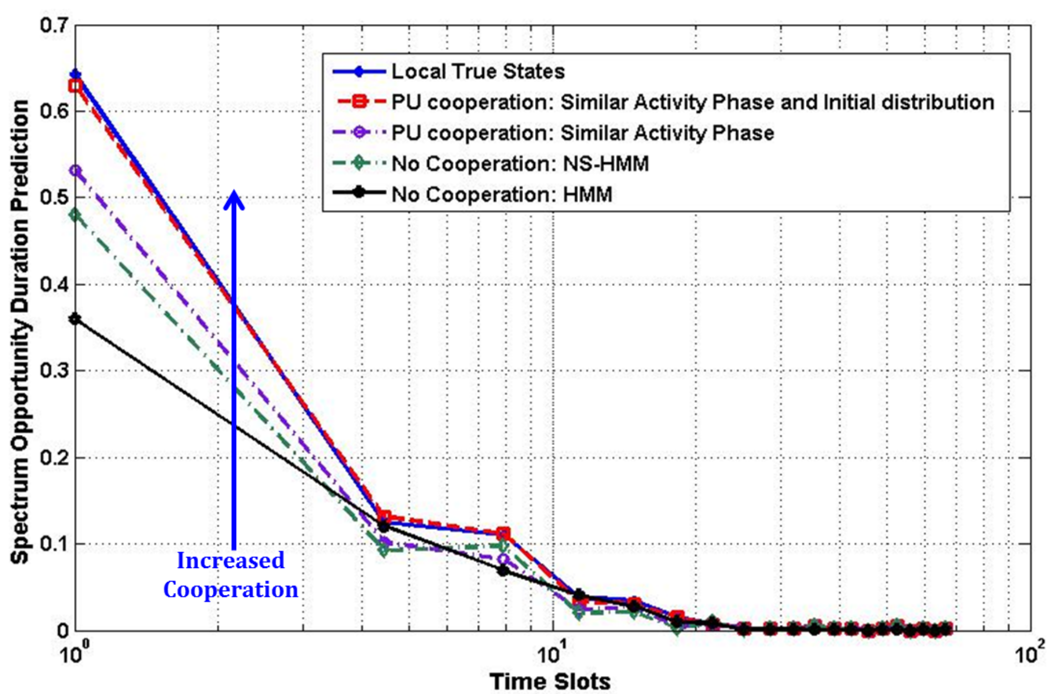


Figure 14: Impact of Primary User Cooperation on the Prediction Accuracy of SODA Values

The last approach uses Non-Stationary Hidden Markov Model based prediction where the Incumbent SAS generates estimation of model parameters for all three (3) activity phases but initializes the model parameters according to (10) instead of random initialization. As expected the prediction accuracy improves to 96% as a result of segmentation and initialization based on previously stored channel monitoring results. The simulation also shows the performance improvement achieved by cooperation based segmentation (89%) compared to random segmentation (84%). We also present the impact of primary user cooperation on the accuracy in predicting the probabilistic assurance about the duration of the spectrum opportunities (SODA) in Figure 14. Primary user cooperation improves the performance of the Non-Stationary Hidden Markov Model approach in predicting the duration of the available spectrum opportunities. For a spectrum opportunity with duration of two time slots, the Hidden Markov Model approach without using any cooperation predicts the opportunity duration with a prediction accuracy of ~65%. While the Non-Stationary Hidden Markov Model with primary user cooperation, under the similar context, improves the opportunity duration prediction accuracy up to ~95%.

Summary of the Section

In order to realize dynamic spectrum access based spectrum sharing, channel monitoring through different spectrum sensing techniques is applied to detect the presence of spectrum opportunities. If secondary users randomly or sequentially sense the channels until a spectrum opportunity is detected, significant amount of the spectrum and energy resources will be wasted, since secondary users transmit only after a decision has been made. On the other hand, with the use of an intelligent predictive method, secondary users can learn from the past activities of each channel to predict the next channel state. Duration of spectrum opportunity is also another important aspect of successful secondary user operation in a spectrum sharing system. In this chapter we discussed the generation of a probabilistic assurance about the availability and duration of the available spectrum opportunities – the Spectrum Opportunity Duration assurance (SODA) metric. A method to statistically ensure spectrum availability using Non-Stationary Hidden Markov Models was proposed. We used Non-Stationary Hidden Markov Model in place of Hidden Markov Model because the non-stationary approach better approximates the wireless environment. We also introduced primary user cooperation into the prediction algorithms in order to improve the prediction accuracy and reduce the computational complexity of the prediction algorithms. The primary-secondary cooperation provided useful information that was used in the prediction algorithm. The primary user cooperation includes maximum state duration, model parameter initialization, *Similar Activity Phase Identification* vector, etc. The Incumbent SAS, having access to this information and previous observations, performed the Non-Stationary Hidden Markov Model based operation to re-estimate the model parameters and forward it to the Secondary SAS. The Incumbent SAS uses the measurement data from September 13th, 2015, presented in [230], to estimate the model parameters and the Secondary SAS uses the estimated model parameters on the measurement data of September 20th, 2015 to predict the availability and duration of the spectrum opportunities. The Secondary SAS used the re-estimated model parameters to run the prediction algorithm in real time using the current channel monitoring results received from the Environmental Sensing Capability (ESC) system and/or the secondary users. Without primary user cooperation the Hidden Markov Model based approach provides 74% of prediction accuracy. With primary-secondary cooperation (model parameter initialization and *Similar Activity Phase Identification*), the Non-Stationary Hidden Markov Model based approach offers significant improvement in prediction accuracy (96%). The simulation also shows the performance improvement achieved by cooperation based segmentation (89%) compared to random segmentation (84%). Primary user cooperation also improves the performance of the Non-Stationary Hidden Markov Model approach in predicting the duration of the available spectrum opportunities. For a spectrum opportunity with duration of two time slots, the Hidden Markov Model approach without using any cooperation predicts the opportunity duration with a prediction accuracy of ~65%. While the Non-Stationary Hidden Markov Model with primary user cooperation, under the similar context, improves the opportunity duration prediction accuracy up to ~95%. The Spectrum Opportunity Duration Assurance (SODA) values determined for each of the shared channels helps the spectrum sharing systems to achieve the availability and duration information about spectrum opportunities. Thus the secondary user resource management system and/or the SAS become enabled to perform intelligent dynamic spectrum access to improve the spectrum sharing experience of both the primary and secondary users. As a natural extension of the reported work, modeling the generation of the probabilistic assurances about the duration of the available spectrum opportunities with primary-secondary cooperation using a Hierarchical Hidden Markov Model (H-HMM) [231] based approach offers an exciting future research opportunity.

Chapter 4

Impact of Primary-Secondary Cooperation on Spectrum Opportunity Access

Chapter 4: Impact of Primary-Secondary Cooperation on Spectrum Opportunity Access

Introduction

The increasing diversity of use cases and demand of high quality-of-service (QoS) have resulted in overcrowding of spectrum bands. At the same time, the rapid evolution of wireless communications has made the problem of spectrum utilization ever more critical. Such explosive demand from wireless communications and service applications has contributed to a huge demand of new wireless services in both the licensed and unlicensed bands. Wireless communities and regulatory bodies have predicted a rapidly increasing demand for mobile data services in North America that may exceed capacity in the near future [4, 6]. Static spectrum assignment, applied to radio frequencies for almost a century, has significantly aggravated the situation. A number of surveys and reports, however, have shown that a significant portion of the spectrum remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum scarcity problem [232]. It would be thus logical to allow unlicensed users to opportunistically exploit licensed frequencies when they are 'unused' at a specific place and time. Theoretically, such approach would increase overall frequency reuse and would boost the throughput for applications that opportunistically use the idle channels. This observation has led wireless communication to the paradigm of dynamic spectrum access, where users can actively search for unused spectrum in licensed bands and communicate using these spectrum opportunities. In this chapter we address the aspect of dynamic access to the available spectrum opportunities especially when primary user cooperation is available and is used to improve the performance of the spectrum sharing system. We present a method to maximize the utility duration of the probabilistic assurance by judiciously employing a combination of primary user cooperation and channel monitoring techniques to reduce the likelihood of interference. The discussion presented in this chapter focuses on the advantage of having primary-secondary cooperation from the perspective of dynamic spectrum opportunity access and present algorithms and analysis to show the improvement in dynamic access performance in terms of interference avoidance and secondary user throughput.

To address the issue of inefficient spectrum utilization due to the fixed spectrum assignment policy, Cognitive Radio has emerged as the solution to improve the spectrum utilization by detecting and accessing vacant licensed spectrum in frequency, time, and space while avoiding interference with the original license holders [143, 145]. Federal communications commission defines cognitive radio as a radio capable of changing its transmitter parameters based on its interaction with the environment [233]. Over the past decade, the research interests on cognitive radio networks have been growing tremendously due to its capability of exploiting the unused spectrum in dynamically changing environments. The cognitive radio enabled with cognition and reconfigurability features addresses the problem of spectrum scarcity, improving the quality of service, as well as communication reliability. Dynamic spectrum access is one of the key features for cognitive radio networks, which allows secondary users to access unused channels in an opportunistic manner. This way, primary users who own the license have priority for spectrum access, and secondary users can also access the channel when the spectrum is not occupied by primary users. Consequently, the system performance of the secondary user network depends on the dynamics of the primary user network. A cognitive radio, however, should do more than only access spectrum opportunistically. It should autonomously learn and acquire helpful primary and secondary user information and use patterns, rather than only passively sensing the radio spectrum [147, 196]. In order to fully exploit the cognitive radio potential, proactively acquiring information about primary and secondary user operation is hence imperative.

Cognitive radio addresses the underutilization problem of the spectrum licensed to different organizations, and it supports dynamic spectrum access. In a dynamic spectrum access system primary users have higher priority in using the licensed channels. Therefore, whenever a primary user is detected, secondary users must vacate the relevant channels or decrease their transmitted power to reduce the interference on primary users [137, 139, 234, 235]. Also in some situations, due to the activities of primary users, secondary users may need to vacate the current channel and switch to other available channels or terminate communication frequently. This would lead to temporal connection loss of secondary users. In addition, if a secondary user cannot vacate a channel in a timely manner, it would interfere with primary users. To reduce the temporal connection loss and interference on primary users, secondary users need to avoid using the channels that are only available for a short time period. Therefore, secondary users should be able to consider the probability of channel being available for a given time period. In general, the traffic stochastic parameters vary slowly. Hence, they can be estimated by using the historical data [6]. Various traffic prediction techniques have been proposed in the literature for different wireless systems [236-238].

Prediction of future availability and duration of available channels based on historical information helps a cognitive radio to select the best channels for control and data transmission. A cognitive radio should have the ability to learn from past experiences to improve future performance compared to the case where only instantaneous information is taken into account. Secondary users channel selection performance can be improved by utilizing sensed past information about the channel use. For channels where the activity of the primary users varies quickly over time, instantaneous sensing information might become obsolete in the near future. This will cause frequent service disruptions for secondary users since they have to refrain from transmissions and search for new available channels. Frequent channel switching causes delays and reduces throughput. In addition, interference is produced towards primary users. Cognitive radio performance may be improved if primary user behavior is accurately modelled, since accurate prediction allows the secondary users to make proactive channel switching decisions. Therefore, the channel selection algorithm should take into account the cost or probability of such future change in channel availability when selecting a channel.

Performance in cognitive radio networks is significantly influenced by the spectrum sensing and channel selection process. In a cognitive radio network, spectrum sensing, occupancy modelling, channel switching and secondary user performance are interdependent. Inaccurate spectrum opportunity detection and subsequent suboptimal channel selection could result in unnecessary delays. These delays may lead to degradation in secondary user performance and may also bring about unnecessary interference for existing primary users. Accurate, proactive channel occupancy predictions should improve the channel allocation process by helping to minimize the probability of missed detection and false alarm in spectrum opportunity detection. This in turn actively reduces interference delays and transmission gaps due to sub-optimal channel switching [239]. Reliability and availability have long been used as quantitative measures in computing and communication systems. These concepts are used to evaluate the system performance in terms of the time that the system can function without failure and the fraction of time that a system is operational respectively. Access to the information about the availability and duration of available spectrum opportunities plays a critical role to ensure reliability of the secondary user system performance. As expected a trade-off exists between achievable secondary user throughput and average primary user disruption rate. Channel occupancy prediction is indeed a challenging task due to the random nature of the wireless environment and also its users. Even with all its challenges, an accurate prediction model will offer significant performance improvements in terms of increased secondary user throughput and decreased primary user disruption, particularly under heavy traffic density conditions.

The fundamental difference between a dedicated spectrum system and a shared spectrum system is the right of spectrum usage for the secondary users. The objective of dynamic spectrum access paradigm is the opportunistic secondary use of shared spectrum in a way that ensures uninterrupted PU operation. As expected the researchers focus on opportunity detection, dynamic opportunity scheduling, and interference protection for the PU [17, 33-36] to achieve that objective. In this context, the root problem between shared and dedicated spectrum systems that leads us to the above mentioned research areas is the lack of knowledge about the availability and duration of spectrum opportunities. For wireless systems with dedicated spectrum and homogeneous systems, we know which channels are available for use and the duration for which the channels can be used is not an issue. As expected, in the dedicated spectrum paradigm, some of these problems do not exist and there are well established and matured solutions for the other problems. In a shared spectrum system, the users do not know which channel they can use and for how long. So the lack of information about the availability and duration of spectrum opportunity is the root problem that the research community tries to overcome by exploring solutions for the above mentioned research focuses.

In dynamic spectrum access, secondary users opportunistically access the shared channels when absence of primary user has been detected. A new secondary user request may be blocked and an ongoing secondary user service may also be discarded if no sufficient spectrum is available. Thus the fate of a new secondary user request is significantly influenced by the availability of spectrum opportunities. Spectrum opportunity availability is an important metric for secondary user operation to be considered when accessing channels in a cognitive radio network. In order to facilitate dynamic access of spectrum opportunities, various techniques have been proposed in the literature including spectrum sensing [176], channel access schemes and resource allocation [240, 241], and spectrum management [242]. However, there has not been many reported work on the availability and duration of available spectrum opportunities in the spectrum sharing systems. From the perspective of a secondary user operation, the reliability and dependability of the service provided by a secondary network depends on the achievable quality of service (QoS) while using the shared spectrum opportunities.

The primary-secondary cooperation can have significant impact on the spectrum sharing performance from the perspective of either side. Without any prior information about the availability and duration of spectrum opportunities, the secondary user operations need to continuously monitor the spectrum blocks under consideration in order to identify the opportunities and also the return of the primary user operations. This continuous monitoring results in significant consumption of time, energy, and spectrum resources. As expected, the continuous monitoring approach adversely impacts the achievable QoS while accessing the shared channels. Also the performance of the detection techniques influences the outcome of the continuous monitoring. Any missed detection results in interference and false alarms lead to missed opportunities. The generation of a probabilistic assurance (SODA) for the availability and duration of available channels was presented in Chapter 3. The SAS generates a Spectrum Opportunity Duration Assurance (SODA) based on the spectral characteristics, usage pattern, and tentative future usage plane of the incumbent operations [45]. The only involvement of the primary is to allow the authorized SAS to access its operational information and usage log of previous activities. The SODA metric provides the SAS and the secondary user resource manager (SU-RM) a probabilistic estimation about the availability of the spectrum opportunities for specific time period. This helps the SAS and the SU-RM to develop efficient resource allocation algorithms and improves achievable QoS from the perspective of the secondary user operation without exposing the primary user operations. The SODA approach allows the spectrum sharing system to consider interference avoidance techniques while allocating the available spectrum opportunities. The resource allocation algorithms can have flexibility to vacate different spectrum opportunities at different instances of the opportunity duration based on the probabilistic assurance SODA. Thus the incumbent operations can ensure desired interference environment through the SAS by providing required information towards the SODA metric.

In this problem, we look in to the ways to efficiently use the primary user cooperation in order to improve the spectrum sharing experience of both primary and secondary operations. The SODA metric generated periodically by SAS is used to facilitate cognitive use of the spectrum opportunities. In order to reduce the overhead in frequently generating and accessing this information, we propose to maximize the utility duration of the SODA information using the concept of "Time Discounted Value of Information". We determine the effective value of the information at any particular time instant within the assured duration and decide whether to improve the assurance by employing sensing techniques or not. In this analysis, we propose interference avoidance schemes that use channel monitoring based on the time discounted value of the PU cooperation and reduce the number of time slots in collision between the primary and secondary operations. These interference avoidance schemes facilitate the desired interference environment for both the primary and secondary operations. Next we use the interference avoidance schemes to analyze their impact on the achievable QoS from the perspective of secondary user operations. The interference avoidance schemes use a combination of primary user cooperation and channel monitoring techniques to reduce the resource consumption for channel monitoring during the early stage of the assured duration and at the same time reduce the likelihood of interference in the later stage of the duration with help of channel monitoring. We analyze and theoretically model the reduction in number of sensing events which is required to achieve a desired interference environment and also the improvement in secondary user throughput as a result of primary user cooperation.

Related Work

In Chapter 3, we discussed the generation of the probabilistic assurances about the spectrum opportunities. In this chapter, we focus on making efficient use of this probabilistic assurance to enable dynamic access into the spectrum opportunities. The core activities in a spectrum sharing context include spectrum opportunity identification, QoS prediction, dynamic management of spectrum opportunities including efficient allocation of the available opportunities, continuous monitoring of the opportunity, and maintaining desired interference environment. The opportunistic users can use the information gathered from spectrum opportunity identification and QoS prediction to achieve efficient dynamic access to available opportunities. Literature on predictive dynamic spectrum access generally falls into two categories. A first group explores the prediction techniques themselves and validates these with measurements. The second group optimizes the dynamic spectrum access sensing engine using predictions. The QoS prediction approaches mainly focus on PU usage modeling.

Predictive models have been proposed for cognitive radios to make channel selection more intelligent [186, 239, 243, 244]. However, these approaches have a common problem of restricting the prediction to the known traffic model only. In [243] the exponential weighted moving average based method is proposed to use idle times in TV broadcast channels. Exponential ON-OFF traffic models and periodic-exponential models are investigated in [239]. Reference [186] investigates the predictability when primary traffic is assumed to be a cyclostationary random process. Traffic prediction in [244] is performed using binomial distributed call arrival times and gamma distributed call holding times. A more general method that works with a variety of traffic classes is presented in [245]. The method classifies the traffic in the sensed primary user channels as deterministic and stochastic and uses specific prediction methods for different types of traffic to estimate the expected idle times. The optimal prediction rule for exponential traffic was analytically shown in [246]. The rule is shown also to work well with a Weibull distributed stochastic pattern. [196] extends the work presented in [245] and shows how classification-based predictive method works with various traffic models and analyses the impact of sensing and switching times on the throughput. The authors in [196], proposed a simple classification and learning method to detect the pattern type and to gather the needed information for intelligent channel selection. The paper claimed that the proposed method outperforms opportunistic random channel selection both with stochastic and periodic channel patterns. The intelligent channel selection algorithm also reduces the amount of channel switches needed over time, thus reduces the delay and increases the throughput. The authors in [247], discuss about different traffic models in Broadband Networks. Similarly, the traffic model built on historical data for the secondary users to predict the primary user traffic pattern for the future use is presented in [248]. The classification method and predictive channel selection method proposed in [249], is claimed to outperform opportunistic random channel selection both with stochastic and deterministic patterns. Spectrum opportunity is viewed as a finite delay connectivity due to temporal dynamics of the channel in CRNs without considering the spectrum sensing performance of cognitive radios in [250]. The authors in [251] consider only the spatial properties of successful communication in cognitive radio network. Spectrum sensing performance can be enhanced by exploiting the spatial diversity of sensors and temporal diversity between the slots in a cooperative sense. Although cognitive radios with multiple antennas are costly for resource constrained networks, the spectrum sensing performance can be increased by an improved energy detector and cognitive radios with multiple antennas [252]. The authors in [253] investigate the detection of spatial-temporal opportunity. However, they do not consider successful utilization of spectrum opportunities during a packet transmission. The authors in [254] investigate the joint probability of successful idle channel detection and packet transmission, termed as the utilization of spectrum opportunity (USOP). They determined the probability of USOP in a dynamic radio environment under imperfections in the channel sensing for different network topologies.

The authors in [255], presented an approach for channel availability and call arrival rate. The results were used to evaluate the probability of the channel availability of a frequency band within a time period. They also proposed an algorithm for predicting the call arrival rate which is used to predict the traffic process. The authors in [244], proposed a technique that enables secondary users to evaluate channel availability in cognitive radio networks. Here, secondary users estimate the utilization of channels via predicting the traffic pattern of primary user, and select a proper channel for radio transmission. The proposed technique reduces the channel switching rate of secondary users and the interference on primary users, while maintaining a reasonable call blocking rate of secondary users. The work in [239] proposed a proactive spectrum access approach where secondary users utilize past channel histories to make predictions on future spectrum availability, and intelligently schedule channel usage in advance. It also proposed a two channel selection and switching techniques to minimize disruptions to primary users and maintain reliable communication at secondary users. The authors in [256], constructed an algorithm, based on future use patterns within the licensed bands. It finds the optimal trade-off between packet buffering and channel switching, while guaranteeing delay demands. This paper explores the limits of prediction for scheduling and channel selection. In [239], the goal is to minimize interference to primary users, decrease spectrum handoff delay and, hence, maximize throughput. The proposed mechanism consists of two core modules: the prediction module, that assumes an exponential primary user arrival and the switching module. With a high probability the opportunistic user switches to a channel when it predicts that the current channel will no longer be idle. This minimizes interference towards the PU. Furthermore, the channel with the longest remaining idle period is preferred, as this maximizes secondary user throughput and decreases the secondary user switch frequency. Also in [196], the goal is to minimize collisions with primary users and to minimize the secondary user channel switching frequency. The prediction module, however, is claimed to handle any primary user traffic pattern. In [257] proactive decision for spectrum handoff is modeled and analyzed. Similar to [196], a greedy target channel selection scheme is proposed. The goal is to reduce the total service time. As a result, it always switches to another free channel if the current channel is expected to be busy for a period longer than the switching delay.

The authors in [216] investigated she interdependency amongst spectrum sensing, occupancy modelling, channel switching, and secondary user performance in a cognitive radio network. They also validated the achievable secondary user data throughput and primary user disruption rate with real-world spectrum measurements done in Pretoria, South Africa. A channel switching simulator was developed to investigate secondary user performance, where a Hidden Markov Model was employed to model and predict primary user behavior, from which proactive channel allocations could be made. In [211], a two-state Hidden Markov model, which is used to predict primary user behavior, is proposed. This model relies on historical usage data. In [258], usage of historical primary user behavior, measured from the 6 GHz region, was shown to improve the secondary user decision making process. Furthermore, intelligent approaches to channel switching, based on proactive channel predictions, were proposed in [239, 245]. The authors in [216] extend the work in [239, 245] by using the Hidden Markov Model approach used in [211], to investigate the effect that intelligent channel switching has on secondary user performance in a cognitive radio network. The interdependent relationship between spectrum sensing, primary user traffic modelling, channel switching, secondary user throughput and average primary user disruption rate, is the main focus of the article. The authors presented a proactive channel switching simulator for performing simulations to investigate the effect that the channel occupancy model has on the channel switching process and the subsequent effect that this has on secondary user data throughput and primary user disruption rate. In [9], for a given frame duration, Liang et al considered the design of optimal sensing slot duration to achieve the maximum throughput of cognitive radio network, yet to protect the primary users by achieving certain probability of detection. Intuitively, the longer time that the cognitive users spend on sensing the channel, the better the protection that the primary users will get; however, longer sensing time will result in a reduction in the amount of time for data transmission and hence affect the achievable throughput of the CR users. The authors in [259] formulate a collision-throughput tradeoff problem which, based on the sensing time requirement and the traffic pattern of primary users, finds optimal value for the frame duration of CR operation so that the throughput of the CR network is maximized, yet the collision probability of the primary users is not greater than a threshold. Since secondary users can only access the licensed channels when they do not cause intolerable interference to primary users, they have to monitor the occupancy of the licensed channels continuously. Spectrum sensing, which aims at monitoring the usage and characteristics of the covered spectral bands, is thus required for cognitive radio users both before and during the use of the licensed spectrum bands [137]. The periodic spectrum sensing during the use of licensed channels is critical to any practical CR networks since it determines the protection level provided to the primary system. In the literature, statistical characteristics of the licensed channel occupancy, including the distributions of the idle and the busy durations of the licensed channel, have been utilized to optimize the cognitive radio frame structure [175, 259-261] and improve spectrum sensing scheduling in determining when and which licensed channel to sense [261-263]. However, such statistical characteristics have not been taken into account for spectrum sensing scheme design. Instead, it has been always implied that the primary user appears at the beginning of a sensing block. In reality, the primary user may appear at any time within a sensing block. Based on the statistical characteristics of the licensed channel occupancy, [177] presented a probability model regarding the appearance of a primary user at any sample of a CR user frame. Based on the Neyman-Pearson criterion, the paper proposed an optimal spectrum sensing scheme under this probability model that maximizes the detection probability for a given false alarm probability. While the conventional spectrum sensing scheme always allocates the same weight to each sample, the authors in [177] developed a suboptimal probability based energy detection scheme, in which the weight for each sample is based on the probability of the presence of primary user at the corresponding sample.

The authors in [264] define a few reliability metrics for channel access in multichannel cognitive radio networks that are analogous to the concepts of reliability and availability in classical dependability theory. Continuous-time Markov chains are employed to model channel available and unavailable time intervals based on channel occupancy status. The impact on user access opportunities based on channel availability is investigated by analyzing the steady-state channel availability and several system times such as mean channel available time and mean time to first channel unavailability. Moreover, the complementary cumulative distribution function for channel availability is derived by applying the uniformization method, and it is evaluated as a measure of guaranteed availability for channel access by secondary users. Reliability is of fundamental importance for the performance of secondary networks in cognitive radio networks. The authors in [264] propose a number of reliability and availability metrics for channel access in cognitive radio networks are defined from the perspective of dependability theory [265], including mean time to first channel unavailability, mean time to channel unavailability, mean channel available and unavailable times, and steady-state channel availability. They also introduced a scale of guaranteed availability and deduced the complementary cumulative distribution function (CCDF) of channel availability of cognitive radio networks. In [266], a resource management controller was designed for primary and secondary traffic in vehicular networks. The proposed controllers provide reliable guarantees to PU traffic in terms of aggregate goodput and collision rate. Moreover, Cordeshi *et al.* also proposed a reliable adaptive resource management controller in [267] for cognitive cloud vehicular networks to provide hard reliability guarantees to PU traffic in the presence of mobility and fading-induced changes in vehicular networks. To maximize the network performance of a single channel cognitive radio network, a combined scheme considering primary user activity and spectrum opportunity detection was proposed in [268] to address the potential drawbacks of the Poisson model. The availability and reliability of wireless multihop networks, not of cognitive radio networks, were evaluated in [269] by considering stochastic link failures. By placing redundant nodes at appropriate locations in the existing network, the availability of wireless links is improved. The availability of a multicell cognitive radio network under time-varying channels was studied in [270], and accordingly, an efficient spectrum allocation mechanism was proposed. In the proposed network model therein, the average number of available channels is determined based on busy probabilities of channels. In [271], Liu et al. demonstrated that deterministic channel failure models might result in a significant overestimation or underestimation of network reliability. Therefore, a reliability assessment was performed for wireless mesh networks in [271] by considering a probabilistic regional failure model that analyzed the geographical location of the network. Another recent paper [272] focused on investigating the security–reliability tradeoff of cognitive relay transmission in the presence of realistic spectrum sensing. Therein, reliability was characterized in terms of outage probability. In [248], the probability of the availability for a spectrum band in cognitive radio network was evaluated by incorporating the results of an algorithm that can predict the arrival patterns of primary users. Thereafter, a similar but improved technique was also proposed by Li and Zekavat in [273] to evaluate channel availability in cognitive radio networks. In [274], three availability metrics were defined from the perspective of dependability theory. In [275], Azarfar et al. analyzed the feasibility of opportunistic spectrum access in cognitive radio networks to provide a robust infrastructure for wireless networks. Moreover, in [276, 277], the reliability aspects in CRNs are also analyzed. Precise assessment of the available channels based on channel utilization status is one of the essential tasks in [278]. Accurate channel availability measurements help the secondary network to appropriately select the available channels. This would lead the cognitive radio network to minimize the instability problem for secondary user connections and the interference to primary user services while facilitating optimal resource allocation [143], e.g., achieved by building an availability map for the channels that can be used [278, 279]. Therefore, the probability of channel being available for a given time period is a useful parameter to evaluate the performance of a cognitive radio network. To evaluate channel idleness and occupancy, a validated probabilistic model was developed in [174]. Therein, real time measurements of spectrum utilization, e.g., transmission power, center frequencies and time duration of operations are used to determine the primary user occupancy patterns. However, the model developed in [174] does not provide a method for evaluating the overall spectrum availability. Thereafter, a follow-up [280] focused on building a predictive model on spectrum availability based on publicly available and accredited data over several spectra. A combined approximation of Poisson and normal distributions called Poisson-Normal approximation was used in [280] to determine the distribution of the number of idle channels. However, important parameters such as mean channel idle time and mean channel busy time are not evaluated in [280].

One of the major constraints of coexistence is ensuring the desired interference environment for all the parties involved. The Federal Communications Commission (FCC) introduced the interference temperature model to be used for interference avoidance schemes in wireless communication [281]. The interference temperature is defined as the radio frequency (RF) power measured at a receiving antenna per unit bandwidth. Using this model, cognitive radios operating in licensed frequency bands would adjust their transmission power to avoid raising the interference temperature over the interference temperature limit. The authors in [282] described two interpretations of the interference temperature model and discussed how to select an optimal radio bandwidth for a particular interference environment. In [283] expressions for achievable capacity and impact to licensed users for protocols implementing the interference temperature model were derived. Papers considering interference temperature as main constraint for cognitive radio network include [284-286]. Another major type of interference avoidance approach is dynamic spectrum access based spectrum sharing which allows secondary users to access licensed channels when primary users are not transmitting. To seize transmission opportunities left by the primary users and limit the interference, the secondary user needs to sense the channel before transmitting. Due to the fact that secondary user could not sense the channel while transmitting; collision with the primary user is inevitable. The access protocol for dynamic spectrum access system was discussed in [287, 288] and a number of other papers. The authors in [289] adopted collision probability with the primary user as major constraint on secondary user and considered the problem of maximizing the throughput of the secondary user. In [158], Hidden Markov Model was used to predict the channel state and algorithm was proposed to reduce collisions and improve throughput of the secondary user.

System Model

In this section, we present the system model for analyzing the impact of having knowledge about the availability and duration of spectrum opportunities on the performance of a spectrum sharing system. Within the context of spectrum sharing, the secondary user tries to use the spectrum owned by the primary user without interrupting its operation. In order to ensure uninterrupted primary user operation, the secondary user needs to identify spectrum opportunities that are not used by the primary users at that instant. This identification of spectrum opportunities can be done by the secondary user system with or without primary user cooperation. The work presented in this section analyzes what impact the '*with or without primary user cooperation*' has on the performance of the spectrum sharing system.

In this work we define primary-secondary cooperation as the event in which the primary user informs the secondary user about its usage model in a probabilistic sense. For a given primary user, the usage model and the return of the primary user in a period of 'no-activity' can have a specific pattern or may follow any particular distribution [42]. For a given opportunity duration, T_{opp}, the primary user operation may return after X units of time has elapsed. The random variable X follows a distribution $\wp(X)$. Figure 15 shows the opportunity duration for the secondary user and the return of primary user operation within the opportunity according to the distribution $\wp(X)$.

The secondary user on the other hand tries to identify the availability and estimate the duration of available spectrum opportunities as accurately as possible. If the secondary user doesn't get any cooperation from the primary user, it tries to know the availability and duration information through channel monitoring using different spectrum sensing techniques. For the use cases where the primary user agrees to cooperate with the secondary user operation, the extent of primary user cooperation determines the methodology for estimating the availability and duration of the available spectrum opportunities.

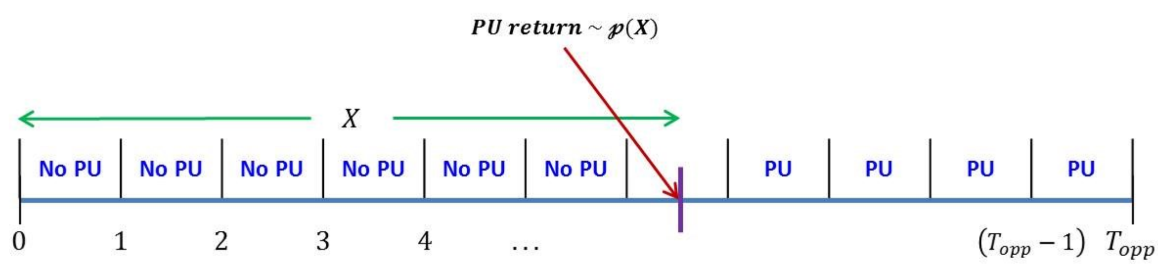


Figure 15: PU operation returns within the opportunity duration according to $\wp$(X)

If the secondary user has cooperation from the primary user, it utilizes that information to estimate the fraction of the opportunity duration for which it may transmit without employing any channel monitoring techniques while achieving a certain probability of not interfering with the primary user. In order to lay out the system model for this work, we assume that the secondary user utilizes information from both sources, the primary user cooperation and the channel monitoring sensors, to improve the system performance and interference avoidance. We also assume that the secondary user vacates the channel once it identifies the presence of primary user operation and does not return to or monitor the channel once vacated. According to these assumptions, the duration of primary user operation will determine the amount of idle spectrum once the secondary user vacates a spectrum opportunity. For primary user operations with small ON time, the system model presented here should be modified to improve the usage efficiency of the available spectrum opportunities. If the secondary user has access to the probability density function (pdf) of primary user usage model, $\wp(X)$, it can calculate the probability of primary user returning outside the duration of the spectrum opportunity.

$$\int_0^{T_{opp}} \wp(x)\,dx = P\left(X \leq T_{opp}\right)$$

$$\Rightarrow P\left(X \geq T_{opp}\right) = 1 - \int_0^{T_{opp}} \wp(x)\,dx$$

(11)

Now the primary user may return anytime within the opportunity duration, T_{opp}, with the probability $P\left(X \leq T_{opp}\right)$. But the secondary user may access the opportunity only if the primary user does not return within the opportunity duration. Thus we are more interested with the event that describes the probability that primary user will return after the opportunity duration: $P\left(PU\ return\ after\ T_{opp}\right),\ i.e.\ P(X \geq T_{opp})$.

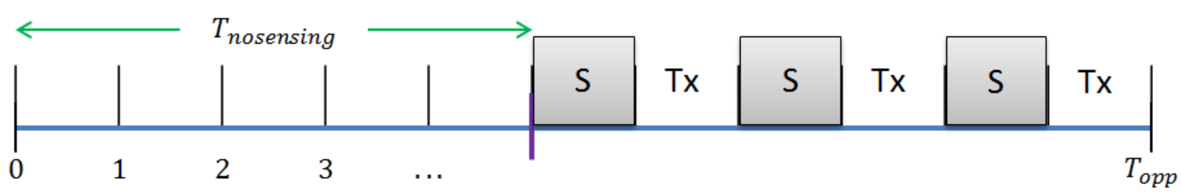


Figure 16: Secondary Users use PU Cooperation and Channel Monitoring to access the Spectrum Opportunities

We are also interested in estimating the 'mean channel available time', that is the average time duration after which the primary user operation may return within the opportunity duration. If the secondary user's opportunistic access to the shared spectrum is based on the primary-secondary cooperation only, the secondary user operation can use this duration and achieve interference avoidance probability of $1 - P\left(X \leq T_{opp}\right)$. We call this fraction of the opportunity duration $T_{nosensing}$, within which the secondary user can transmit without sensing and hope to achieve interference avoidance with a probability of $1 - P(X \leq T_{opp})$. As can be seen from Figure 16, the secondary user transmits for $T_{nosensing}$ amount of time before employing the first sensing event. When calculating $T_{nosensing}$, we keep in mind that the primary user operation may return to the channel at any instant after T_{opp}. But for the purpose of $T_{nosensing}$ calculation it does not matter at which instant after T_{opp} the primary user return. We are only interested in the fact that the primary user operation returned after the opportunity duration. Therefore, to determine the time within which the secondary user can transmit without sensing and still achieve interference avoidance with probability $1 - P(X \leq T_{opp})$, we consider that all the instants after T_{opp} as a single absorbing instant. Now, using the pdf of primary user usage model, $\wp(X)$, we can calculate $T_{nosensing}$ using (12).

$$T_{nosensing} = \int_0^{T_{opp}} x\wp(x)\,dx + \int_{T_{opp}}^{\infty} T_{opp}\wp(x)\,dx \tag{12}$$

■ **Trust Margin**: Interference Avoidance Control parameter

The probability of not interfering with the primary user operation depends on the probability density function (pdf) of the primary user usage model. But the secondary user system may want to increase the interference avoidance probability by employing sensing mechanism at an earlier instance than $T_{nosensing}$. To facilitate this control over the occurrence of the first sensing event, at this stage of the system model we propose a system parameter to control the interference avoidance probability, a "trust margin", α. The trust margin will enable the secondary user system to employ the sensing mechanism such that it can achieve desired level of interference avoidance. This can be done by using the trust margin to reduce the duration for which the secondary user operates trusting the primary user usage model only and don't employ any sensing mechanism. So by reducing the duration of the opportunity, the secondary user boosts its trust on the primary user assurance of the availability and usability of the spectrum opportunity. The value of $\alpha \geq 0$ can be set to achieve any desired probabilistic assurance of not interfering with the PU operation.

$$\begin{aligned} 1 - P_{desired}(X \leq T_{opp}) &= (1+\alpha)\left[1 - P(X \leq T_{opp})\right] \\ \alpha &= \frac{1 - P_{desired}(X \leq T_{opp})}{1 - P(X \leq T_{opp})} - 1 \end{aligned} \tag{13}$$

■

In the following, we will discuss a number of system parameters and how the Trust margin parameter affects them. With trust margin α that achieves the desired interference avoidance, the time to employ the 1st sensing event, $T_{nosensing,desired}$ can be calculated according to Eq. (14).

$$\int_{T_{nosensing,desired}}^{\infty} p(x)\,dx = (1+\alpha)\left[1 - P\left(X \le T_{opp}\right)\right] \tag{14}$$

In this work we set the trust margin ($\alpha \ge 0$) such that $T_{nosensing,desired} \le T_{nosensing}$ to ensure that the secondary user operation uses the spectrum opportunities without employing any sensing mechanism only when there is a low probability of primary user returning with the duration of spectrum opportunity. As can be seen from Figure 17, the secondary user operation makes use of the pdf of the primary user usage model, the trust margin, and the sensing mechanism to improve its system performance and at the same time to achieve desired interference avoidance. According to the system model presented here, the secondary user operation employs the first sensing event after $T_{nosensing,desired}$ time has elapsed in order to improve the interference environment at the later part of the spectrum opportunity.

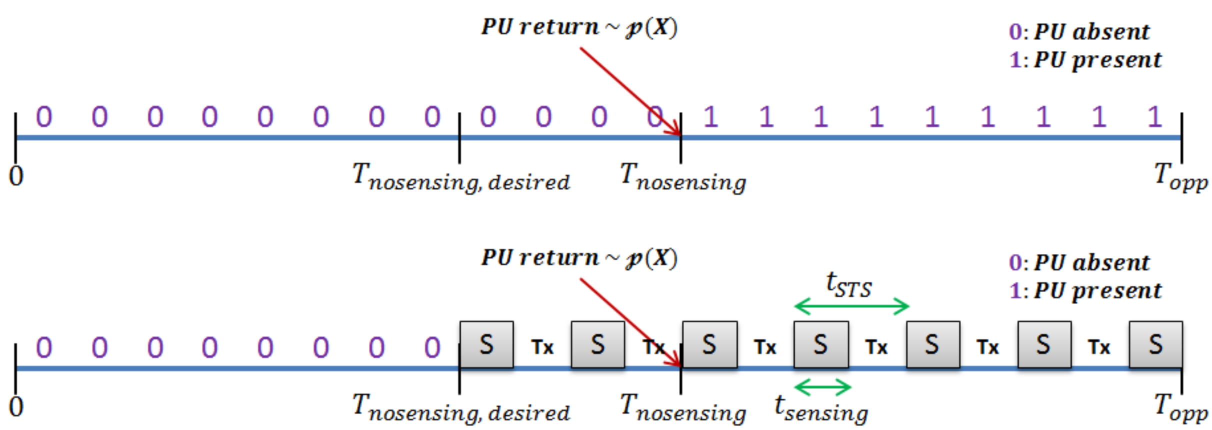


Figure 17: Trust margin improves interference avoidance by reducing time to employ first sensing event

For the purpose of analysis, we assume that the sensing mechanism employed by the secondary user operation can be characterized by the performance parameters, such as probability of false alarm, P_f, and probability of missed detection, P_m. For the system model presented here, the time between two sensing events, the sensing period, is constant throughout the remainder of the spectrum opportunity. So once the channel monitoring starts, the spectrum sensing techniques used are similar to those used in a Sense-Transmit-Sense system that does not use primary user cooperation. We also assume that once the sensing mechanism indicates the presence of primary user operation, the secondary user operation vacates the shared channel for the whole duration. We can calculate the maximum number of sensing events, $N_{S_{max}}$, required to achieve the desired interference avoidance.

$$\begin{aligned} N_{S_{max}} &= N_{S_{max\_1}} + N_{S_{max\_2}} \\ &= \frac{t_{STS} - t_{sensing}}{t_{STS}}\left(T_{nosensing} - T_{nosensing,desired}\right) \\ &\quad + \frac{t_{STS} - t_{sensing}}{t_{STS}}\left(T_{opp} - T_{nosensing}\right) \end{aligned} \qquad (15)$$

Here $N_{S_{max\_1}}$ represents the maximum number of sensing events between $T_{nosensing,desired}$ and $T_{nosensing}$. $N_{S_{max\_2}}$ represents the maximum number of sensing events for the remainder of the spectrum opportunity. Amongst the two time variables used in Eq. (15), t_{STS} represents the sensing period and $t_{sensing}$ represents the sensing time. As the secondary user operation vacates the shared channel permanently after the detection of primary user presence, the number of sensing events employed will depend on the performance of the sensing mechanisms (P_f, P_m). We can estimate the total number of sensing events employed ($N_S = N_{S_1} + N_{S_2}$) over the duration of the spectrum opportunity, T_{opp}, as follows:

$$\begin{aligned} N_{S_1} &= P_f 1 + (1 - P_f)P_f 2 + (1 - P_f)^2 P_f 3 + \cdots + (1 - P_f)^{N_{S_{max\_1}} - 1} N_{S_{max\_1}} \\ &= P_f \sum_{i=1}^{N_{S_{max\_1}}} i(1 - P_f)^{i-1} + (1 - P_f)^{N_{S_{max\_1}}} N_{S_{max\_1}} \\ &= \frac{1}{P_f}\left[1 - (N_{S_{max\_1}} + 1)(1 - P_f)^{N_{S_{max\_1}}} + N_{S_{max\_1}}(1 - P_f)^{(N_{S_{max\_1}}+1)}\right] + (1 - P_f)^{N_{S_{max\_1}}} N_{S_{max\_1}} \end{aligned} \qquad (16)$$

$$\begin{aligned} N_{S_2} &= (1 - P_f)^{N_{S_{max\_1}}}\left[(1 - P_m)1 + P_m(1 - P_m)2 + P_m^2(1 - P_m)3 + \cdots + P_m^{N_{S_{max\_2}} - 1} N_{S_{max\_2}}\right] \\ &= (1 - P_m)(1 - P_f)^{N_{S_{max\_1}}} \sum_{i=1}^{N_{S_{max\_2}}} i P_m^{i-1} + P_m^{N_{S_{max\_2}}} N_{S_{max\_2}} \end{aligned}$$

$$= \frac{\left(1-P_f\right)^{N_{S_{max\_1}}}}{(1-P_m)}\left[1-\left(N_{S_{max\_2}}+1\right){P_m}^{N_{S_{max\_2}}}+N_{S_{max\_2}}{P_m}^{(N_{S_{max\_2}}+1)}\right]+P_m^{N_{S_{max\_2}}}N_{S_{max\_2}}$$

(17)

At the same time, we can determine the number of slots in which the secondary user system interfered with the primary user operation. These are the slots with collision resulting from the proposed system model. In calculating the number of collision slots, we assume that the primary user usage status remains same after a slot of sensing. If the primary user is present in the sensing slot, it will continue to operate at least for the next SU transmission period. The number of slots with collision can be estimated as,

$$\begin{aligned}
N_C &= N_{C_1}\left(between\ 0\ to\ T_{nosensing,desired}\right) \\
&\quad + N_{C_2}\left(between\ T_{nosensing,desired}\ to\ T_{nosensing}\right) \\
&\quad + N_{C_3}\left(between\ T_{nosensing}\ to\ T_{opp}\right) \\
&= \left[1-(1+\alpha)P\left(X \geq T_{opp}\right)\right] * T_{nosensing,desired} \\
&\quad +\alpha P\left(X \geq T_{opp}\right) * \left[P_m.(1-P_m).1+P_m^2.(1-P_m).2+\cdots+P_m^{N_{S_{max_1}}}.N_{S_{max_1}}\right] * \left(t_{STS}-t_{sensing}\right) \\
&\quad +P\left(X \geq T_{opp}\right) * P_m^{N_{S_{max_1}}} * \left[P_m.(1-P_m).1+P_m^2.(1-P_m).2+\cdots+P_m^{N_{S_{max_2}}}.N_{S_{max_2}}\right] \\
&\qquad * \left(t_{STS}-t_{sensing}\right)
\end{aligned}$$

$$\begin{aligned}
&= \left[1-(1+\alpha)P\left(X \geq T_{opp}\right)\right] * T_{nosensing,desired} + P\left(X \geq T_{opp}\right) * \left(t_{STS}-t_{sensing}\right) \\
&* \left[\begin{array}{l}
\alpha * \left\{\dfrac{P_m-\left(N_{S_{max_1}}+1\right){P_m}^{N_{S_{max_1}}+1}+N_{S_{max_1}}{P_m}^{\left(N_{S_{max_1}}+2\right)}}{(1-P_m)^2}+P_m^{N_{S_{max_1}}}.N_{S_{max_1}}\right\} \\
+P_m^{N_{S_{max_1}}} * \left\{\dfrac{P_m-\left(N_{S_{max_2}}+1\right){P_m}^{N_{S_{max_2}}+1}+N_{S_{max_2}}{P_m}^{\left(N_{S_{max_2}}+2\right)}}{(1-P_m)^2}+P_m^{N_{S_{max_2}}}.N_{S_{max_2}}\right\}
\end{array}\right]
\end{aligned}$$

(18)

The primary-secondary cooperation also allows the secondary user operation to achieve better system performance while achieving the desired interference avoidance with the primary user operation. We can estimate the average throughput of the secondary user operation while the spectrum sharing involves both the primary-secondary cooperation and sensing mechanisms. The amount of that can be sent using a spectrum opportunity depends on the time after which the primary user operation returns to the shared channel. For a spectrum opportunity of duration T_{opp}, the amount of data transmitted by the secondary user, R_{total}, can be estimated using Eq. (19).

$$R_{total} = \begin{cases} T_{nonsensing,desired}C_0 + \frac{t_{STS} - t_{sensing}}{t_{STS}}\left(T_{opp} - T_{nosensing,desired}\right)C_0 & , \quad t \geq T_{opp} \\ T_{nonsensing,desired}C_0 + \left(t - T_{nonsensing,desired}\right)\left(1 - P_f\right)^{\frac{t - T_{nonsensing,desired}}{t_{STS}}} & , \quad T_{nonsensing,desired} \leq t < T_{opp} \\ tC_0 & , \quad 0 \leq t < T_{nonsensing,desired} \end{cases}$$

(19)

As the primary user operation follows the distribution, $\wp(\mathrm{X})$, on average the primary user will return within the opportunity after $T_{nosensing}$ has elapsed (Figure 17). Accordingly, we can also estimate the average throughput, R_{avg}, of the secondary user operation for a spectrum opportunity of T_{opp} duration using Eq. (20).

$$R_{avg} = C_0\left[\left\{1 - (1+\alpha)P\left(X \geq T_{opp}\right)\right\}T_{nonsensing,desired} + \alpha P\left(X \geq T_{opp}\right)T_{TX,sensging}\right]$$

$$Here,$$

$$T_{TX,sensging} = \left\{\left(1 - P_f\right).P_f.1 + \left(1 - P_f\right)^2.P_f.2 + \cdots + \left(1 - P_f\right)^{N_{S_{max\_1}}}.N_{S_{max\_1}}\right\}$$

$$= \left\{\frac{1}{P_f}\left[P_f - \left(N_{S_{max\_1}} + 1\right)\left(1 - P_f\right)^{N_{S_{max\_1}}+1} + N_{S_{max\_1}}\left(1 - P_f\right)^{N_{S_{max\_1}}+2}\right] + \left(1 - P_f\right)^{N_{S_{max\_1}}+1}.N_{S_{max\_1}}\right\}$$

(20)

Time Discounted Value of Information

The system model presented in this discussion assumes that the secondary user operation knows the distribution of the primary user usage model $\wp(\mathrm{X})$. This information is used to determine the probability, $P\left(X \geq T_{opp}\right)$, with which the primary user resumes its operation on the particular channel under consideration. The SODA values determined (as proposed in Chapter 3) provides us with the probabilistic assurance about the duration of the available spectrum opportunities. So we will be using the SODA value generated by the SAS with primary user cooperation as $P\left(X \geq T_{opp}\right)$. The SAS generates the SODA values periodically and uses this information to facilitate cognitive use of the spectrum opportunities. In order to reduce the overhead in frequently generating and accessing this information, we propose to maximize the utility duration of the SODA information using the concept of "Time Discounted Value of Information" [290, 291].

The value of information degrades with time. Let $X(r)$ be the value of the information at time r. To avoid trivialities, let's assume that $X(r) \neq 0$. In its most general form, for $t \geq r$, the discounted value of X at time t is given by,

$$X(t) = X(r)g(r,t) \tag{21}$$

where $g(r,t)$ is the time discount function. In many practical applications, such as the one we are interested, the discount function is (21) is a function of the difference $(r - t)$. Based on this the time discounted value of information can be presented as,

$$\begin{aligned} &X(t) = X(r)\delta(r-t) \\ &with, \qquad \delta(0) = 1, \lim_{x \to \infty} \delta(x) = 0, and\ 0 < \delta(x) < 1 \end{aligned} \tag{22}$$

Olariu et al., [291], proposed a theoretical analysis for the time discounted value of information and showed that the discount function can be modeled to be an exponential decay.

[291] Theorem 4.12 For $\forall r, t\ \ with\ 0 \leq r \leq t$

$$\begin{aligned} &\delta(r-t) = \exp\big(-\lambda(t-r)\big) \\ &with, \qquad \lambda = -\ln \delta(1) > 0 \end{aligned} \tag{23}$$

So the time discounted value of information can be expressed as

$$X(t) = X(r)\exp\big(-\lambda(t-r)\big) \tag{24}$$

We use the concept of time discounted information to model the freshness of information or the trust of the SU operations on the probabilistic assurance provided by the SAS. In the primary-secondary cooperation context, the secondary users receive the assurance from the primary users. According to the theory of time discounted information, secondary user's trust or confidence on the assurance provided by the primary users is at its maximum at the moment when the primary user offers the assurance. Based on the assurance and the trust on the assurance, the secondary users decide whether to access the spectrum opportunity or not. If the secondary user accesses the spectrum opportunity, the trust of the secondary user on the primary user assurance diminishes according to the discount function. So the secondary user continuously monitors the time discounted value of the primary user assurance to decide whether to continue its operation or to vacate the channel in order to minimize interference to the primary users. In the following discussions, we will make use of this 'time discounted vale of information' concept in order to ensure the use of time discounted version of the primary user assurance and thus achieve the desired interference environment for both the primary and secondary users.

In this part of the report, we propose interference avoidance schemes that involve primary user cooperation in order to analyze the impact of cooperation of the performance of spectrum sharing systems. The interference scenario with and without using SODA are presented in Figure 18. Without the primary user cooperation in the form of SODA values, secondary users utilize the Sense-Transmit-Sense (STS) approach. Collision time depends on the primary user arrival instances and the accuracy of the detectors. This is the base access scheme and all the other spectrum opportunity access schemes proposed in this work will be compared to the STS scheme to observe their impact of the performance of the spectrum sharing system. If the spectrum sharing system uses a deterministic access scheme such as a deterministic primary user signal before arrival (the red flag in Figure 18), there is no interference. The systems that use Beacon signal to alert the system of the users arrival falls into this category. IEEE 802.11 b/a/g systems using the Network Allocation Vector (NAV) is another commonly used example of deterministic access schemes [292]. From the perspective of interference avoidance, primary user informing the secondary user before its arrival eliminates any chance of interference.

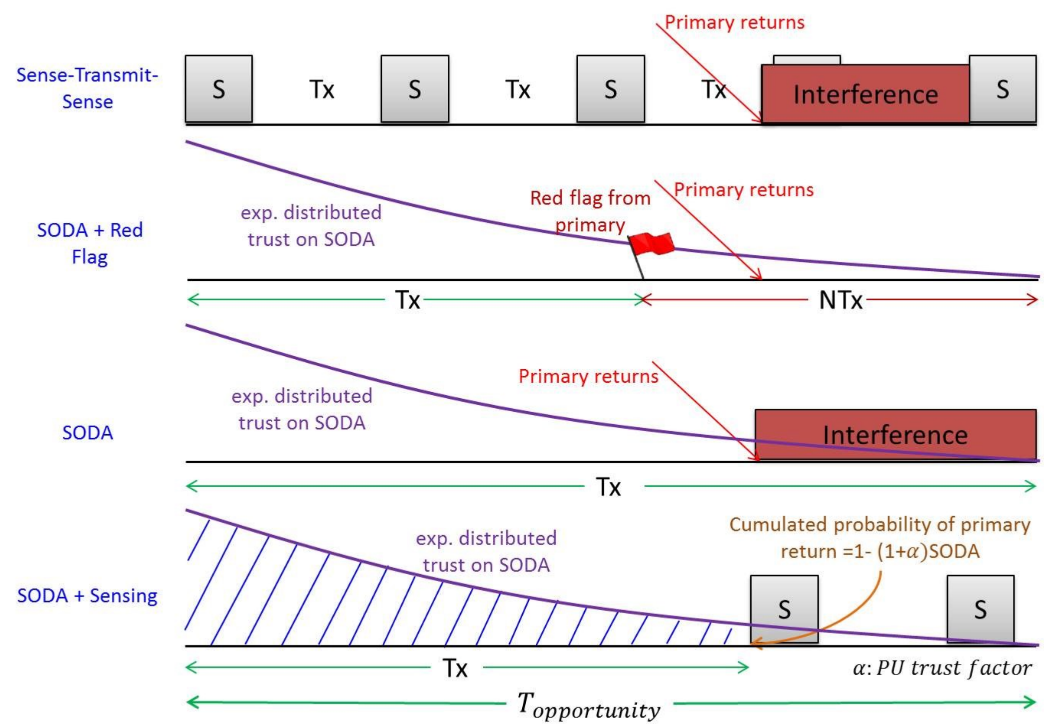


Figure 18: Interference Scenario with and without PU cooperation (SODA)

However, this scheme reduces privacy of sensitive primary user information. Without the primary user "red flag", the secondary user interferes with the primary user with a probability of (*1*-

SODA). For high SODA opportunities this probability will be small. So a spectrum sharing system with low spectrum utilization, i.e., with high probabilistic assurance of not returning within the assured opportunity duration may use the SODA value only to manage the dynamic access to the spectrum opportunities and still achieve a low probability of interference with the primary users. If we employ sensing within the opportunity duration, the likelihood of interference is reduced further. The SODA value probabilistically assures the secondary user operations about the duration of the spectrum opportunities. In other words, it indicates the chances of primary user not returning within the spectrum opportunity. The SAS, using the primary user cooperation, provides the assurance about a channel that it knows to be idle. As this assurance is coming from the source (primary user cooperation), it is more trustworthy compared to any secondary user dependent identification mechanism at the time when the cooperation is received.

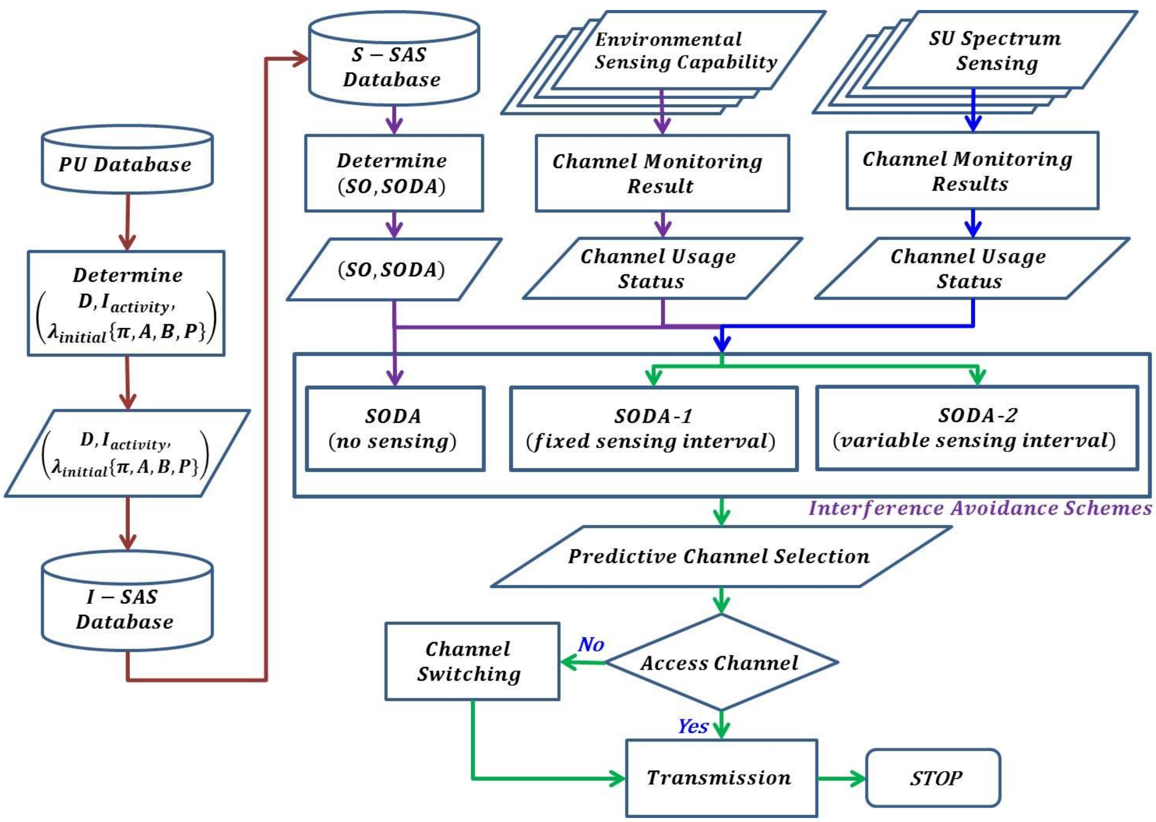


Figure 19: Block Diagram of the Spectrum Opportunity Access based on Interference Avoidance Schemes using Primary-Secondary Cooperation (SODA)

According to the concept of the time-discounted value of information discussed in the previous subsection, it is most likely that the assurance will be more reliable in near future and the reliability will decrease with time. So the probabilistic assurance with which the primary user operation will not return within a specific period decays exponentially. This motivates us to use the exponential distribution to model the trust of secondary users on the primary user cooperation and thus we assume that the time of primary user return within an assured spectrum opportunity is exponentially distributed. Figure 19 presents the block diagram of the spectrum opportunity access based on the interference avoidance schemes using Primary-Secondary Cooperation. As can be seen from the block diagram, the Incumbent SAS gathers the agreed primary user information based on the level of cooperation agreed upon by both parties. In this case the information include the maximum duration of a state (D), the similar activity phase identification $\left(I_{activity}\right)$, the initial Non-Stationary Hidden Markov Model parameters ($\lambda_{initials}$). The Incumbent SAS forwards these primary user information to the Secondary SAS. Upon receiving the primary user cooperation, the Secondary SAS utilizes this information along with the channel monitoring results received from the Environmental Sensing Capability (ESC) system and also from the secondary users. In this submission we propose a number of interference avoidance schemes that make use of both the primary user cooperation and the channel monitoring results to efficiently manage the spectrum opportunity so that the interference to the primary user is avoided. The block diagram shows three of these interference avoidance schemes in operation. Based on the decisions made by the interference avoidance schemes, the secondary SAS performs the predictive channel selection.

The predictive channel selection ensures increased spectrum opportunity availability and at the same time reduced interference to the primary user operation. Based on the prediction channel selection decision the secondary SAS makes the decision whether the secondary user should access the spectrum opportunity or not. If the secondary SAS decide that the secondary user may access the spectrum opportunity, then the secondary user starts transmitting over the shared channel. On the other hand, if the secondary SAS decides not to access the channel then the secondary user is instructed to switch to another spectrum opportunity that satisfies the interference requirements that the secondary SAS is trying to achieve. The interference avoidance schemes proposed in this submission uses both the primary user cooperation (the SODA values) and the spectrum sensing techniques. In order to implement an interference avoidance mechanism, we need to consider two aspects: i) when to start sensing, and ii) the sensing interval. Based on the sensing interval, we propose three interference avoidance schemes in this submission. First we briefly discuss the Sense-Transmit-Sense (STS) approach as presented in Figure 18.

Interference Avoidance Scheme STS: Sense-Transmit-Sense

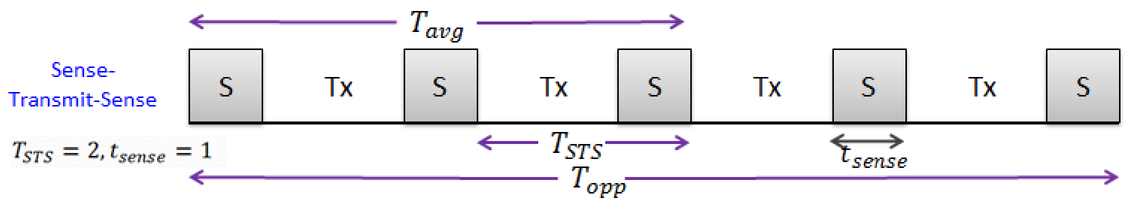


Figure 20: STS Approach for Spectrum Sharing Systems

The *STS* approach does not consider the primary user cooperation (SODA information) and employs sensing throughout the duration of the opportunity (Figure 20). The secondary user throughput in this approach is degraded primarily due to i) the sensing overhead, ii) the dynamic rescheduling and switching overhead, and iii) the session termination and re-establishment overhead. Let's assume P_f and P_m are the probabilities of false alarm and missed detection for the channel monitors employed. Number of sensing events, $N_{S_{STS}}$, and the number of collision slots, $N_{C_{STS}}$, for the STS approach can be determined as follows.

$$N_{S_{STS}} = \frac{T_{STS} - t_{sense}}{T_{STS}} T_{opp} = 0.5T_{opp}$$

(25)

$$N_{C_{STS}} = \left(1 - P_f\right)^{N_0} \left(\frac{P_m}{1 - p_m}\right)\left(1 - (N_1 + 1)P_m^{N_1} + N_1 P_m^{N_1+1}\right) - N_1\left(1 - P_f\right)^{N_0} P_m^{N_1+1}$$

$P_m: probability\ of\ missed\ detection$

$P_f: probability\ of\ false\ alarm$

$N_0: \#\ of\ sensnig\ events\ till\ T_{avg} = 0.5T_{avg} = 0.5xT\_opp$

$N_1: \#\ of\ sensing\ events\ between\ T_{avg}\ and\ T_{opp} = 0.5\left(T_{opp} - T_{avg}\right) = 0.5(1 - x)T_{opp}$

(26)

Interference Avoidance Scheme SODA: SODA without Sensing

The interference avoidance scheme SODA trusts the assurance provided by the SAS. So in this interference avoidance scheme the secondary user do not employ any channel monitoring techniques. Intuitively, one can come to an inference that this approach will boost the achievable throughput by the secondary users because it does not consume any frequency-time resource for monitoring the channel. Also this approach will have less energy consumption compared to those schemes that use spectrum sensing. The SODA scheme operates based on the primary user cooperation and the secondary user utilizes the entire duration of the spectrum opportunity. The probability of interference is $(1 - SODA)$ as no sensing is performed. For high assurance opportunities this probability will be small. We determine the parameter of the exponential distribution, λ, using the SODA value of the spectrum opportunity provided by the SAS:

$$\int_0^{T_{opp}} \lambda e^{-\lambda t}\, dt = 1 - SODA$$
$$\Rightarrow \lambda = \frac{-1}{T_{opp}} \ln(SODA)$$

(27)

We can easily see the similarity of the expression of the parameter, λ, in Eq. (27) and that proposed in [291]. Based on λ and the duration of the opportunity, T_{opp}, we can calculate the mean channel availability duration which is also the average time after which the primary user returns. The mean channel availability duration for the SODA scheme can be determined using Eq.(28).

$$T_{avg} = \int_0^{T_{opp}} t\lambda e^{-\lambda t}\, dt + \int_{T_{opp}}^{\infty} T_{opp}\lambda e^{-\lambda t}\, dt$$
$$\Rightarrow T_{avg} = \frac{1}{\lambda}\left(1 - e^{-\lambda T_{opp}}\right)$$
$$\Rightarrow \frac{T_{avg}}{T_{opp}} = \frac{1 - e^{-\lambda T_{opp}}}{\lambda T_{opp}} = \frac{SODA - 1}{ln(SODA)} = x$$
$$\Rightarrow T_{avg} = xT_{opp}$$

(28)

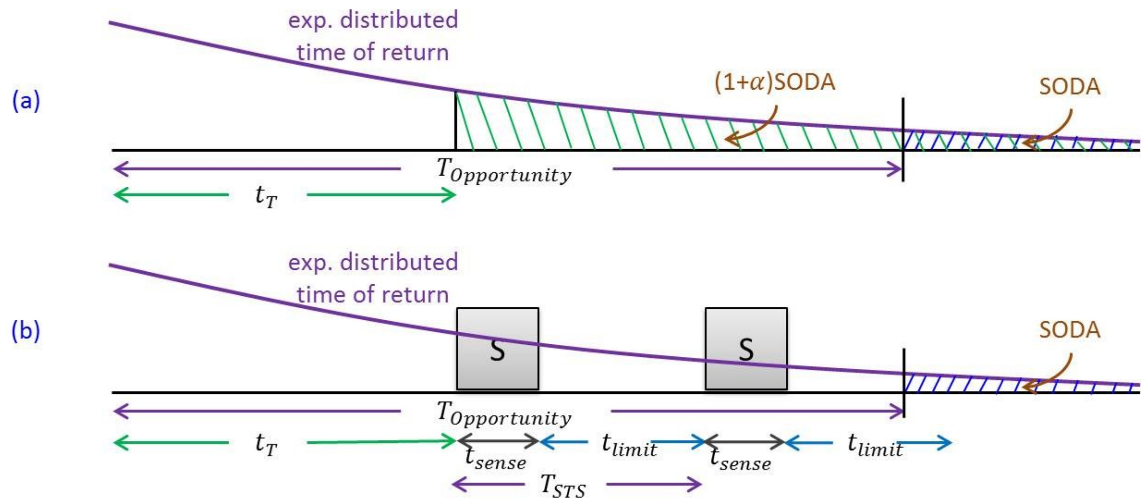
Number of sensing events, $N_{S_{SODA}}$, and the number of collision slots, $N_{C_{SODA}}$, can be determined as follows.

$$N_{S_{SODA}} = 0$$

(29)

$$N_{C_{SODA}} = T_{opp} - T_{avg}$$
$$\Rightarrow N_{C_{SODA}} = (1 - x)T_{opp}$$

(30)



t_{limit}: *collision time that PU can tolerate (from protection requirement constraints)*
t_T: *time to employ 1st sensing event with* $(1+\alpha)QoSA$ *assurance*

Figure 21: SODA-1 Approach: Employing Fixed Sensing Interval: a) Time to employ 1st sensing event with $(1+\alpha)SODA$; b) Fixed interval sensing employed after t_T

Both $SODA_1$ and $SODA_2$ approaches use the probabilistic assurance provided by the SAS and the channel monitoring results to achieve throughput improvement without increasing the chances of interfering with the primary user. In both of these SODA approaches, we assume that the secondary user enjoys the opportunity for t_T amount of time before employing sensing as the primary user is more likely to return in the later part of the opportunity. We use the trust margin parameter, α, to determine the mean channel available time that satisfies the desired probability of interference avoidance. We use this mean channel available time with high assurance as the time to employ the first sensing event with a higher assurance. The trust margin increases the assurance by reducing the duration of the spectrum opportunity. The value of $\alpha \geq 0$ can be set to achieve any desired value of the SODA metric. The time to employ the 1st sensing event, t_T, to achieve the desired assurance of $(1+\alpha)SODA$ can be calculated as (Figure 21 (a)):

$$\int_{t_T}^{\infty} \lambda e^{-\lambda x} dx = (1+\alpha)SODA$$

$$\Rightarrow t_T = \frac{-1}{\lambda} \ln[(1+\alpha)SODA]$$

$$\Rightarrow \frac{t_T}{T_{opp}} = \frac{-1}{\lambda T_{opp}} \ln[(1+\alpha)SODA]$$

$$\Rightarrow \frac{t_T}{T_{opp}} = \frac{\ln[(1+\alpha)SODA]}{ln(SODA)} = y$$

$$\Rightarrow t_T = yT_{opp}$$

(31)

In this scheme, the secondary user waits t_T amount of time before employing sensing at a frequency equal to that of the STS approach (Figure 21(b)). So, $SODA_1$ uses the more conservative STS approach for the later part of the opportunity where the primary user is more likely to return. The number of sensing events required and number of slots with collision in the $SODA_1$ approach is given by:

$$N_{S_{SODA_1}} = (1-P_f)\frac{T_{STS}-t_{sense}}{T_{STS}}(T_{avg}-t_T) = 0.5(1-P_f)(x-y)T_{opp}$$

(32)

$$N_{C_{SODA_1}} = P_m\frac{T_{STS}-t_{sense}}{T_{STS}}(T_{opp}-T_{avg}) = 0.5P_m(1-x)T_{opp}$$

(33)

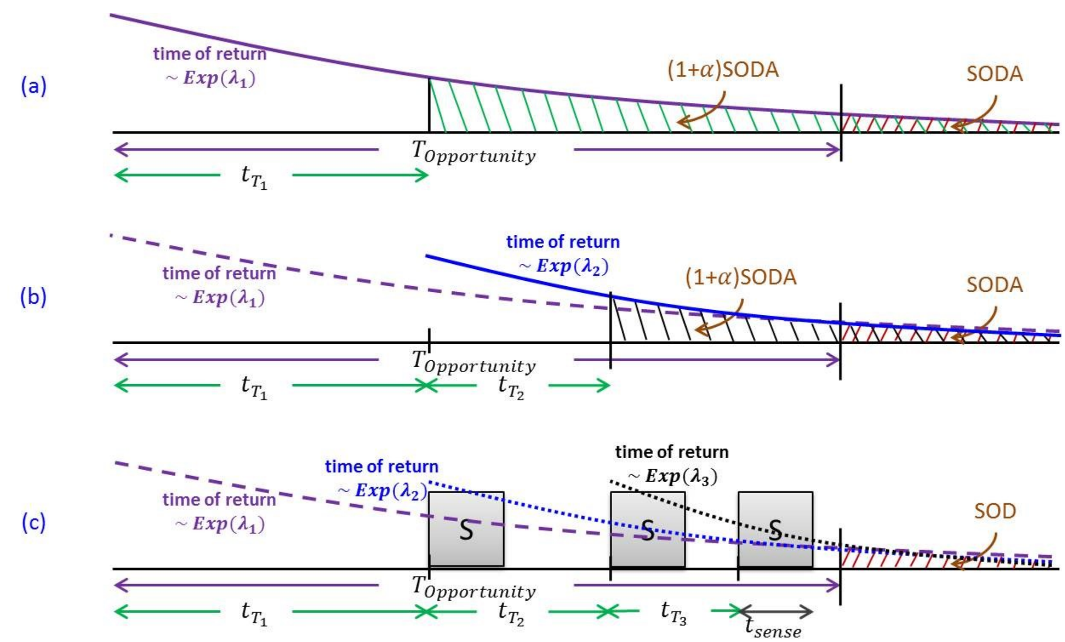


Figure 22: SODA-2 Approach: Employing Variable Sensing Interval: a) Time to employ 1st sensing event with $(1+\alpha)SODA$; b) Time to employ 2nd sensing event; c) Variable interval sensing employed with higher sensing frequency at the later part of the opportunity

Interference Avoidance Scheme $SODA_2$: SODA with Variable Interval Sensing

The $SODA_2$ scheme employs sensing events with variable intervals instead of fixed sensing interval. In this approach, the secondary user transmits without sensing such that the time for employing the first sensing instance is t_{T_1}. This wait time can be calculated as was done with the $SODA_1$ approach. After that the SODA for the rest of the opportunity changes as the secondary user has already enjoyed a portion of the opportunity. The rest of the opportunity now has a different SODA value. We calculate λ_i and t_{T_i} for the rest of the sensing events considering the modified duration of opportunity (Figure 22(b)). Then we calculate λ_is and t_{T_i}s with Δt_i as the time to deploy next sensing event as follows.

$$\int_{T_{opp}-t_{T_1}}^{\infty} \lambda_2 e^{-\lambda_2 x} dx = SODA$$
$$\Rightarrow \lambda_2 = -\frac{1}{(1-y)T_{opp}} \ln(SODA) \tag{34}$$

$$\int_{t_{T_2}-t_{T_1}}^{\infty} \lambda_2 e^{-\lambda_2 x} dx = (1+\alpha)SODA$$
$$\Rightarrow \Delta t_1 = t_{T_2} - t_{T_1} = -\frac{1}{\lambda_2} \ln\big((1+\alpha)SODA\big)$$
$$\Rightarrow \Delta t_1 = y(1-y)T_{opp} \tag{35}$$

Following the same calculation,

$$\lambda_1 = -\frac{1}{T_{opp}} \ln(SODA) \qquad \Delta t_1 = y(1-y)T_{opp}$$
$$\lambda_2 = -\frac{1}{(1-y)T_{opp}} \ln(SODA) \qquad \Delta t_2 = y(1-y)^2 T_{opp}$$
$$\vdots$$
$$\lambda_i = -\frac{1}{(1-y)^{i-1}T_{opp}} \ln(SODA) \qquad \Delta t_i = y(1-y)^i T_{opp} \tag{36}$$

Each sensing interval is smaller than the previous one and ensures more frequent sensing to avoid interfering with the primary user. The $SODA_2$ scheme senses the channel more frequently as we approach the end of the opportunity (Figure 22(c)). The number of sensing events required for the $SODA_2$ approach can be calculated as follows.

$$\Delta t_1 + \Delta t_2 + \cdots + \Delta t_{N_{S_{SODA_2}}} = T_{avg}$$

$$\Rightarrow y + y(1-y) + y(1-y)^2 + \cdots + y(1-y)^{N_{S_{SODA_2}}} = \frac{T_{avg}}{T_{opp}} = x$$

$$\Rightarrow N_{S_{SODA_2}} = \frac{\ln(1-x)}{\ln(1-y)} - 1$$

(37)

The proposed SODA approaches (*SODA₁* and *SODA₂*) make use of both the primary user cooperation and the existing spectrum monitoring techniques (spectrum sensing) to reduce the number of slots in collision. The *SODA₂* uses a variable sensing interval that allows more monitoring in the later part of the spectrum opportunity to reduce interference with the primary user operation. In the next subsection, we analyze the impact of the proposed *SODA₁* and *SODA₂* interference avoidance schemes on the achievable QoS of the secondary user operations using the spectrum opportunities.

In a spectrum sharing context, the achievable throughput by accessing the spectrum opportunities depend on the resources consumed in channel monitoring, channel switching in case of PU return, and session re-establishment as a result of terminated sessions due to the absence of available spectrum opportunities. Thus the secondary user throughput in a spectrum sharing context can be expressed as:

$$R_S = aW - bX - cY - dZ$$

$$c = \sum_i h_i P_h, \quad and \quad d = \sum_i t_i P_t$$

$Here,$

$a: number\ of\ time\ slot\ required\ to\ finish\ the\ transmission$

W: $achievable\ bit\ rate\ per\ time\ slot$

$b: number\ of\ time\ sensing\ is\ required$

$X: sensing\ overhead$

$c: average\ number\ of\ hopping$

$h_i: number\ of\ hopping\ for\ i^{th}\ user$

$P_h: probability\ of\ hopping$

$Y: rescheduling\ and\ hopping\ overhead$

$d: number\ of\ time\ session\ terminated$

$t_i: number\ of\ termination\ for\ i^{th}\ user$

$P_t: probability\ of\ session\ termination$

$Z: session\ reestablishment\ overhead$

(38)

In this work we focus on the performance degradation due to the resource consumption as a result of employing sensing events. We will ignore the channel switching and session termination overhead. Without primary user cooperation, the secondary user utilizes the STS approach to identify and access the spectrum opportunities. As a result a significant amount of time slots are consumed by the sensing events which reduces the achievable throughput by the secondary user operations. Also it potentially increases the channel switching rate and session drop rate due to the return of the primary user operations back in the channel. The SODA based interference avoidance schemes proposed in this report allow the secondary user operations to cut down the number of sensing events employed and improves the achievable secondary user throughput. Before analyzing the achievable secondary user throughput for the interference avoidance schemes $SODA_1$ and $SODA_2$, we present the secondary user throughput for the access schemes that use only primary user cooperation (SODA without sensing) and that for the STS approach.

SU Throughput for SODA without sensing:

For this access approach, the SU operations depends only on the PU cooperation and do not employ any channel monitoring mechanism for the whole duration of the probabilistically assured spectrum opportunities. The achievable SU throughput, assuming a channel capacity of C_0 (b/s/Hz) can be expressed as:

$$R_{SODA} = \frac{T_{avg}}{T_{opp}} C_0 = x C_0 \tag{39}$$

SU Throughput for STS Approach:

On the other hand, the STS approach does not consider the PU cooperation and depends solely on the channel monitoring mechanism to identify and access the spectrum opportunities. The achievable SU throughput, assuming a channel capacity of C_0 (b/s/Hz) and a probability of false alarm of P_f,

$$R_{STS} = \left(1 - P_f\right) \frac{T_{STS} - t_{sense}}{T_{STS}} \frac{T_{avg}}{T_{opp}} C_0$$
$$\Rightarrow R_{STS} = 0.5\left(1 - P_f\right) x C_0$$
$$P_f : probability\ of\ false\ alarm \tag{40}$$

SU Throughput for the $SODA_1$ Approach:

In the *SODA₁* interference avoidance scheme, the SU operations access the spectrum opportunity for t_T amount of time without employing any sensing event. The time to employ the first sensing event, t_T, is determined using Eq. (31) using the SODA value and the duration of the spectrum opportunity. After that the SU operations employ the basic STS approach to identify the return of PU operations into the spectrum opportunity. The SU throughput for the $SODA_1$ approach can be calculated as follows.

$$R_{SODA_1} = \frac{t_T + (1 - P_f)(T_{avg} - t_T - N_{SODA_1} t_{sense})}{T_{opp}} C_0 \tag{41}$$

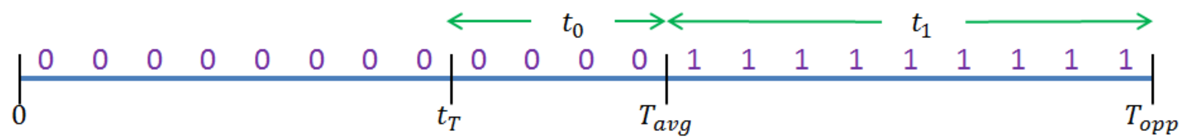


Figure 23: Throughput Analysis for the SODA1 Approach

In order to express the achievable secondary user throughput in terms of the SODA values, here we present a different approach to determine the secondary user throughput for the *SODA₁* approach. According to the assurance from the SAS, on average the primary user will return after T_{avg} amount of time. The secondary user employs the first sensing event after t_T as within this period the secondary user has higher assurance (Figure 23). After t_T the time slots in which secondary user can transmit successfully depends on the performance of the spectrum sensor employed. Considering the effect of sensor performance, the achievable throughput can be determined as follows.

$$
\begin{aligned}
&R_{SODA_1} = \frac{t_T + t_{0_{avg}}}{T_{opp}} C_0 \\
&Where, \\
&\quad t_{0_{avg}} = (1 - P_f)P_f.1 + (1 - P_f)^2 P_f.2 + \cdots + (1 - P_f)^{N_0} P_f.N_0 \\
&\Rightarrow t_{0_{avg}} = \frac{z_0}{1 - z_0}\left(1 - (N_0 + 1)z_0^{N_0} + N_0 z_0^{N_0+1}\right) + N_0 z_0^{N_0}(1 - P_m - P_f) \\
&Here, \\
&\quad t_0 = T_{avg} - t_T \\
&\quad z_0 = (1 - P_f), \\
&\quad N_0 = N_{S_{SODA_1}} = 0.5(x - y)T_{opp} \\
&\quad x = \frac{1 - SODA}{ln(SODA)}, \\
&\quad y = \frac{ln[(1 + \alpha)SODA]}{ln(SODA)}
\end{aligned}
\qquad (42)
$$

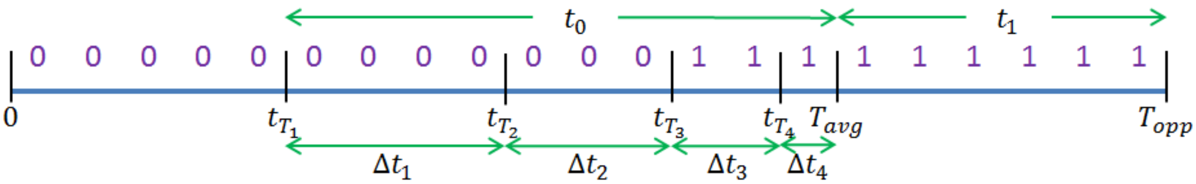


Figure 24: Variable Sensing Time for SODA 2 Approach

SU Throughput for the SODA2 Approach:

The achievable secondary user throughput for the *SODA2* interference avoidance scheme will be influenced by the amount of time the secondary user access the opportunity without employing sensing events, the total number of sensing events employed throughout the duration of the spectrum opportunity, and the sensing time and performance of each of the sensing events. Similar to the expression of the achievable secondary user throughput expression of Equation (41), for *SODA2* approach the expression of secondary user throughput, R_{SODA_2}, can be expressed as:

$$R_{SODA_2} = \frac{t_{T_1} + (1 - P_f)\left(\sum_{i=2}^{N_{SODA_2}} t_{T_i} - N_{SODA_2} t_{sense}\right)}{T_{opp}} \tag{43}$$

Using our understanding of the occurrence of sensing events and the primary user return as shown in Figure 24, the mathematical formulation of the achievable secondary user throughput for the $SODA_2$ scheme can be expressed as follows.

$$R_{SODA_2} = \frac{t_{T_1} + t_{0_{avg}} - N_0}{T_{opp}} C_0$$

$$Here, \quad N_0 = N_{S_{SODA_2}} = \frac{ln(1-x)}{ln(1-y)} - 1 \tag{44}$$

As the *SODA2* interference avoidance scheme employs variable sensing interval in the later part of the spectrum opportunity, the calculation of the second term $t_{0_{avg}}$ on the numerator of R_{SODA_2} in Eq. (44) can be calculated as follows.

$$t_{0_{avg}} = (1 - P_f)P_f \Delta t_1 + (1 - P_f)^2 P_f(\Delta t_1 + \Delta t_2) + \cdots$$
$$+ (1 - P_f)^{N_{S_{SODA_2}}}(1 - P_m)\left(\Delta t_1 + \Delta t_2 + \cdots + \Delta t_{N_{S_{SODA_2}}}\right) \tag{45}$$

Now using the expression of Δt_i's presented in Eq. (36),

$$\Delta t_1 = y(1 - y)T_{opp}$$

$$\Delta t_1 + \Delta t_2 = y(1-y)\{1 + (1-y)\}T_{opp}$$
$$\Delta t_1 + \Delta t_2 + \Delta t_3 = y(1-y)\{1 + (1-y) + (1-y)^2\}T_{opp}$$

So,

$$\Delta t_1 + \Delta t_2 + \cdots + \Delta t_i = y(1-y)\{1 + (1-y) + (1-y)^2 + \cdots + (1-y)^i\}T_{opp}$$
$$= \{(1-y) - (1-y)^{i+1}\}T_{opp}$$

(46)

Using Equation (46) in the expression of $t_{0_{avg}}$ presented in Equation (45) results in the following expression:

$$t_{0_{avg}} = (1-P_f)P_f\{(1-y) - (1-y)^2\}T_{opp} + (1-P_f)^2 P_f\{(1-y) - (1-y)^3\}T_{opp} + \cdots$$
$$+ (1-P_f)^{N_{S_{SODA_2}}} P_f \left\{(1-y) - (1-y)^{N_{S_{SODA_2}}+1}\right\} T_{opp}$$
$$\Rightarrow t_{0_{avg}} = z_1(1-z_0)^{N_0}T_{opp} - \frac{z_1^2(1-z_0)}{z_0} . \frac{1-z_1^{N_0}}{1-z_1}T_{opp} + z_0^{N_0}(1-P_m-P_f) . \frac{z_1}{z_0}\left(1 - \left(\frac{z_1}{z_0}\right)^{N_0}\right)T_{0pp}$$

$Here,$

$$z_0 = (1-P_f),$$
$$z_1 = (1-P_f)(1-y)$$
$$N_0 = N_{S_{SODA_2}} = \frac{ln(1-x)}{ln(1-y)} - 1$$
$$x = \frac{1-SODA}{ln(SODA)}, \qquad y = \frac{ln[(1+\alpha)SODA]}{ln(SODA)}$$

(47)

The proposed SODA schemes improve the interference avoidance ability and the achievable throughput for the secondary user. Without employing sensing events, the probability of interfering with the primary user operation is $(1 - SODA)$ which is small for high assurance opportunities. The *SODA₂* scheme employs the sensing events less frequently at the early part of the spectrum opportunity where the trust on the primary user cooperation is still high. As the secondary user keep on accessing the opportunity, this trust decays and the secondary user operation employs the sensing events more frequently. Thus the $SODA_2$ interference avoidance scheme improves the achievable secondary user throughput by balancing the number of sensing events according to the updated SODA values.

Performance Evaluation

Simulation Setup:

In this section, we present simulation results to validate our claim that the proposed SODA approach offers improved spectrum sharing performance. We assume that the Incumbent-SAS has generated the SODA values using PU cooperation and forwarded the probabilistic assurances for the available opportunities to the Secondary-SAS. We also assume that whenever the SU employs the channel monitoring mechanism (spectrum sensing), it does so for one whole time slot. The channel monitors employed perform sensing with a probability of missed detection of 0.1 and a probability of false alarm of 0.1. The duration of the opportunity used in the simulations is 20 time slots. The trust margin, α, is calculated to achieve a range of desired $SODA$ from 0.6 to 0.9. The arrival of the PU within the opportunity duration is generated using an exponential distribution with parameter λ. If the PU returns in the assured opportunity, the SU vacates the channel and the opportunity is no longer considered. Using different $SODA$ values, the values of λ and the mean channel available time, t_T, are calculated using Eq. (27) and (31) for the $SODA_1$ scheme. For the dynamic spectrum opportunity access scheme $SODA_2$, Eq. (36) is used to calculate the variable sensing intervals. In order to analyze the performance improvement offered by the proposed access schemes, we observe improvement in channel monitoring overhead, probability of interfering with the PU operation, channel switching rate for the SUs, and the normalized SU throughput for each of the schemes. We also observe the impact of the desired interference environment on the achievable SU QoS in dynamic spectrum sharing systems. In the following sections, we present our observations for the four schemes discussed in the paper: *STS*, *$SODA_1$* *$SODA_2$*, and *SODA without sensing*.

Channel Monitoring Overhead:

For dynamic spectrum sharing systems, monitoring the shared spectrum to identify the 'use' status of the channel consumes significant amount of resource in the frequency-time-space resource grid. PU cooperation can significantly reduce this channel monitoring overhead by providing information about the channel usage status. In the spectrum opportunity schemes proposed in this paper, the SUs use the probabilistic assurance provided by the PU cooperation to reduce the channel monitoring overhead. Enabled with PU cooperation, the SUs may enjoy the assured opportunity duration even without employing sensing. Therefore, the $SODA$ approach is expected to reduce the number of sensing events.

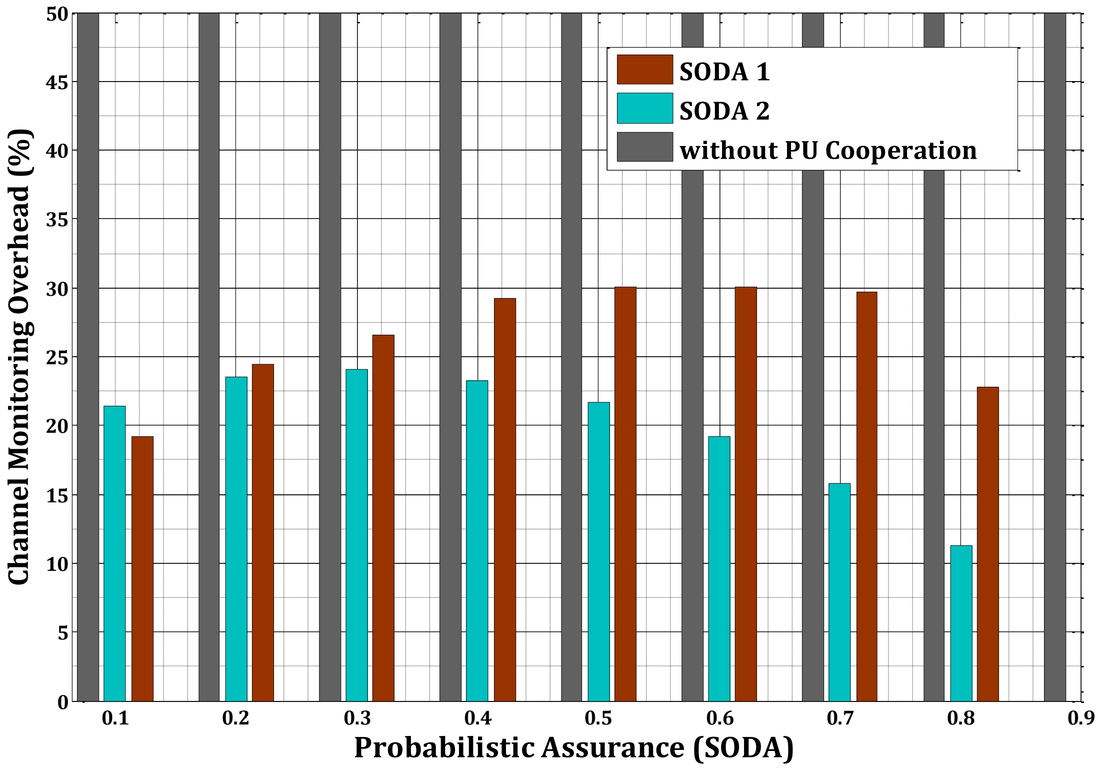


Figure 25: Impact of PU Cooperation (SODA values) on the channel monitoring overhead

Figure 25 presents the channel monitoring overhead for the STS, $SODA_1$, and $SODA_2$ approaches. For a given $SODA$ value, the required numbers of sensing events are determined for different approaches to achieve the desired probabilistic assurance of not interfering with the primary user operations. We did not include the scheme that uses only the PU cooperation as it does not employ channel monitoring. The STS approach consumes 50% of the opportunity as it does not consider the PU cooperation ($SODA$). The variable sensing interval access scheme, $SODA_2$, requires less overhead compared to that for the fixed sensing interval scheme $SODA_1$. Although this difference in channel monitoring overhead is not prominent in the low assurance opportunities, but for the spectrum opportunities with high $SODA$ values, $SODA\_2$ access scheme significantly cuts down resource consumption for monitoring the shared spectrum. The reduction in monitoring overhead can be explained by the less aggressive channel monitoring employed by $SODA_2$ in the initial part of the opportunity. Both the proposed approaches offers significant reduction in the channel monitoring overhead compared to the STS approach. Even for the low assurance opportunities (for example with $SODA = 0.2$), the proposed dynamic access schemes cuts the sensing overhead almost down to half ($\sim 25\% - 30\%$). For a spectrum opportunity with high probabilistic assurance, $SODA = 0.7$, the $SODA_2$ dynamic access scheme results in significant reduction in sensing overhead ($\sim 15\%$).

From the simulation results it is evident that by using PU cooperation ($SODA$ values), we can reduce the channel monitoring overhead and thus improve the SU throughput.

Interference Avoidance:

The dynamic opportunity access schemes proposed in this paper considers the interference avoidance to achieve the desired interference environment for all the parties involved in spectrum sharing. Both the interference avoidance schemes, $SODA_1$and $SODA_2$, use both the PU cooperation and the channel monitoring results to achieve the interference avoidance performance. If the SU operates solely depending on the probabilistic assurance provided by the PU cooperation (through SAS), it cuts down the number of sensing employed throughout the duration of the opportunity. As expected this has adverse effect on the interference environment faced by both the PUs and SUs. The reduction in channel monitoring overhead results in an increase in the number of collision instances. However, this increase in slots with collision may be minimized as the schemes target for the desired $SODA$ by reducing the effective duration of the spectrum opportunity.

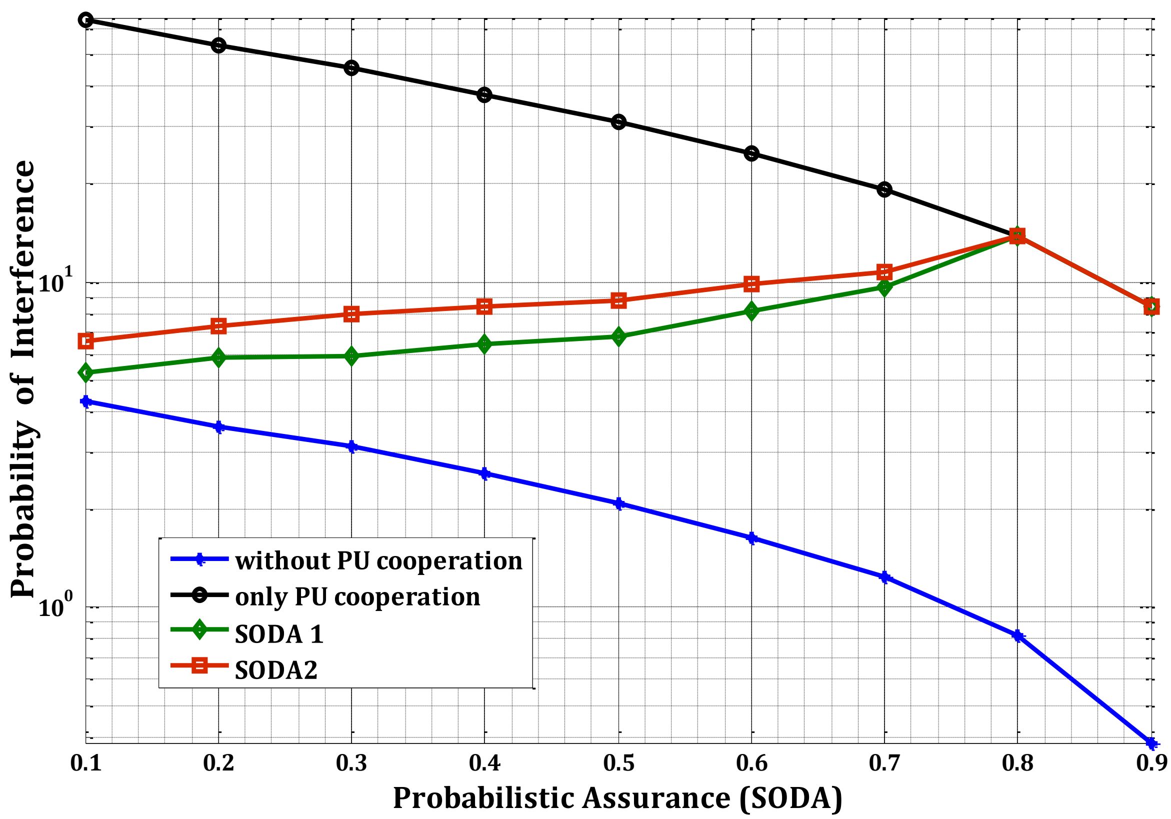


Figure 26: Impact of PU Cooperation (SODA) on the probability of PU-SU interference

Figure 26 presents the impact of PU cooperation on the probability that the SU will be interfering with the PU operation over the duration of the spectrum opportunity. The STS approach, without considering the PU cooperation, offers the best results in terms of avoiding interfering with the PU operation. This can be easily explained by the periodic channel monitoring employed by this scheme throughout the duration of the opportunity. On the other hand, the $SODA$ approach that uses only the PU cooperation and do not employ any channel monitoring, has the highest probability of interfering with the PU operation. Both the dynamic access schemes $SODA_1$ and $SODA_2$ offers similar interference avoidance capability. The $SODA_1$ approach performs slightly better compared to the $SODA_2$ approach as the later employs channel monitoring less aggressively in the initial part of the spectrum opportunity.

Figure 27 presents the channel switching rate experienced by the SU operations. In a spectrum sharing system, if the PU operation returns back to the spectrum opportunity that is being opportunistically accessed by the SU operation, the SU has to cease its operation and switch to another opportunity to continue its transmission. The probabilistic assurance (SODA) offered by the PU cooperation allows the SUs to reduce the channel switching rate and thus save on the channel switching overhead. For low assurance spectrum opportunities, Figure 27 shows that the SU channel switching rate is comparable with that of the STS scheme (without considering the PU cooperation). For the spectrum opportunities with high $SODA$ values, the secondary user channel switching rate is less than 10%. This increase in channel switching rates is due to the reduction of channel monitoring events for the high $SODA$ value spectrum opportunities. Both $SODA_1$ and $SODA_2$ schemes offer similar performance in terms of offering low channel switching rates. The $SODA_2$ scheme results in slightly higher channel switching compared to $SODA_1$, as it employs fewer sensing events at the initial part of the spectrum opportunity.

Figure 27 also shows that the channel switching rate is significant for the access scheme using only the PU cooperation as it does not employ channel monitoring while accessing the opportunity. The channel switching rate is particularly high, especially for the low assurance spectrum opportunities. As the opportunity has low probabilistic assurance ($SODA$ value), the chances that the primary user will return within the opportunity duration are high. Thus the SU operation has to switch to another suitable opportunity in order to continue its transmission. And without employing any channel monitoring, the secondary users are more likely to interfere with the returning primary users. This explains the severely degraded interference environment for the $SODA$ without sensing approach as shown in Figure 26 for low $SODA$ opportunities. But for the spectrum opportunities with high SODA values, the channel switching rate is less than 10%.

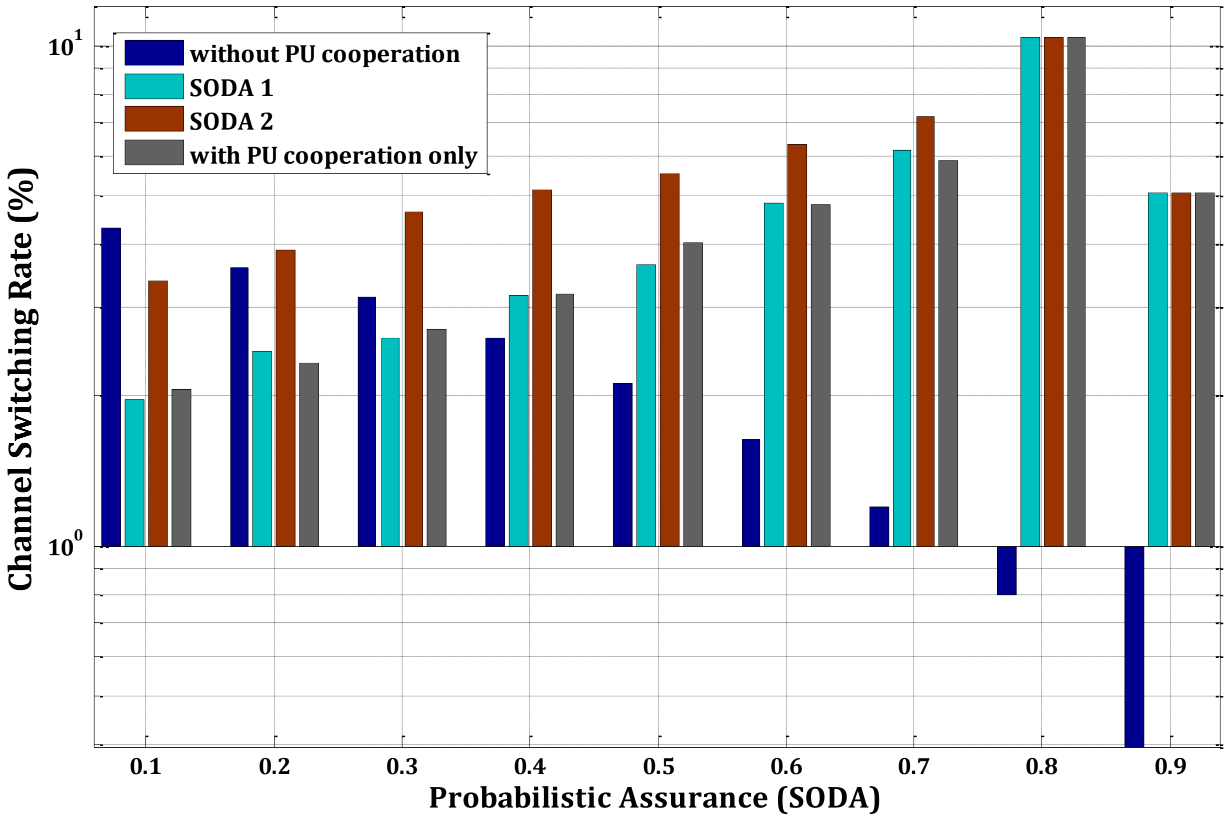


Figure 27: Impact of PU Cooperation (SODA values) on the channel switching rate

Achievable QoS by Secondary Users

The dynamic spectrum opportunity access schemes proposed in this paper takes advantage of the probabilistic assurance offered by the PU cooperation to reduce the dependency on channel monitoring. Thus these access schemes cuts down the channel monitoring overheads and as expected saved resources significantly boost the achievable throughput by the SU operations while accessing the spectrum opportunities. So the throughput of the secondary user is expected to improve as the SODA schemes reduces the number of sensing events without significantly increasing the collision time. Figure 28 presents the achievable secondary user throughput for all the schemes discussed in the paper. Although the STS approach does not consider the PU cooperation, there is a small increase in SU throughput for spectrum opportunities with high $SODA$ values. This is due to the fact that the primary user is returning less frequently in these opportunities. On the other hand, the $SODA$ scheme, without using channel monitoring, offers the highest SU throughput. But this scheme also significantly increases the probability of interference and the SU channel switching rate compared to the other schemes in Figure 27.

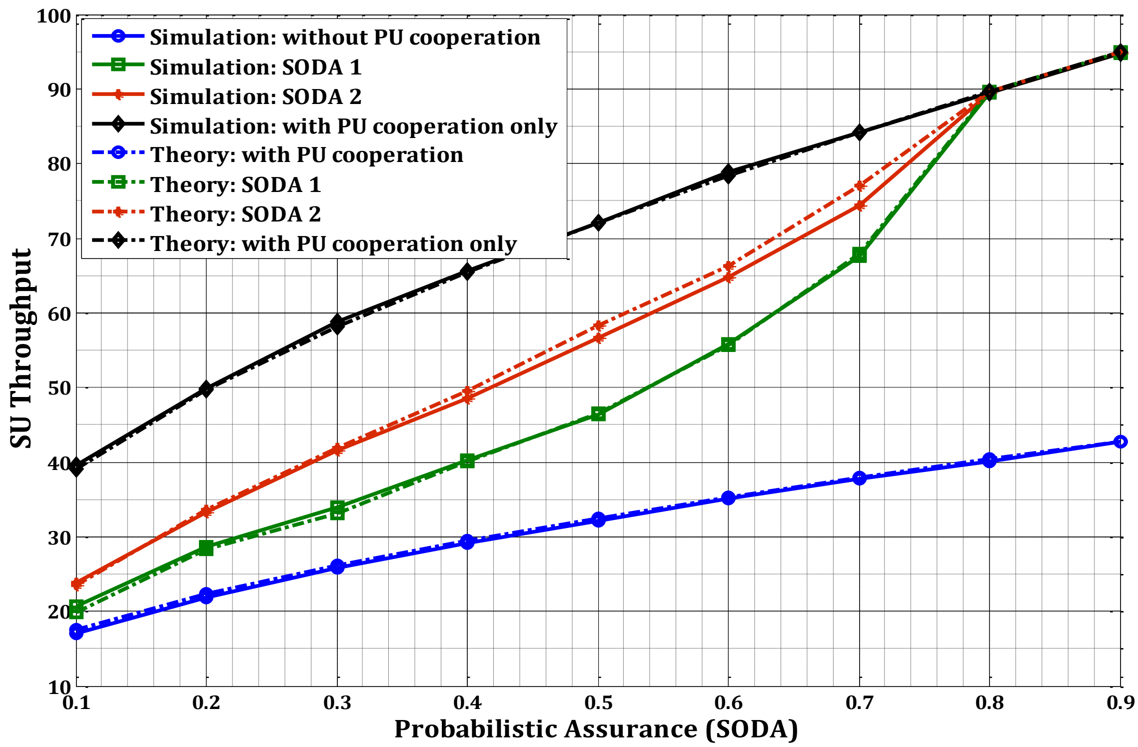


Figure 28: Impact of PU Cooperation (SODA Values) on the SU throughput

The variable sensing interval access scheme, $SODA_2$, performs better compared to the fixed sensing interval access scheme, $SODA_1$, because the later scheme imposes higher channel monitoring overhead on the system performance. For low assurance opportunities the dynamic access schemes $SODA\_1$ and $SODA_2$ performs close to that by the STS scheme. This can be explained by the target interference avoidance performance set by the system. For the purpose of this simulation, the desired SODA value was assumed to be 0.8. So for low $SODA$ value channels, the SU has to employ channel monitoring very early in the duration of the opportunity. Thus both the $SODA$ schemes effectively work as the STS approach. On the other hand, for high assurance opportunities the probabilistic assurance provided by the PU cooperation closely approximates the desired interference environment. So the SU operation may enjoy a big portion of the opportunity without employing channel monitoring. Both the $SODA$ schemes proposed in the paper perform similarly when the given probabilistic assurance ($SODA$) is equal to or higher than the desired $SODA$ (0.8 used for the result presented in Figure 28). In this case, the whole opportunity may be used with the desired $SODA$ and both $SODA$ schemes work like the $SODA$ without sensing approach.

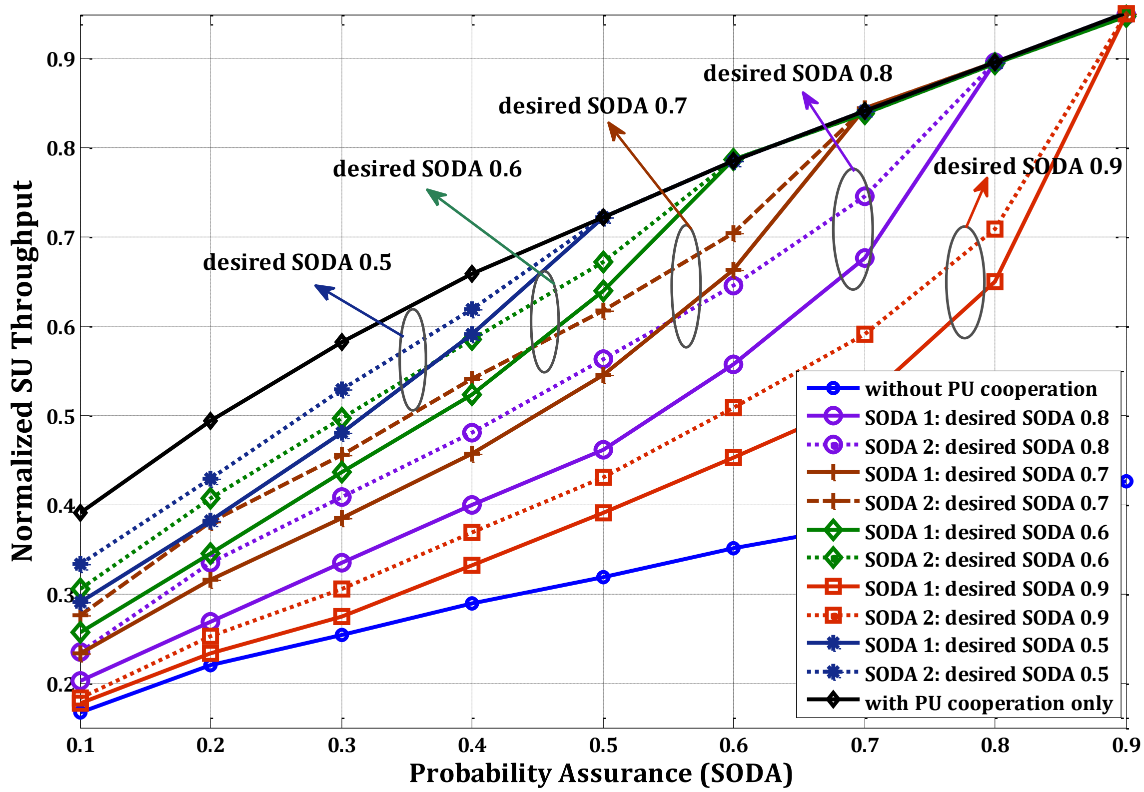


Figure 29: Impact of the desired interference environment on the performance of the spectrum sharing systems

The target interference avoidance performance set by the spectrum sharing system significantly influences the achievable QoS by the SU operation that is opportunistically accessing the spectrum opportunities. Figure 29 presents the simulation results for a number of different interference environment desired by the spectrum sharing system. As can be seen from the simulation results, in order to achieve a high target interference avoidance performance, the dynamic access schemes has to heavily rely on channel monitoring mechanisms in addition to the probabilistic assurances provided by the PU cooperation. For the 'desired $SODA$' value of 0.9 or 0.8, both the $SODA_1$ and $SODA_2$ access schemes performance closely approximates that of the STS approach for spectrum opportunities with low to middle given probabilistic assurance ($SODA$). On the other hand, if the system is willing to tolerate more interference and settle for a relatively low interference avoidance performance then the $SODA$ schemes may reduce their dependency on channel monitoring and rely more on the probabilistic assurance provided by the PU cooperation. This allows the SUs to use the saved resources, as a consequence of reduced channel monitoring overhead, to improve the throughput of the system. Thus the target interference environment naturally influences the inclination of the proposed dynamic opportunity access schemes towards PU cooperation or channel monitoring.

Summary of the Section

In this section we explored the impact of primary secondary cooperation on the dynamic access of spectrum opportunities. We looked in to a number of approaches to efficiently use the primary user cooperation in order to improve the spectrum sharing experience for both primary and secondary operations. The SODA metric generated by SAS is used to facilitate cognitive use of the spectrum opportunities. The cooperation from primary users in the form of supplying SODA values allowed us to propose spectrum opportunity access schemes based on the principle of interference avoidance. In order to reduce the overhead in frequently generating and accessing this information, we proposed to maximize the utility duration of the SODA information using the concept of "Time Discounted Value of Information". We determined the effective value of the information at any particular time instant within the assured duration and decided whether to improve the assurance by employing sensing techniques or not. For a spectrum opportunity with high probabilistic assurance, $SODA = 0.7$, the $SODA_2$ dynamic access scheme results in significant reduction in sensing overhead (~5%). Even with low assurance spectrum opportunities (for example with $SODA = 0.2$), the proposed dynamic access schemes cuts the sensing overhead almost down to half ($\sim 25\% - 30\%$). In this analysis, we proposed interference avoidance schemes that use channel monitoring based on the time discounted value of the primary user cooperation and reduce the number of time slots in collision between the primary and secondary operations. For opportunities with high SODA values, the collision slots are less than 10% of the total time slots. These interference avoidance schemes facilitate the desired interference environment for both the primary and secondary operations. Next we used the interference avoidance schemes to analyze their impact on the achievable QoS from the perspective of secondary user operations. The interference avoidance schemes use a combination of primary user cooperation and channel monitoring techniques to reduce the resource consumption for channel monitoring during the early stage of the assured duration and at the same time reduce the likelihood of interference in the later stage of the duration with help of channel monitoring. We analyzed and theoretically modeled the reduction in number of sensing events which is required to achieve a desired interference environment and also the improvement in secondary user throughput as a result of primary user cooperation. The simulation results show reasonable improvement in the secondary user performance. $SODA$ without sensing scheme results in high throughput (~25% more compared to STS scheme even for $SODA$ as low as 0.1) for secondary user systems. But it also significantly increases the collision time compared to any other scheme. For low assurance opportunities (low $SODA$ values), the proposed access scheme performances (~15-20%) closely approximate that of the STS scheme. As the $SODA$ value increases, the performances of the proposed $SODA_1$and $SODA_2$schemes (~$65-70\%$ for SODA=0.7) gradually approaches that of the $SODA$ without sensing (using primary cooperation only, no sensing employed) scheme (~80% for SODA=0.7).

The SODA approach improves the secondary user throughput even without employing sensing but degrades the interference scenario. If sensing is employed in the later part of the opportunity, it improves the secondary user performance with minimal increase in the collision time. A comprehensive analysis of the secondary user throughput promises interesting insights towards a quantitative metric for the shared band capacity. We plan to analyze the impact of context-aware adaptive SODA values on the performances of the proposed spectrum opportunity access schemes. Replacing QoS prediction by the probabilistic assurance (SODA) proposes a strategic change in the framework of spectrum sharing. The work presented in this chapter provides initial theoretical framework of the SODA approach and our analysis show that the proposed SODA approach improves the overall spectrum sharing efficiency significantly.

Chapter 5

Spectrum Opportunity Auction using Primary-Secondary Cooperation

Chapter 5: Spectrum Opportunity Auction using Primary-Secondary Cooperation

Introduction

With the ever-increasing demand for wireless communications, efficient use of wireless spectrum has become a major challenge. Spectrum regulatory authorities around the world including the Federal Communications Commission (FCC) have reported that the conventional fixed spectrum assignment is no longer capable of meeting today's wireless spectrum requirements [3]. Also, according to the spectrum usage measurements by the FCC's Spectrum Policy Task Force, many of the allocated spectrum bands are idle most of the times or not used in some areas [293]. As expected, the above mentioned reasons prompted the wireless industry to call for better spectrum management techniques and policies. Today, available radio spectrum is allocated in a static manner, often by a government regulator [294]. Growing demands for spectrum and recent studies (e.g., [293, 295-298]) indicate that much of the allocated spectrum is underutilized in many places, revealed the shortcomings of static allocation and the needs for more efficient and flexible spectrum allocation and management.

The explosive growth of wireless technology along with the insatiable demands from content rich applications has made spectrum a critical yet scarce resource. Indeed, the FCC and its counterparts across the world have released licenses of unused spectrum and collected billions of dollars in the past decade. Fundamentally different from conventional goods, spectrum is reusable. Users can share the same channel as long as they can transmit signals simultaneously without disrupting each other's operation. Therefore, the primary license holders may be motivated to open up their underutilized spectrum for sharing, so that they may make profit by leasing access to spectrum resources. In addition, allowing spectrum to be shared by multiple users can also improve the spectrum utilization efficiency. When the spatial reusability is considered, one challenge is to characterize interference relationship among users in cognitive radio networks. Most of the existing spectrum auctions adopt the protocol interference model [299], which simplifies the step of allocation by scheduling users according to conflict graphs.

Dynamic spectrum sharing has been deemed as an effective approach to better utilize limited spectrum resource [19, 20] because clearing and reallocating licenses are extremely expensive. For example, the National Telecom & Information Administration (NTIA) of U.S. reported that the reallocation of 95 MHz (1755-1850 MHz) band would cost $18 billion US dollars over ten years [11]. In order to enable spectrum sharing, international regulators such as the FCC in the US and U.K. Office of Communications (Ofcom) have implemented different spectrum sharing schemes such as licensed shared or license exempt access in different bands including UHF, 2.3 GHz, 3.5 GHz and 5 GHz bands [21, 27]. Take UHF bands as an example. After the transition from analog TV to digital TV, a considerable amount of unoccupied spectrum between 600 MHz and 800 MHz has been released. These bands, referred to as TV white space (TVWS), have been approved for secondary access by FCC [300], Ofcom [301] and Electronic Communications Committee (ECC) in Europe [302]. With the rapid developments of fast mobile broadband access technologies like Long Term Evolution (LTE) and LTE-Advanced (LTE-A), demands for spectrum resource are growing at a surprising pace. In view of high costs and long timeline of spectrum re-farming and reallocation, Citizen Broadband Radio Service is an exciting and highly anticipated spectrum sharing approach proposed by FCC [3] in collaboration with NTIA [46] and Wireless Telecommunication Bureau [31]. The 3.5 GHz NPRM [2] encouraged deployment of small cells and introduced an innovative General Authorized Access tier or lowest priority, in addition to the Priority Access and Incumbent Access tiers to facilitate opportunistic and non-interfering spectrum use within designated geographical areas. The Spectrum Access System was identified as the governing entity of this framework. Its role is manage access to shared spectrum and bridge the interaction between the two sides of the spectrum sharing system to ensure coexistence between primary and secondary users [303, 304]. The research efforts so far mainly focused on efficient detection[305-307] and secondary allocation of the spectrum opportunities[308-310]. Exploitation of underutilized spectrum is an effective approach to meet the explosive demand for wireless communications. When heterogeneous secondary networks are allowed to operate in the same underutilized spectrum, their coexistence becomes a critical issue. The objectives and operational requirements of the primary user operations may vary depending on the nature of their operations. Some primary user operations require operational privacy, whereas others define revenue maximization as their primary objectives. Even within the same shared band different primary user operations may have different operational objectives. The physical propagation characteristic of the shared band and the application/service requirements need to match as well. Different secondary users have different Quality of Service (QoS) requirements and priorities and the different shared bands and opportunities will provide a different value for each user.

Auctions are agnostic to user utility functions, and can build a diverse range of allocation mechanisms with little overhead. Spectrum auctions provide a platform for licensed spectrum users to share their underutilized spectrum with unlicensed users. Due to their perceived fairness and allocation efficiency [311], auctions are among the best-known market-based mechanisms to allocate spectrum [312-317]. In most proposed auctions, the spectrum resource is treated as goods in traditional auctions studied by economists, i.e., one licensed band is awarded to one SU. However, spectrum auction differs from conventional auctions in that it has to address radio interference. Spectrum auction is essentially a problem of interference-constrained resource allocation. And those spectrum auctions that use the protocol interference model to characterize interference relationship generally do not allow the primary and secondary users to share channels simultaneously.

Spectrum being a limited and expensive resource (the 2006 FCC auctions for 700-800 MHz are estimated to have raised almost $19 billion [318]), the barrier to entry for potential spectrum buyers is high. One can either buy a lease on spectrum covering a large area at a high price or use the limited frequency bands classified as unlicensed (e.g., Wi-Fi). Such unlicensed bands are subject to a "tragedy of the commons" where, because they are free to use, they are overused and performance suffers [319]. Efforts such as the recent FCC ruling on white spaces are attempting to free additional spectrum by permitting opportunistic access [320]. However, such efforts are being met with opposition by incumbents (such as, Department of Defense, TV broadcasters and wireless microphones manufacturers) who have no incentive to permit their spectrum to be shared. Motivated by these observations, many researchers and companies (e.g., [321-323]) have proposed allowing spectrum owners and spectrum users to participate in a secondary market for spectrum where users are allocated the use of spectrum in a small area on a dynamic basis (dynamic spectrum access). This approach is beneficial for two reasons. First, it allows flexible approaches to determine how best to allocate spectrum, rather than relying on the decision making of regulators. Second, it provides an incentive for sharing spectrum, which is currently owned but underused, to be made available. The term secondary market indicates to a transaction in which the owner leases it to many small users, as opposed to the monolithic allocations in primary markets. The FCC also recognizes the potential of a secondary spectrum market, and is encouraging spectrum subleases in certain bands [324]. Designing an auction for a secondary market where sharing is allowed requires accounting for the interference users impose on each other when they share a channel.

Designing a spectrum sharing mechanism that can efficiently allocate the spectrum bands to secondary users is imperative for successful operation of a dynamic spectrum access system. It is necessary for the mechanism to provide sufficient incentives for both the primary user and the secondary users to participate in spectrum sharing. In a simple spectrum auction scenario, the primary users act as auctioneers and sell their idle spectrum bands to secondary users to make a profit, and the secondary users act as bidders who want to buy spectrum bands. In such a setting, auction-based mechanisms appear to be the most appropriate approach because they can capture many of the key features of the spectrum sharing problem. First, in an auction, it is possible to consider situations where the seller is not assumed to know any prior information about the valuation of items to the buyers. This aspect cannot be easily taken into account in pricing-based or other conventional market-based mechanisms. Second, auctions can be designed to allocate items to the buyers with highest valuations, thus making an efficient allocation. Third, auctions require minimum interactions between seller and buyers, because the buyers just need to submit their bids over the items. This makes the implementation of auction mechanisms easier and more practical compared to the other market mechanisms. An underlying assumption in existing spectrum auctions is that secondary users know the exact value of channel access, and they bid accordingly. However, in real world scenarios, the value of obtaining channel access is not exactly known to the secondary users a priori, but they learn it over time. In fact, secondary users revise their estimates of values for channel access based upon what they experience.

Spectrum Opportunity Auctioning considering the Probabilistic Assurance

Dynamic spectrum sharing approach proposed by FCC is a challenging problem because of the requirements of peaceful coexistence between the primary and secondary users. In recent years, game theory has been increasingly used to model and understand the difficulties of dynamically managing limited resources in a competitive environment [325, 326]. An important aspect of dynamic spectrum sharing is the pricing of spectrum from the perspective of both the primary and the secondary users [327-329]. Although a number of auction-based spectrum sharing models have been used to provide a framework for spectrum pricing and resource allocation problems [330-332], the research efforts in the context of spectrum sharing have overlooked an important aspect of successful secondary user operation in the shared band which is the duration of available spectrum opportunity. Following the research trend of spectrum sharing aspects, the application of game theory and auction theory has been limited to power and spectrum allocation among the SUs and pricing structure for auction-based spectrum sharing. In order to achieve any desired level of QoS, the secondary user service providers need information about the QoS predictability of the channel. The QoS predictability of a shared spectrum is a function of the duration of the available spectrum opportunity [333] and plays an important role in reducing interference to the primary user. In its current form, the secondary user is responsible for predicting the achievable QoS in the shared band. The initiatives for QoS prediction are mainly focused on primary usage modeling. In a previous work [334], we proposed the Quality of Service (QoS) Assurance (QoSA) approach with minimum primary user involvement to estimate the achievable QoS for a spectrum opportunity.

In this chapter we present a dynamic and self-adjusting auction scheme for dynamic spectrum access based spectrum sharing systems that accounts for the quality of the available spectrum opportunity in terms of the probabilistic assurance generated by the SAS under the primary-secondary cooperation framework. The dynamic auction procedure allows both the primary and secondary operations to adjust their evaluation of the available opportunities based on their experiences with the channel quality from past usage statistics and past auction results, and over time achieves a price combination that maximizes both the primary and secondary user objectives. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users. The primary-secondary cooperation is manifested in the form of spectrum opportunity duration assurance (SODA) in the auction process. The SODA approach, as opposed to the QoS prediction approach, estimates the spectrum opportunity duration for operations with non-deterministic or unknown spectrum reservations or usage patterns. Knowing the realistically achievable QoS considering the uncertainty due to the return of the primary user to the shared spectrum allows the secondary user access points to more effectively determine the number of spectrum opportunities for which it will participate in the auction process. The quantitative measure of the usability of a spectrum opportunity has great impact on the performance of any spectrum sharing system, and should be incorporated in spectrum management. The proposed channel quality based dynamic auction scheme allows the secondary users to take advantage of the predictive models of spectrum availability, prioritize spectrum opportunities accordingly, and bid for their preferred channels to maximize spectrum utilization while minimizing the occurrence of disruptions to primary users.

Related Work

Dynamic spectrum sharing has been deemed as an effective approach to better utilize limited spectrum resource [19, 20] because clearing and reallocating licenses are extremely expensive. Spectrum auctions provide a platform for licensed spectrum users to share their underutilized spectrum with unlicensed users. Due to their perceived fairness and allocation efficiency [311], auctions are among the best-known market-based mechanisms to allocate spectrum [312-317]. Auction theory serves as an efficient tool in modeling interactions among multiple competing users and in distributing resources in wireless networks. Recently, spectrum auction has received considerable attention [335-338]. Chang and Chen [335] proposed a spectrum-management policy based on auction theory to construct the co-win situation for a spectrum regulator, a service provider, and PUs and SUs. Stanojev et al. [336] proposed an auction-based distributed scheme to combine cooperative ARQ with the spectrum leasing paradigm. Yi and Cai [337] studied the recall-based combinational spectrum auction among multiple heterogeneous SUs. Chen et al. [338] proposed an auction framework for heterogeneous spectrum transaction. The authors in [339] focused on the challenges in auction theory driven spectrum management. The explained the contribution of auctions in spectrum allocation in dynamic spectrum markets. The presented the impact of complex spectrum transactions among network entities, the spatiotemporal channel and flow dynamics, as well as the multiple hierarchies among entities from the perspective of auction design for spectrum management. The authors in [340] presents the design and implementation of a prototype of online Auction platform for Licensed Shared Access (LSA) based Short-term Spectrum Sharing (ALS3). The auction platform utilizes two economically-robust and computation time efficient single-round auction mechanisms, one unilateral and one bilateral, proposed by Zhan et al. [341]. Core to system implementation of ALS3 is a solution stack of Windows-Apache-MySQL-PHP (WAMP), which runs auction algorithms in the background, facilitates market player communications and brokerage database management, and provides user friendly interfaces. The leasing period of spectrum access right is short-term and ranges from hours to days [342, 343]. LSA improves on the inefficiency of "command-and-control" spectrum management [344] through shared use of spectrum by secondary users while maintaining a certain level of QoS. The spectrum bands targeted for sharing with a good potential for effective global harmonization [345] include 2.3~2.4 GHz and 3.5~3.7 GHz. These two bands were licensed for use by wireless cameras, video links, defense applications and aeronautical telemetry, etc. [346]. There have been growing interests in the LSA framework in Europe and in the US [27]. Prominent research and development projects and pilot trial are the CORE+ project of Finland [347] and the European project METIS [348]. How to effectively coordinate sharing among multiple incumbents and licensees in a HetNet environment has been identified as a significant challenge [341]. By adopting auction-based market approach, the spectrum sharing problem in HetNet can be treated as a resource allocation problem [341]. Recently there have been some LSA-based sharing framework and efficient and fair resource allocation mechanisms proposed [349], but the facilitation of LSA still lacks of an open resource trading and leasing platform to map with the framework and mechanism. In addition, how to match systems and methods proposed with potential short-term spectrum sharing business models remains a challenge [350-352].

The authors in [353] proposed an auction framework for spectrum allocation with interference constraint in cognitive radio networks. The proposed framework allows unlicensed secondary users (SUs) to share the available spectrum of licensed primary users (PUs) fairly and efficiently, subject to the interference temperature constraint at each PU. To study the competition among SUs, the paper formulated a non-cooperative multiple-PU multiple-SU auction game and studied the structure of the resulting equilibrium by solving a non-continuous two-dimensional optimization problem. A distributed algorithm was developed in which each SU updates its strategy based on local information to converge to the equilibrium. The authors then extended the proposed auction framework to the more challenging scenario with free spectrum bands. They developed an algorithm based on the no-regret learning to reach a correlated equilibrium of the auction game. The proposed algorithm, which can be implemented based on local observation, is especially suited in decentralized adaptive learning environments as cognitive radio networks. Fundamentally different from conventional goods, spectrum is reusable, which is referred to as spatial reusability. Users can share the same channel as long as they can transmit signals simultaneously without disrupting each other's transmission. Therefore, the primary license holders may be motivated to open up their underutilized spectrum for sharing, so that they may make profit by leasing access to spectrum resources. In addition, allowing spectrum to be shared by multiple users can also improve the spectrum utilization efficiency. When the spatial reusability of the spectrum is considered, one arising challenge is to characterize interference relationship among users in cognitive radio networks (CRNs). Existing spectrum auctions either use the protocol interference model to characterize interference relationship as binary relationship, or do not allow the primary and secondary users to share channels simultaneously. Most of the existing spectrum auctions adopt the protocol interference model [299], which simplifies the step of allocation by scheduling users according to conflict graphs. But in practice for wireless networks, a conflict graph may not be precise, as the interference from other users is cumulative. To fill this void, the authors is [354] proposed a single-sided spectrum auction with spatial reusability under the physical interference model, which considers the interference to be cumulative. The auction allows the primary user and secondary users to share channels simultaneously, as long as the signal quality of the primary user is guaranteed.

There has been significant work on spectrum auctions where a regulatory agency, such as the FCC, leases the right to spectrum across large geographic areas (see, e.g., [355, 356]). Most approaches to secondary-market auctions preclude sharing among auction participants [312, 316, 323, 357-359]. VERITAS [323] was the first spectrum auction algorithm based on a monotone allocation rule, and thus strategy-proof. However, VERITAS does not support sharing. The use of a spectrum database in facilitating secondary market auctions has been proposed [322]. Turning to sharing, Jia et al. [360] envision spectrum owners auctioning off spectrum rights to a secondary user when it is not being used by the owner, and investigate how revenue can be maximized. While winners share with the spectrum owner, there is no sharing among bidders in the auction. Gandhi et al. [361] use an approach that allocates many small channels, effectively enabling sharing. However, their algorithm allows sharing only among bidders who want only a portion of a channel. Thus, it cannot take advantage of bidders who are only intermittently active. In addition, the approach is not strategy-proof and there is no equilibrium analysis, which makes its efficiency and revenue properties hard to evaluate. Closest to our work is that of Kasbekar and Sarkar [314], who use a strategy-proof auction and provide for sharing. But rather than providing a structured bidding language the design allows bidders to express arbitrary externalities, and their proposed approach is intractable. The issue of externalities in auctions has been considered more generally. Jehiel et al. [362] consider situations, such as the sale of nuclear weapons, where bidders care not just about winning but about who else wins. But the settings do not include combinatorial allocation problems. A number of papers have considered externalities in online advertising (e.g., [361, 363]). Krysta et al. [364] explored the problem of externalities in general combinatorial auctions. The authors in [365] present a scalable, strategy-proof auction algorithm that permits users able to sharing spectrum to coexist in one market with those requiring exclusive-use. The proposed auction algorithm considers the effect of interference on the value of an allocation to all participants. The authors in [330] proposed an auction-based cognitive radio network model to characterize competitiveness among PUs by a non-cooperative game. The proposed model considers multiple primary users along with multiple secondary users. It also uses an auction based model and competitiveness among primary users as well as secondary users. These primary users compete with each other so that they can earn more profit while the secondary users pay less and earn higher payoffs. This situation is formulated as an oligopoly market. Based on this model, [330] analyzed how each primary user updates its parameters of cost function to attract more SUs' demands to maximize its own payoff. The authors considered that secondary users are selfish and self-interested, and define their bids for frequency spectrum by maximizing their Hackner utility functions [366] and then choose PUs rationally to maximize their own payoffs.

The authors in [341] considers a coexistence network that involves one spectrum provider sharing unused spectrum resources to multiple heterogeneous secondary networks. To coordinate interference-free spectrum sharing among these heterogeneous secondary networks, they adopt an auction-based approach and designs a unilateral Vickrey-Clarke-Groves (VCG)-based Auction for heterogeneous secondary networks. The proposed auction method has three novel designs that make it a practical and efficient solution. Firstly, effective partition of auction regions takes into account the SP's non-uniform amount of supply units in a target area. Secondly, based on the partition, the auction methods provides heterogeneous secondary networks with a highly expressive package bidding format to freely specify the amount of demand units and operating regions. Lastly virtual bidders by regions are introduced so as to resolve the revenue deficiency problem of VCG while retaining the property of truthfulness. With these three designs, the proposed auction method maximizes the social welfare of the coexistence network without sacrificing the overall spectrum utilization. The authors in [367] considered a cognitive radio network consisting of a primary spectrum owner (PO), multiple primary users and multiple secondary users. The authors designed an auction-based spectrum sharing mechanism where the secondary users bid to buy spectrum bands from the PO who acts as the auctioneer, selling idle spectrum bands to make a profit. Existing auction mechanisms assume that all the channels are identical. However, [367] considered a more general and more realistic case where channels have different qualities. Also, the proposed auction algorithm allowed secondary users to express their preferences for each channel separately. That is, each secondary user submits a vector of bids, one for each channel. The proposed auction mechanism results in efficient allocation that maximizes secondary users' valuations, and has the desired economic properties.

Game theory and auction design have been used for wireless spectrum allocation and management [312, 335, 353, 368-376]. In [335], an auction-based spectrum management scheme for cognitive radio networks has been presented. The network consists of a primary base station and several primary and secondary users. The service provider determines the number of channels to be sold and holds the auction among the secondary users. Since the channels are assumed to be identical, the Vickrey auction determines the winners and payments. A similar network topology has been considered in [369], however channels are assumed to be different. The model is based on the contract theory in which the PO acts like a monopolist and determines the qualities and prices for spectrum bands with the objective of maximizing his own revenue. However, in this approach secondary users cannot submit bids and the PO needs some prior information about secondary users' valuations. In [368], the idea of having multiple auctioneers, i.e. multiple POs, has been presented. In this setting, each PO gradually raises the trading price and each secondary user chooses one auctioneer for bidding. After several bidding/asking rounds, the mechanism converges to equilibrium where no PO and secondary user would like to change his decision. Also, [370] considers two wireless service providers, and the authors study the optimal pricing for service providers and optimal service provider selection for secondary users. They show that the equilibrium price and its uniqueness depend on the secondary users' geographical density and spectrum propagation characteristics. In [371], the authors study the dynamics of spectrum sharing and pricing in a competitive environment where multiple POs try to sell spectrum bands to multiple secondary users. They use evolutionary game theory to model the evolution and the dynamic behavior of secondary users. The competition among POs has been modeled as a non-cooperative game, and an iterative algorithm has been presented to find the Nash equilibrium. In [312], Zhou et al. proposed TRUST, a general framework for truthful double spectrum auctions. This framework aims to provide spectrum reuse while achieving truthfulness and other desired economic properties. TRUST takes any reusability driven spectrum allocation method as an input, and applies its own winner determination and pricing policy. There is an external auctioneer with complete information that holds the auction between POs and secondary users. The authors in [372] consider a setting in which secondary users have flexibility to bid for a bundle of frequencies at different times. In fact, the spectrum opportunity is divided by frequency and time, so that secondary users can bid for a combination of them. This flexibility, however, brings computational complexity. Since the general problem falls into the combinatorial auctions category, obtaining the efficient allocation is NP-hard, and only approximate solutions can be achieved. In [373], the authors study the effect of interference created among different agents who may obtain the right to use the same spectrum at nearby locations. Since finding the efficient allocation is NP-hard, some constant factor approximations have been discussed. Recently, a group of researchers considered two-tier market models for dynamic spectrum access. In tier-1, secondary users buy the spectrum from the POs in a large time scale, and in tier-2, secondary users trade the obtained spectrum among themselves in a small time scale. In [374], for example, the authors use Nash bargain games to derive the equilibrium prices for each tier. However, each tier is studied independently and the connection of tiers has not been explored yet.

The authors in [377] investigated the problem of designing a secondary spectrum trading market when there are multiple sellers and multiple buyers and propose a general framework for the trading market based on an auction mechanism. To this end, the paper first introduced a new optimal auction mechanism, called the generalized Branco's mechanism (GBM). The GBM, which is both incentive-compatible and individually rational, is used to determine the assigned frequency bands and prices for them. Second, it was assumed that buyers of the spectrum are selfish and model their interaction as a non-cooperative game. Using this model, the authors proved that when the sellers employ the GBM to vend their frequency bands, they can guarantee themselves the largest expected profits by selling their frequency bands jointly. Third, based on the previous finding, the paper modeled the interaction among the sellers as a cooperative game and demonstrated that, for any fixed strategies of the buyers, the core of the cooperative game is nonempty. This suggested that there exists a way for the sellers to share the profits from the joint sale of the spectrum so that no subset of sellers will find it beneficial to vend their frequency bands separately without the remaining sellers. Finally, [377] proposed a profit-sharing scheme that can achieve any expected profit vector in the nonempty core of the cooperative game while satisfying two desirable properties. In [369], the authors present a pricing method in which the PO offers channels of different qualities. In the model, the PO has prior knowledge about secondary users' values for accessing the channels. Thus, the PO acts monopolistically and determines channel prices such that its revenue is maximized. A truthful auction mechanism for sharing variable bandwidth spectra is presented in [378]. The key assumption is that SUs bid their valuation functions to the PO so that the PO can evaluate secondary users' values for any bandwidth. The authors in [367], propose an efficient heterogeneous spectrum sharing auction in which the SUs can submit channel-specific bids depending on channel characteristics. The model is extended to a reserve price auction in [379] where the PO imposes reserve prices on the available channels. Spectrum sharing in presence of multiple POs is studied in [368]. In the model, POs compete with each other by gradually raising the prices. The authors show that the algorithm converges to an equilibrium point where no secondary user and PO deviates. In a similar competitive environment, Niyato et al. [371] utilize the non-cooperative game theory to model the dynamics of spectrum pricing. The authors in [370], study the competition between two POs that offer channels on different frequency bands. They show that the equilibrium price and its uniqueness is dependent on the SUs' geographical density and the spectrum propagation characteristics. Spectrum double auctions provide a framework in which the POs can request their asking prices and secondary users can submit their bids. Zhou et al. [312], proposed a double auction framework that enables spectrum reuse. The framework takes any reusability-driven spectrum allocation method, and implements its own winner determination and payment scheme. Another truthful double auction, called TAHES, is proposed in [380] that considers heterogeneous spectrum bands. The main assumption in double auctions is that, there must be an external third party with complete information to run the auction. Spectrum auctions have also been studied in dynamic settings. For instance, [381, 382] present online spectrum auctions that allow secondary users to join and leave the auction at different times. The authors in [383] present a repeated second price auction in which secondary users can choose to enter the auction or stay out and monitor the results. Learning algorithms are utilized by secondary users to optimize their decisions. Similarly in [370], a sequential second price auction is utilized for power and bandwidth allocation where one resource unit is auctioned at each time step. Thus, a static auction is performed repeatedly and auction results are observed by secondary users. The authors in [384] presented a revenue maximizing dynamic auction. A nonmonetary QoS-aware auction framework toward secure communications for cognitive radio networks was presented in [385]. The proposed spectrum auction framework jointly formulates the optimal cooperator selection and the corresponding resource allocation problems by taking into consideration the QoS demands of individual users. The proposed framework ensures that bidding truthfully is the dominant strategy for all bidders and, thus, is invulnerable to market manipulation and eliminates the overhead of strategizing over other bidders.

The authors in [386] presented a study of the cooperative spectrum sharing under incomplete information, where secondary users' types (which capture the relay channel gains and the secondary users' power costs) are private information and are not known to the PU. Inspired by the contract theory, the paper modeled the network as a labor market. The primary user is an employer who offers a contract to the secondary users. The contract consists of a set of items representing combinations of spectrum access time (i.e., reward) and relay power (i.e., contribution). The secondary users are employees, and each of them selects the best contract item to maximize its payoff. The authors studied the optimal contract design for both weakly and strongly incomplete information scenarios. First, they provided necessary and sufficient conditions for feasible contracts in both scenarios. In the weakly incomplete information scenario, they further derived the optimal contract that achieves the same maximum primary user's utility as in the complete information benchmark. In the strongly incomplete information scenario, [386] proposed a Decompose-and-Compare algorithm that achieves a close-to-optimal contract. The paper further showed that the primary user's expected utility loss due to the suboptimal algorithm and the strongly incomplete information are both relatively small. Market-driven spectrum trading is a promising paradigm to address the incentive issue in dynamic spectrum sharing. With spectrum trading, primary users temporarily sell the spectrum to SUs to obtain either a monetary reward or a performance improvement. A particularly interesting trading scheme is cooperative spectrum sharing, where secondary users relay traffics for primary users in order to get their own share of spectrum [329, 386-390]. The cooperative spectrum sharing leads to a win-win outcome for both primary and secondary users. The study of cooperative spectrum sharing mechanisms has only started recently [387, 391-393]. The prior results all assumed complete network information, i.e., primary and secondary users' channel conditions, resource constraints, and costs of transmission powers. This assumption is often too strong for practical networks. The only related paper that also deals with incomplete information is [394], which studied the interactions between a single primary user and a single secondary user.

The dynamic spectrum sharing approach proposed by the FCC is a challenging problem because of the requirements of peaceful coexistence between the primary and secondary users. In recent years, game theory has been increasingly used to model and understand the difficulties of dynamically managing limited resources in a competitive environment [325, 326, 395]. An important aspect of dynamic spectrum sharing is the pricing of spectrum from the perspective of both the primary and the secondary users [327-329, 396-398]. A number of auction-based spectrum sharing models have been used to provide a framework for spectrum pricing and resource allocation problems [330-332, 399-401]. The authors in [402] explored the spectrum auctions in a dynamic setting where SUs can change their valuations based on their experiences with the channel quality. They proposed a dynamic auction for spectrum sharing with time-evolving values of channel qualities that maximizes the social welfare of the SUs. The proposed auction scheme is based on multi-armed bandit models [403] where for each user an allocation index is independently calculated in polynomial time. [402] also generalizes the proposed auction scheme to adapt auctioning multiple channels at each time. The research efforts in the context of spectrum sharing have overlooked an important aspect of successful secondary user operation in the shared band which is the duration of available spectrum opportunity. Following the research trend of spectrum sharing aspects, the application of game theory and auction theory has been limited to power and spectrum allocation among the secondary user and pricing structure for auction-based spectrum sharing. This lays the foundation for a potential research topic which explores an auction-based spectrum sharing framework that accounts for the quality of the available primary user idle channels. The measurement of the channel quality and the generation of the spectrum opportunity quality parameters can be a responsibility of the SAS and naturally calls for cooperation from the primary users.

System Model for Spectrum Opportunity Auction

In this part of the submission, we propose an auction-based spectrum sharing framework that accounts for the quality of the available spectrum opportunity in terms of the probabilistic assurance generated by the SAS under the primary-secondary cooperation framework. The dynamic auction procedure allows both the primary and secondary operations to adjust their evaluation of the available opportunities based on their experiences with the channel quality and past auction results, and over time achieves a price combination that maximizes both the primary and secondary user objectives. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users. Our work in [334] proposed a Spectrum Opportunity Duration Assurance (SODA) approach. The SODA approach, as opposed to the QoS prediction approach, estimates the RF spectrum opportunity duration for operations with non-deterministic or unknown spectrum reservations or usage patterns. SODA is a metric that measures the probabilistic assurance about idle primary user channels stating that the channel under consideration will be available for secondary use for certain duration of time with probability SODA. From Chapter 4:, the normalized effective channel availability can be determined using the SODA approach as: $\alpha = \frac{SODA-1}{\ln(SODA)}$ [334].

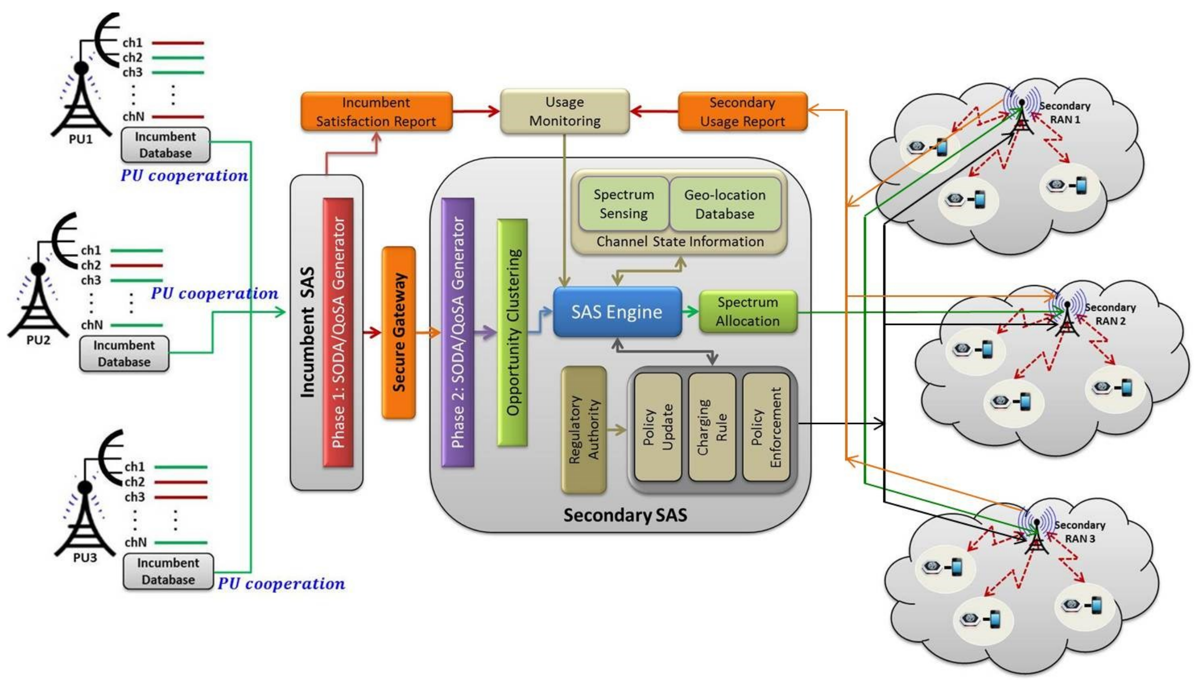


Figure 30: Spectrum Opportunity Duration Assurance (SODA): Primary-Secondary Cooperation for Spectrum Sharing Systems

Figure 30 presents the primary-secondary cooperation based spectrum sharing system. Each of the primary users has a number of channels for the primary user operation. At any given point in the time a primary user utilizes some of its licensed channels to achieve the operational objectives. In the spectrum sharing paradigm, the remaining of the primary user channels (the 'unused' ones) are spectrum opportunity that the secondary users may opportunistically access. The proposed spectrum sharing system puts the SAS in a central role to facilitate dynamic management of the available spectrum opportunities. The SAS framework proposed to incorporate the SODA approach has two major blocks: the incumbent SAS and the secondary SAS (Figure 30).

Incumbent SAS gathers the usage statistic and the tentative future usage plan from the incumbent database. The Environmental Sensing Capability (ESC) system may monitor the incumbent usage and store the usage data and the associated statistics in the primary user database. The introduction of a separate entity, the ESC, for incumbent usage monitoring takes the responsibility away from the incumbent users. It allows the incumbent users to conduct their operation uninterrupted and without the expectation of performing any additional responsibility for spectrum sharing. Incumbent SAS and Secondary SAS perform two phases of the probabilistic assurance calculation for each of the idle channels. The Secondary SAS then generates clusters of similar quality opportunities based on the associated SODA. Based on the SODA metric, the Secondary SAS helps the secondary user resource manager (SU-RM), serving multiple secondary users with different QoS demands, to perform an assignment problem that maximizes the overall spectrum efficiency for the shared bands. The usage monitoring module uses the Incumbent satisfaction report and the secondary usage report to ensure that the secondary opportunistic usage of the opportunities is operating within the agreed rules so as to offer the desired interference environment from the primary users' perspective.

We also propose to establish a minimum QoS which will ignore spectrum availability with durations below a specified threshold. This will reduce frequent channel switching and improve secondary user operations. Based on the minimum QoS requirement of the secondary user operations, we can decide on the minimum state duration (channel availability) for which an idle channel will be considered a spectrum opportunity. The Incumbent SAS can access the primary user database to determine the probability of state durations. While training the model parameters, spectrum availability durations below the threshold will be grouped into availabilities with larger durations. This approximation will result in degradation in the prediction performance as we are ignoring information.

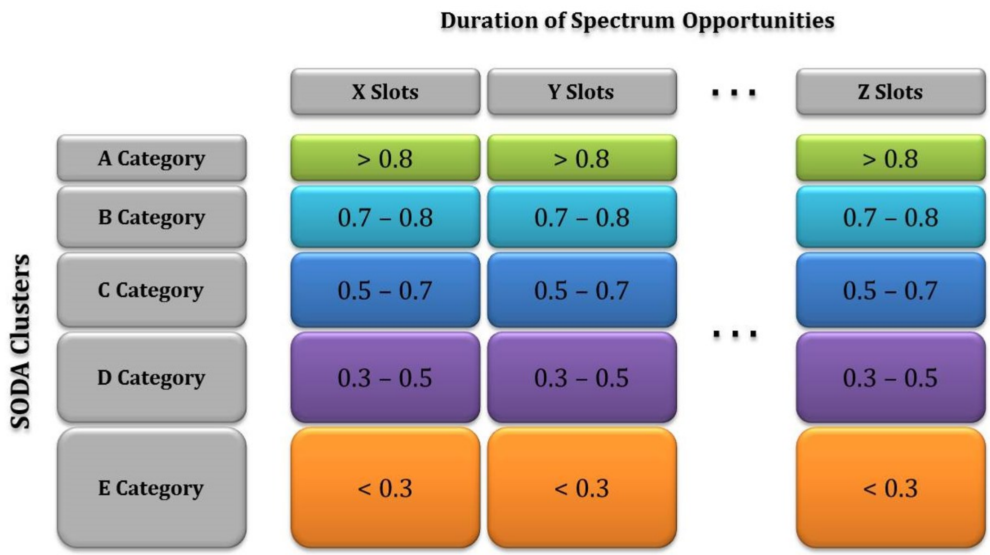


Figure 31: Spectrum Opportunity Clustering at Secondary SAS

In this submission we focus more on the effective duration of the spectrum opportunity based on the assurance from the primary users. We are interested to observe the reduction in complexity while maintaining the performance degradation within tolerable limits. The SODA approach does not make any assumption on the primary user traffic. We only assume that the trust on the probabilistic assurance of the time of primary user return is exponentially distributed. This assumption is justified as follows: The primary user provides assurance for only those channels that are idle at the moment of reporting. Since this assurance is coming from the source, it is most likely that the assurance will be more reliable in near future and the reliability will decrease with time. Based on the SODA associated with the channels, the SAS generates cluster of similar quality channels. The SODA approach requires minimal involvement from the primary user and reduces the likelihood of exposing sensitive primary user information using an "*opportunity clustering"* mechanism (Figure 31). The SAS will take into account spectrum availability (SODA value) and price to allocate spectrum accordingly where similar quality spectra will be clustered for auctioning.

Spectrum Opportunity Auction Model

We consider a simple spectrum sharing system that is governed by the SAS (Figure 32). The block diagram describes how a spectrum opportunity is to be auctioned based on the SODA metric provided by the SAS using the primary user cooperation. There are a set of M primary users and N secondary user service providers. The primary users, with the help of Incumbent SAS, determine the available spectrum opportunities, related SODA values, and initial price of the opportunities and forward this information to the Secondary SAS. The Secondary SAS generates cluster of similar quality opportunities and determines the effective duration metric for each of these clusters. The Secondary SAS also receives requests for spectrum opportunities from the secondary user access points along with their individual offered prices and makes a decision about the allocation of spectrum for secondary usage. The secondary user access point, on its end, performs an estimation of the aggregate QoS demand of all of its end users. Based on the projected revenue earned from these users, the secondary user access point determines the price of the bid for the current stage.

We follow the system parameters proposed by the FCC for the Citizen Broadband Radio Service (CBRS) [304]. Each of the primary user channels has a bandwidth of 10 MHz and the transmission power of each of the secondary users is 24 dBm. Each primary user determines the number of available 10 MHz spectrum opportunities and associated SODA value. We will use the normalized effective duration of the spectrum opportunity [42] as a measure of the quality of the channel. The primary and secondary users involved in the auction-based spectrum sharing framework will consider this measure of the channel quality and also the experiences gained from past auction stages to adjust the valuation of the resource.

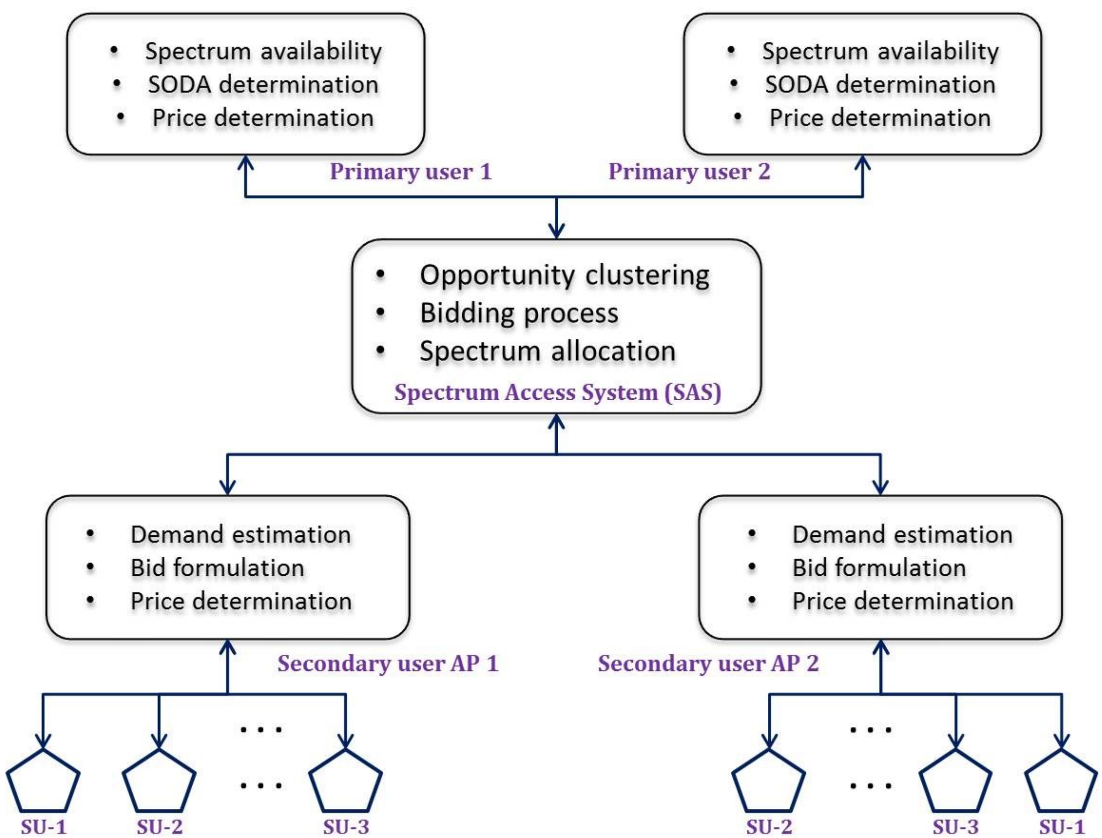


Figure 32: System model for the auction based spectrum sharing framework

Metrics for the Auction Procedure

The Secondary SAS generates L spectrum opportunity clusters, where each cluster groups spectral opportunities that have a similar probabilistic assurance, i.e. the $SODA$ value, about the usability and QoS achievability of the opportunities. The corresponding effective opportunity duration metric, the α_l values, where $l = 1, 2, \ldots, L$, can then be computed. Primary user also informs the SAS about the asking price for its opportunities. For PU_i, the price of one 10 MHz channel is given by the base price $x_i \theta_i$ where x_i is the initial reserve price and θ_i is the primary user price adjustment factor. Each primary user will adjust the price of its spectrum opportunities as a function of the demand of its channels in the previous auctioning stage by adjusting θ_i. This way the primary user can make its channels more attractive for the secondary users based on the secondary user demands in the previous stages. For the purpose of this analysis, the secondary users measure QoS in terms of bit error rate (BER). For the uncoded quadrature amplitude modulation (QAM) with square constellation (e.g., 4-QAM, 16-QAM) the BER is approximated as [404]

$$BER = 0.2 \exp\left(\frac{-1.5\gamma}{2^k - 1}\right) \tag{48}$$

where γ is the Signal to Noise Ratio (SNR) at the receiver and k the spectral efficiency of the digital modulation scheme used. We maintain BER at a target level $\left(BER_{Target}\right)$so that the spectral efficiency of the transmission for secondary user access point j (SU_j) can be described as

$$k_j = log_2\left(1 + \frac{1.5\gamma}{log_e \frac{0.2}{BER_{Target}}}\right) \tag{49}$$

The secondary users determine the bidding price depending on the primary users' asking price ($x_i \theta_i$) and the channel quality factor (α_l) of the spectrum opportunity provided by the primary user. In determining the bidding price, the secondary user access point also considers the expected revenue (r_j) from the end users. For any spectrum opportunity the base price ($x_i \theta_i$) is given by the SAS. The secondary user may decide to bid at a higher price to improve its chances to win. The amount of increase in the bidding price depends on the channel quality factor (α_l). The secondary user decides on the price for a channel and adjusts the bidding price by $y_j \alpha_l$ with respect to the asking price. More precisely, SU_j determines the price, $c_{i,j,l}$, for each of its desired 10 MHz channels of PU_i that belong to the cluster l as follows:

$$\begin{aligned} & c_{i,j,l} = x_i\theta_i + y_j\alpha_l \\ & s.t. \quad c_{i,j,l} < r_j \\ & i = 1,2, \dots, M \\ & j = 1,2, \dots, N \\ & l = 1,2, \dots, L \end{aligned}$$

(50)

Utility Function of the Secondary Users

Each secondary user access point determines the aggregate QoS demand, $\left(Q_{agg_j}\right)$, of its end users. It also calculates the spectral efficiency $\left(k_{ij}\right)$ based on its operational parameters and determines the quality of each channel (l) using α_l and k_{ij}. The secondary user access point then determines its desired channels that are needed to satisfy the aggregate QoS demand:

$$\sum_{l=1}^{L}\sum_{i=1}^{M} k_{i,j}\alpha_l B\tau I_{j,desired_{l,i}} \geq Q_{agg_j}$$

(51)

B is the bandwidth of each channel (10 MHz), τ the duration for which the channel will be allocated, and $I_{j,desired_{l,i}}$ the channel indicator information about the desired channels. The secondary user access point also determines the desired utility that it may achieve if its desired channels are allocated by the SAS. The utility function for secondary user access point j can be expressed as

$$U_{j_{desired}} = \sum_{l=1}^{L}\sum_{i=1}^{M} k_{i,j}\alpha_l I_{j,desired_{l,i}}$$

(52)

Revenue and Payoff function of the Secondary Users

The secondary user access points know the revenue per unit $\left(r_j\right)$ that it earns from its end users. The access point then determine the revenue function using the revenue per unit $\left(r_j\right)$ along with the spectral efficiency $\left(k_{ij}\right)$, SODA value of the channel α_l, and the bandwidth and the duration of the channel. The revenue function of the SU_j for the desired spectrum opportunities $\left(I_{j,desired_{l,i}}\right)$, termed as the channel indicator information, can be expressed as

$$R_{j_{desired}} = \sum_{l=1}^{L}\sum_{i=1}^{M} r_j k_{i,j} \alpha_l B \tau I_{j,desired_{l,i}}$$

(53)

The secondary user access point determines the channel indicator information $I_{j,desired_{l,i}}$ according to Eq. (5) and a bid price y_j to calculate the prices $\left(c_{i,j,l}\right)$ for the desired channels. The cost function of the SU_j can be expressed as:

$$C_{j_{desired}} = \sum_{l=1}^{L}\sum_{i=1}^{M} c_{i,j,l} k_{i,j} \alpha_l B \tau I_{j,desired_{l,i}}$$

(54)

Using Eq. (7) and Eq. (8), the payoff function of the SU_j can be expressed as:

$$\begin{aligned} P_{j_{desired}} &= R_{j_{desired}} - C_{j_{desired}} \\ &= \sum_{l=1}^{L}\sum_{i=1}^{M} (r_j - c_{i,j,l}) k_{i,j} \alpha_l B \tau I_{j,desired_{l,i}} \end{aligned}$$

(55)

Payoff function of the Primary Users

The primary user PU_j cooperates with the SAS to facilitate efficient auction procedure. The spectrum opportunities offered by PU_i is added to one of the L opportunity clusters. The revenue generated by the PU_idepends on the auction result. If all the PU_iopportunities are assigned to the secondary user, then PU_i earns maximum revenue. The payoff function of the PU_j can be expressed as in Eq. (56). Here $I_{j,allocated_{l,i}}$ and I_l are index functions corresponding to the opportunity cluster and the secondary users.

$$\begin{aligned} P_{PU_i} &= \sum_{l=1}^{L}\sum_{j=1}^{N} x_{i,l} \theta_{i,l} I_{j,allocated_{l,i}} I_l \\ \theta_{i,l} &= f_{PU_i}(\alpha_l) \end{aligned}$$

(56)

Problem Formulation and Auction Algorithm

The objective of each SU_j is to find the optimal bidding price per unit (y_j) such that its payoff function $(P_{j_{desired}})$ is maximized and the aggregated QoS demand is satisfied. For an initial price of y_j, the secondary user access point therefore solves the following optimization problem:

$$\max_{I} \quad P_j = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau I_{j,desired_{l,i}}$$
$$s.t. \quad \sum_{l=1}^{L}\sum_{i=1}^{M}k_{i,j}\alpha_l B\tau I_{j,desired_{l,i}} \geq Q_{agg_j}$$

(57)

This problem is modified such that it can be treated as a special binary integer programming problem (Knapsack problem [405]). The secondary user access point solves problem (10) to find $I_{j,desired_{l,i}}$ and forwards this information along with the associated cost $(c_{i,j,l})$ as the bidding information to the SAS. Upon receiving the bidding information from all the secondary user access points, the SAS performs the auction algorithm (Algorithm 1.1 and 1.2). This completes one bidding cycle and the secondary user access points use the allocated channels for the allocated duration (τ). Then the bidding process repeats with updated channel prices from both parties. Figure 33 presents the flow diagram of the SODA based auction algorithm in a spectrum sharing environment. As per the primary-secondary cooperation agreement, the Incumbent SAS access the primary user database and fetches the information required to determine the spectrum opportunities and the associated SODA values. The primary user also decides about the asking price for these spectrum opportunities and forwards the asking price to the Incumbent SAS. Upon receiving the asking price, the Incumbent SAS forwards the primary users auction package (the spectrum opportunities, the associated SODA values and the asking price) to the Secondary SAS. The auction module of the secondary SAS serves as the auction center for the dynamic spectrum access based spectrum sharing system. Alongside with the primary user auction package, the Secondary SAS auction module also receives the same from the secondary user access points. The secondary user access points receive the QoS demands from its end users and determine the aggregate end user QoS demand. They also decide about the revenue associated with these QoS demands. Based on the SODA values of each of the available spectrum opportunities, a secondary user access point determines the desired spectrum opportunities that satisfy the aggregate QoS demand. The secondary user access point then decides the bidding price for the next auction phase based on the

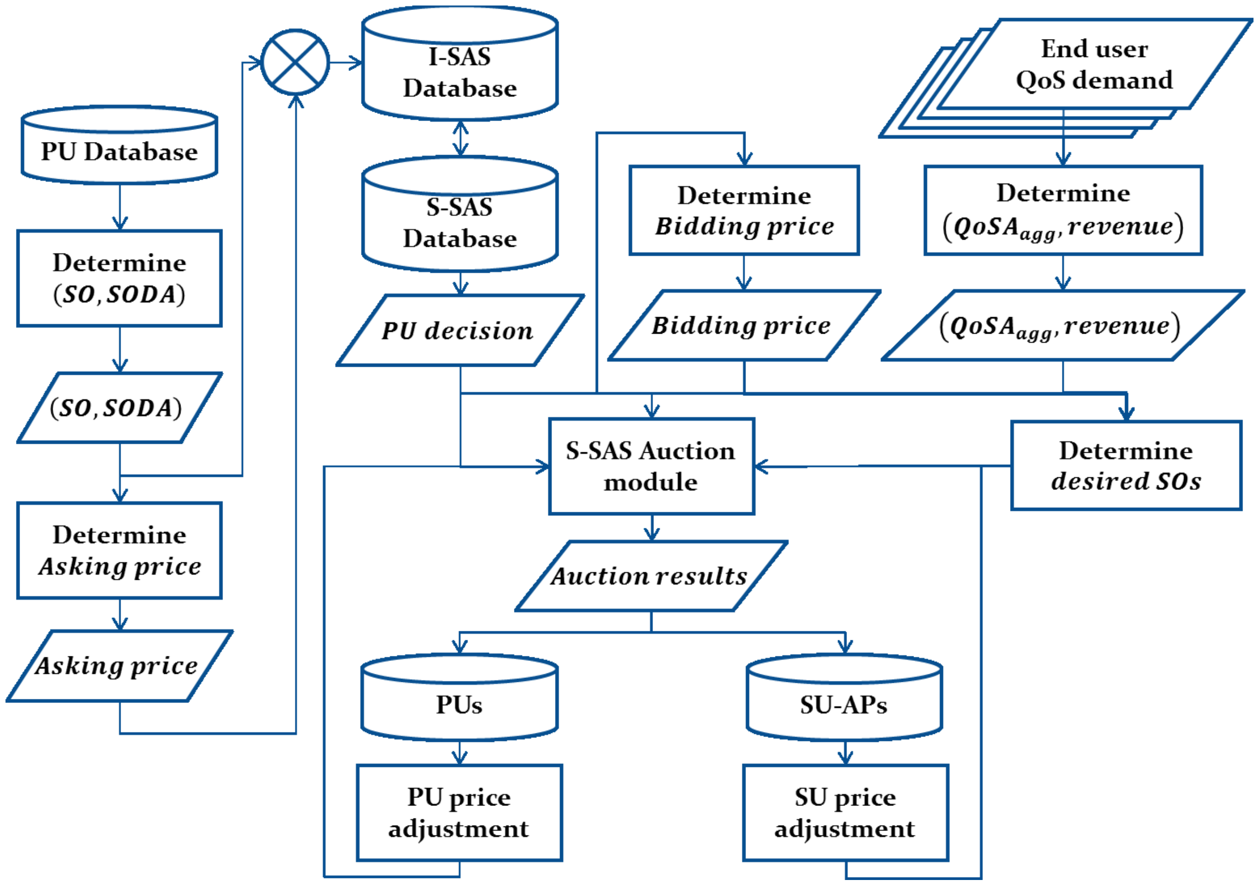


Figure 33: Flow diagram of the dynamic spectrum opportunity auctioning algorithm

expected revenue from the secondary users, the desired spectrum opportunities, and the SODA value and prices associated with the spectrum opportunities. The secondary user auction module receives both the primary and secondary user auction decisions and performs the Vickrey–Clarke–Groves (VCG) auction process to decide the usage right of the spectrum opportunities for the opportunity duration. In auction theory, a Vickrey–Clarke–Groves (VCG) auction is a type of sealed-bid auction of multiple items [406]. The secondary user access points submit bids that report their valuations for the items, without knowing the bids of the other access points in the auction. The auction system assigns the items in a socially optimal manner: it charges each individual the harm they cause to other bidders [407]. It also gives the secondary user access points an incentive to bid their true valuations, by ensuring that the optimal strategy for each access point is to bid their true valuations of the items. The secondary SAS forwards the auction decisions to the primary users and the secondary user access points. Upon receiving the auction results, the primary user re-evaluates their asking price based on the number of unassigned spectrum opportunities and missed revenue. The primary user takes a look at the spectrum opportunities that were not assigned to any secondary user access points during the auction process. The primary user determines the loss in revenue due to the spectrum opportunities not being assigned to secondary user access points. In order to increase the chances of these unassigned spectrum opportunities, the primary user lowers down the asking price of these opportunities by a predetermined amount for the next round of auction. The lower asking price makes these spectrum opportunities more likely to be requested by more secondary user access points and thus in turn increases the likelihood of getting assigned to one of these access points. The secondary user access points also re-evaluate their bidding prices considering the difference in the desired and achieved payoffs as a result of the current bidding prices. Once the access point receives the auction results, it calculates the missed revenue due to not getting all the desired spectrum opportunities for which it did bidding. For the next round of auction, the secondary user access point increases the bidding price by a predetermined amount. The increased bidding price for the spectrum opportunities, which the access point did not win at the last auction round, increases the likelihood of winning in the next round of auction. Thus both the primary users and the secondary user access points adjust their valuation about the available spectrum opportunities. This adjustment phase of the proposed auction scheme helps to maximize the overall spectrum opportunity usage of the spectrum sharing system. The auction algorithm and the price adjustment phase of the proposed spectrum opportunity duration assurance (SODA) based auction scheme is given below:

Algorithm 1.1: Auction Algorithm

1. Spectrum opportunity clusters: $\boldsymbol{SO}: \{(x_{il}\theta_{il},\ \alpha_l),\ \forall i, l\}$; SU demand for each cluster: $\boldsymbol{SU_D}: \{I_{jl} \in (1,0), \forall j, l\}$; SU bidding price for each cluster: $\boldsymbol{SU_P}: \{y_{jl},\ \forall j, l\}$
2. Auction decision set: $\boldsymbol{I_{allocated}}: \{I_{ijl} \in (1,0), \forall i, j, l\}$
3. If any channel has a single claim: $\boldsymbol{SO}: \{(x_{il}\theta_{il},\ \alpha_l)\} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ijl} \in (1,0)\}$
4. If any channel has multiple claims:

   $\boldsymbol{for}\ each\ l\ and\ \forall j, \qquad if\left(sum\left(\left(\boldsymbol{SU_D}: \{I_{jl}\} == 1\right)\right) > 1\right)$

   $\boldsymbol{find}\ j^* = \arg \max_{\forall j \in \{I_{jl}=1\}} \boldsymbol{SU_P}: \{y_{jl}, \qquad \forall i, l\}$

   $\boldsymbol{SO}: \{(x_{il}\theta_{il}, \alpha_l)\} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ij^*l}\}$

   $\boldsymbol{0} \rightarrow \boldsymbol{I_{allocated}}: \{I_{ijl}\}, \forall j \in \{1,2, \dots, L; j \neq j^*\}$
5. S-SAS forwards the allocation indicator information, $\boldsymbol{I_{j,allocated}}: \{I_{ijl} \in (1,0)\}$, to each of the participating SU-APs
6. Perform the allocation procedure for all the available spectrum opportunities.

Algorithm 1.2: Price Adjustment by PU and SU Operations

Chapter 1: S-SAS generate list of unassigned channel and forwards $\boldsymbol{I_{unassigned}}$ to I-SAS:

$\boldsymbol{for}\ \forall l, i, \quad if(SO_{il} \notin \boldsymbol{I_{allocated}}): SO_{il} \rightarrow \boldsymbol{I_{unassigned}}$

Chapter 2: I-SAS in consultation with the corresponding PU adjusts the discount factor θ_{il}

$\boldsymbol{for}\ \forall l, i \in \boldsymbol{I_{unassigned}}, \quad \theta_{il}^{new} = \theta_{il} - \Delta_{PU_{il}}:\ \theta_{il}^{new} \rightarrow \boldsymbol{SO}(x_{il}\theta_{il}^{new}, \alpha_l)$

Chapter 3: The SU-AP calculates the loss in revenue due to the current bidding price

$$\boldsymbol{for}\ \forall l, i \in \boldsymbol{I_{j,desired}},\ P_{j_{achievable}} = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau \boldsymbol{I_{j,desired}}$$

$$\boldsymbol{for}\ \forall l, i \in \boldsymbol{I_{j,allocated}},\ P_{j_{achieved}} = \sum_{l=1}^{L}\sum_{i=1}^{M}(r_j - c_{i,j,l})k_{i,j}\alpha_l B\tau \boldsymbol{I_{j,allocated}}$$

$$\left(P_{j_{missed}} = P_{j_{achievable}} - P_{j_{achieved}}\right): \Delta_{SU_{jl}} = \theta_{adjust}P_{j_{missed}}$$

$$y_{jl}^{new} = y_{jl} + \Delta_{SU_{jl}}$$

Chapter 4: The SU-AP that gets allocated its desired channels does not perform the price adjustment mentioned in Step2

$\boldsymbol{for}\ \forall l, i, \quad if(\boldsymbol{I_{desired}} = \boldsymbol{I_{allocated}}): \Delta_{SU_{jl}} = 0;\ y_{jl}^{new} = y_{jl}$

Chapter 5: The asking and bidding prices for the spectrum opportunities are updated

Performance Evaluation

This section presents the simulation results to evaluate the performance of the proposed auction-based spectrum sharing system. We are mainly interested in observing how the bidding prices, secondary user payoff, spectrum usage, and primary user revenue evolve over consecutive bidding stages.

Parameter Setting

For the purpose of simulation, we assume a spectrum sharing scenario with two primary users ($M = 2$) and two secondary users ($N = 2$). Each primary user offers three channels, each of 10 MHz bandwidth and time duration of 1 unit ($\tau = 1$), for sharing with the secondary users. The SAS calculates the associated QoSA values for each of these spectrum opportunities. The SAS also employs the opportunity clustering mechanism and generate four categories ($L = 4$) of spectrum opportunities as shown in Table 28.

Category	QoSA Range	Cluster QoSA	α value
A	$QoSA > 0.8$	0.9	0.9491
B	$0.6 > QoSA \geq 0.8$	0.7	0.8411
C	$0.4 > QoSA \geq 0.6$	0.5	0.7213
D	$0.4 \geq QoSA$	0.3	0.5814

Table 28: Opportunity Clusters with associated QoSA values

Each of the secondary user access points also calculates the spectral efficiency of each of the spectrum opportunities for a target BER of 10% using Equation (1). The asking price for each of channels at the beginning of the auction is 1.0 unit for primary user 1 and 0.8 units for primary user 2. The initial value for the primary user price adjustment factor is 1. The secondary user access points earn 2.0 units of revenue from each of the spectrum opportunities and start the bidding with a price of 0.8 units for secondary user access point 1 and 0.6 units for secondary user access point 2. Using the above pricing and channel quality information, the secondary user access points calculate the bidding price for the 1st auction stage according to Eq. (50).

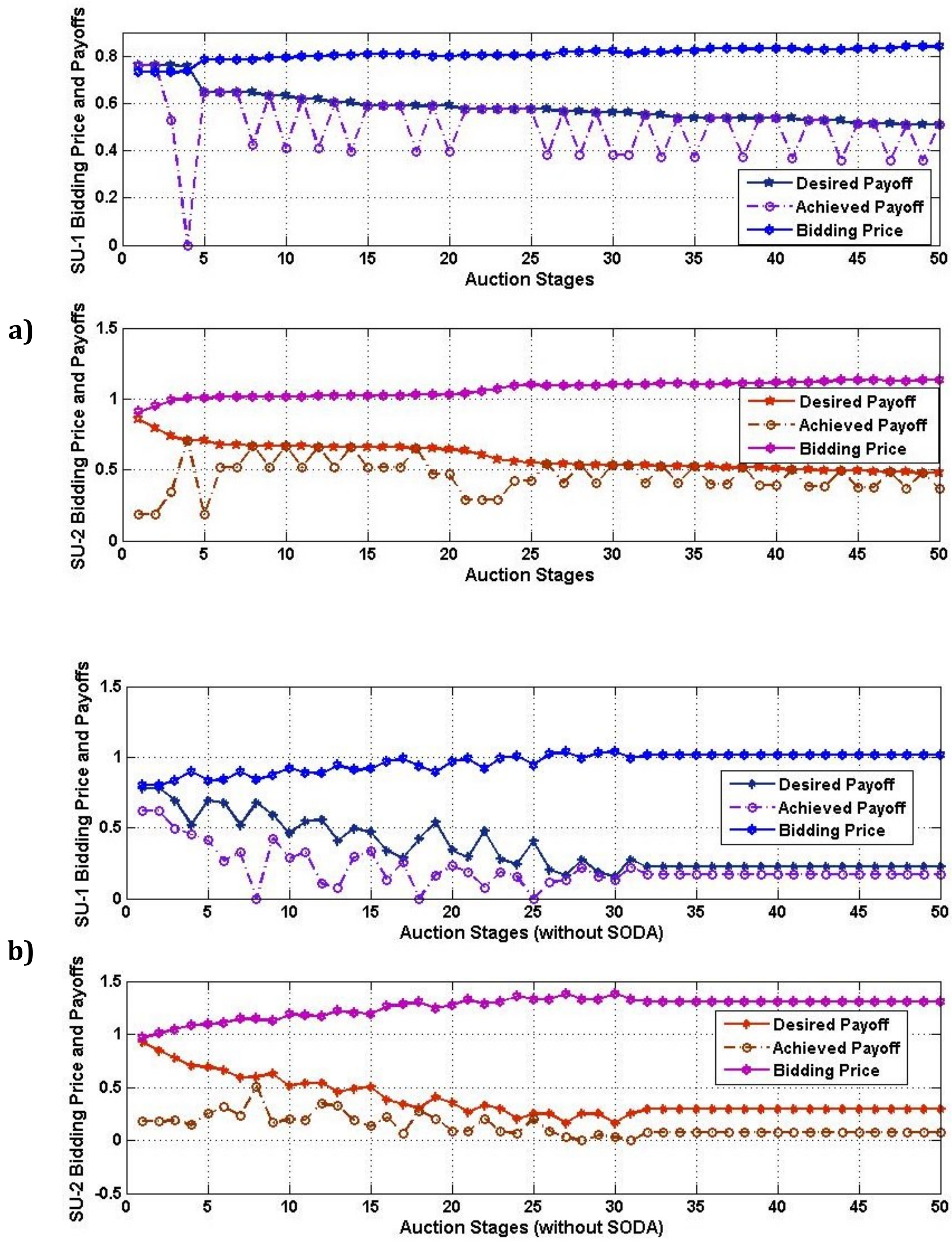
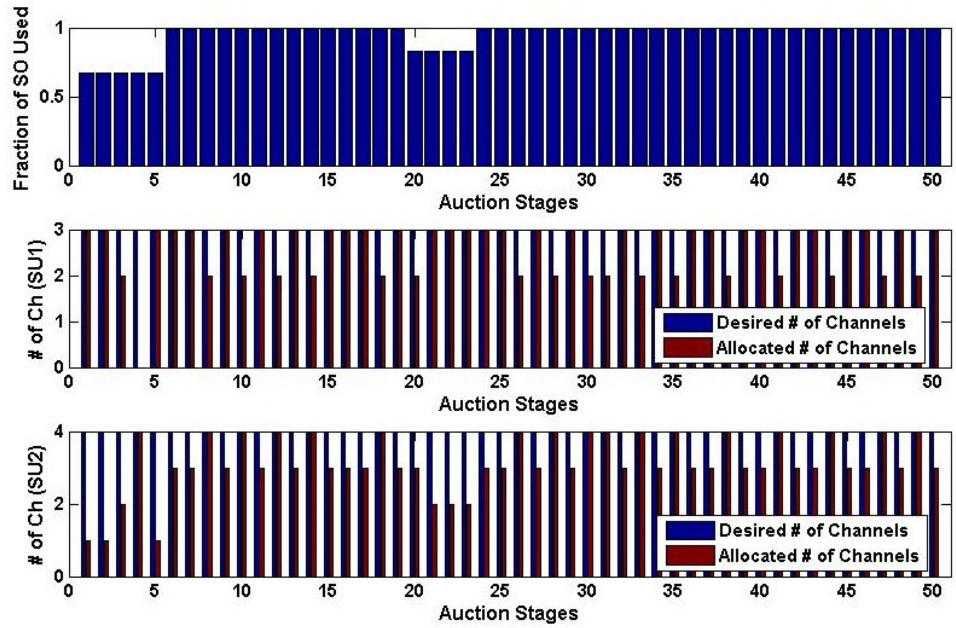


Figure 34: Secondary User Access Point bidding prices and corresponding payoffs: a) Secondary User 1 and b) Secondary User 2

After every iteration of the auction process the primary users re-evaluates their asking price based on the number of unassigned spectrum opportunities and missed revenue. The secondary user access points also re-evaluate their bidding prices considering the difference in the desired and achieved payoffs as a result of the current bidding prices. In the following we present the simulation results and analyze the impact of the proposed iterative auction procedure. We observe the impact on the bidding price and payoffs of the secondary user access points, the revenue and asking price of the primary users, and the fraction of the available spectrum opportunity used by the spectrum sharing system.

a)



b)

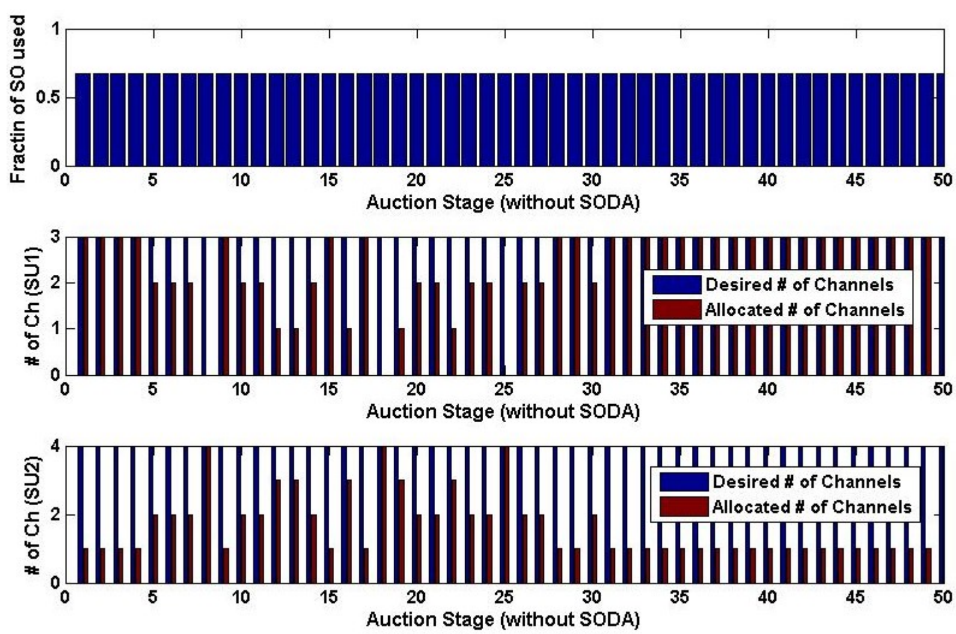


Figure 35: Secondary User Access Point channel allocation & Spectrum usage

Secondary User Bidding Prices and Payoffs

The secondary user access points use the primary user cooperation in the form of SODA (α) values associated with each of the spectrum opportunities to calculate the desired payoff. This helps the secondary user access points to achieve payoffs close to the desired ones as a result of the auction results of each stage. Without the SODA values, the secondary user access points would have assumed that they would be able to access the spectrum opportunity for the whole duration of τ units and accordingly solve the optimization problem presented in Eq. (57). But the uncertainty associated with the return of the primary user within the assured duration in the spectrum opportunity would affect the achievable payoffs out of the allocated opportunities. As can be seen from Figure 34, the iterative adjustments in the bidding prices (secondary user access point 1 in stage 5 and secondary user access point 2 in stage 26) also help the secondary user access points to achieve payoffs close to the desired ones. For an auction process without considering any cooperation from the primary users, the difference between the estimated payoff and the actual payoff is ~40% and ~30% respectively for secondary user 1 and secondary user 2 (Figure 34 (b)). Simulation results also show that this discrepancy in estimation does not go away with increased number of auction stages. This difference in payoffs makes the secondary user bidding decisions inefficient. But if the auction process takes advantage of the probabilistic assurances (SODA) provided by the primary user cooperation along with the proposed iterative auction stages, the differences in estimated and actual payoffs may be reduced.

Spectrum Usage

Figure 35 shows the desired and allocated channels for secondary user access point 1 and secondary user access point 2. The secondary user access points determine the number of channels needed based on the aggregate QoS required by the end users served by each of these access points. If the QoSA values of the spectrum opportunities are not known to the access points, they will over-estimate the achievable QoS from the opportunities. This will result in degraded user experience for the access points. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users and improves the spectrum sharing performance metrics. Without primary cooperation, the access point 1 receives around ~65% more opportunity assignment compared to access point 2. When the auction process considers the SODA values, the difference in opportunity assignment comes down to ~ 20% (in favor of access point 2 in this particular simulation case). The primary-secondary user cooperation also increases the overall spectrum usage from ~55-60% to an impressive ~95%.

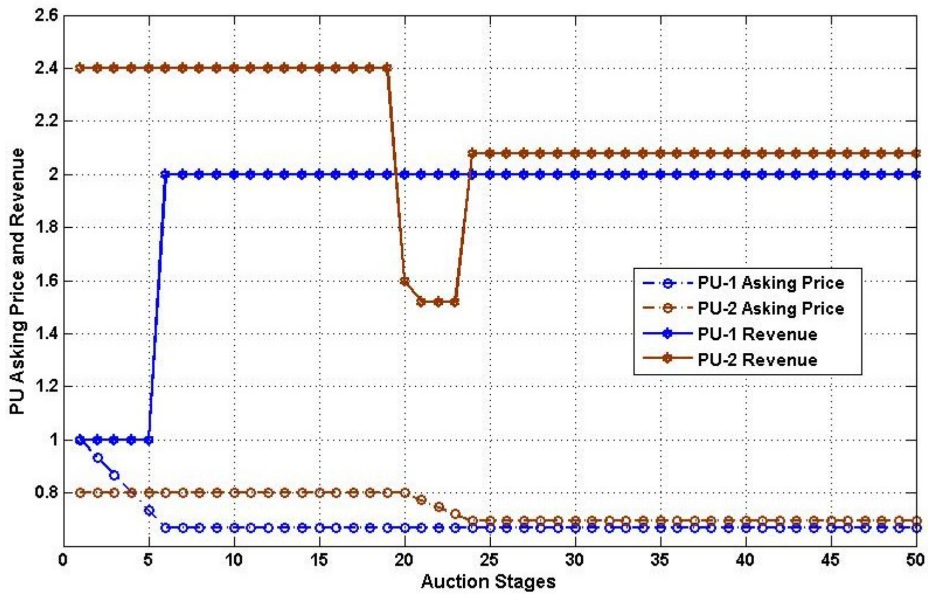


Figure 36: Primary user asking price adjustment and corresponding revenues

Knowing the realistically achievable QoS by the secondary users may be used to gauge the secondary users' interest in the spectrum opportunities offered by the primary users for auctioning. This helps the primary users to more effectively determine the asking price of its own spectrum opportunities based on the opportunity results from each of the auction stages. Figure 36 presents the asking price adjustment by the primary users in order to improve the revenue. By offering a reduction of 80% in asking price, primary user 1 eventually doubled the aggregate revenue earned from all of its spectrum opportunities. Primary user 2 also had to react to this maneuver by primary user 1 and reduced its own asking price down to 25 %. This helped primary user 2 to cut down the reduction in revenue by ~35%. As a result of the iterative price adjustment at the later stages of the auction all the available spectrum opportunities are allocated to the secondary user access points. This readjustment based on the previous auction results and the α values of the opportunities improve the primary user 2 revenue and the auction procedure reaches an equilibrium state in terms of the revenue generated by both the primary user operations shown in Figure 36.

Summary of the Section

Spectrum is a limited and expensive resource. It is a critical yet scarce resource due to the substantial growth of wireless technology and applications. Dynamic spectrum sharing has been deemed as an effective approach to better utilize limited spectrum resource because clearing and reallocating licenses are extremely expensive. By proposing the Citizen Broadband Radio Service for the 3.5 GHz band, FCC has introduced a spectrum sharing paradigm where a separate governing entity such as the proposed Spectrum Access System (SAS) manages access to spectrum for primary and secondary users to coexist. An important aspect of dynamic spectrum management is the pricing of spectrum from the perspective of both the primary and secondary users. Due to their perceived fairness and allocation efficiency, auctions are among the best-known market-based mechanisms to allocate spectrum. However, spectrum auction differs from conventional auctions in that it has to address radio interference. Spectrum auction is essentially a problem of interference-constrained resource allocation. Existing auction-based spectrum sharing models so far has missed out on an important aspect of successful secondary user operation: the duration of the available spectrum opportunity. In this chapter we proposed an auction-based spectrum sharing framework that statistically accounts for the estimates of spectrum opportunity duration. The framework allows both the primary and the secondary user operations to act on the current auction results to update their bidding packages in order to achieve a price combination that maximizes both the primary and secondary user auction goals.

The auction process using the primary-secondary cooperation proposed in this chapter addresses the uncertainty associated with the return of the primary user within the assured duration in the spectrum opportunity. The iterative adjustments in the bidding prices (secondary user access point 1 in stage 5 and secondary user access point 2 in stage 26) also help the secondary user access points to achieve payoffs close to the desired ones. For an auction process without considering any cooperation from the primary users, the simulation results show a ~30-40% of discrepancy between the estimated and the actual secondary user payoff and. Although the difference reduces with increasing number of auction stages, it does not go away. But if the auction process takes advantage of the probabilistic assurances (SODA) along with the proposed iterative auction stages, the differences in estimated and actual payoffs is reduced. Without the SODA values, the access points over-estimate the achievable QoS from the opportunities which results in degraded user experience. The proposed dynamic auction with time-evolving values of channel qualities improves the social equality among the primary and secondary users and improves the spectrum sharing performance metrics. Without primary cooperation, the access point 1 receives around ~65% more opportunity assignment compared to access point 2. When the auction process considers the SODA values, the difference in opportunity assignment comes down to ~ 20% (in favor of access point 2 in this particular simulation case). The primary-secondary user cooperation also increases the overall spectrum usage from ~550-60% to an impressive ~95%. Also the asking price adjustment by the primary users improves the revenue. By offering a reduction of 80% in asking price, primary user 1 eventually doubled the aggregate revenue earned from all of its spectrum opportunities. In response primary user 2 reduced its own asking price down to 25 %. This helped primary user 2 to cut down the reduction in revenue by ~35%. Eventually both the primary users ended up with equal revenue earning as a result of primary-secondary cooperation and iterative auction stages.

In conclusion this chapter proposes a dynamic and self-adjusting auction scheme for dynamic spectrum access based spectrum sharing systems that accounts for the quality of the available spectrum opportunity in terms of the probabilistic assurance generated by the SAS under the primary-secondary cooperation framework. The dynamic auction procedure allows both the primary and secondary operations to adjust their evaluation of the available opportunities based on their experiences with the channel quality from past usage statistics and past auction results, and over time achieves a price combination that maximizes both the primary and secondary user objectives. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users. The primary-secondary cooperation is menifested in the form of spectrum opportunity duration assurance (SODA) in the auction process. The SODA approach, as opposed to the QoS prediction approach, estimates the spectrum opportunity duration for operations with non-deterministic or unknown spectrum reservations or usage patterns. SODA is a metric that measures the probabilistic assurance about idle primary user channels stating that the channel under consideration will be available for secondary use for certain duration of time with probability SODA. Knowing the realistically achievable QoS considering the uncertainty due to primary user return to the opportunity allows the secondary user access points to more effectively determine the number of spectrum opportunities for which it will participate in the auction process. The quantitative measure of the usability of a spectrum opportunity have great impact on the performance of any spectrum sharing system, and should be incorporated in spectrum opportunity management. The proposed channel quality based dynamic auction scheme allows the secondary users to take advantage of the predictive models of spectrum availability, prioritize spectrum opportunities accordingly, and bid for their prefered channels to maximize spectrum utilization while minimizing the occurrence of disruptions to primary users.

Chapter 6

Conclusion

Chapter 6: Conclusion to the Dissertation

Conclusion

The explosive growth of wireless technology along with the insatiable demands from content rich applications has made spectrum a critical yet scarce resource. Spectrum plays a significant role to ensure the continued growth and innovation in nearly every segment of our society. It is an essential tool for connecting communities. Access to adequate spectrum has the power to exponentially maximize our collective potential. Radio spectrum is a limited resource for wireless communications, and service providers in both the commercial and government domains are demanding increased spectrum to meet their customer's demands. The increasing diversity of use cases and demand of high quality-of-service (QoS) have resulted in overcrowding of spectrum bands. At the same time, the rapid evolution of wireless communications has made the problem of spectrum utilization ever more critical. Such explosive demand from wireless communications and service applications has contributed to a huge demand of new wireless services in both the licensed and unlicensed bands. Also access to new spectrum blocks is not a viable solution as clearing and reallocating licenses are extremely expensive and time consuming. Therefore, efficient and flexible utilization of radio spectrum is a key design challenge for the next generation wireless network. Conventional spectrum management policies use static spectrum assignment to prevent interference. Due to spatial and temporal variation of spectrum utilization by the incumbent users, static allocation of wireless bandwidth is observed to be spectrally inefficient. Therefore, dynamic sharing of wireless spectrum seems to be the panacea for higher spectral efficiency. The Citizens Broadband Radio Service is a unique spectrum sharing regime that will, in a word, revolutionize the way we do things. This new service leverages innovative new sharing rules and technologies to create a 150 MHz band of contiguous spectrum to help meet the Nation's wireless broadband needs, including 100 MHz previously unavailable for commercial use. It establishes a three-tier framework for making the entirety of the 3.5 GHz band available for shared commercial use, while putting in place protections for the band's incumbents. With Spectrum Access Systems taking on the complicated and vital role of frequency coordination, the three tiers: Incumbent Access users, Priority Access Licensees and General Authorized Access users, will soon be able to cohabitate in the band and maximize spectrum efficiency.

To address the nomadic and sporadic bursty demand for radio spectrum, opportunistic communications has been and will play a significant role. Dynamic spectrum access allows fast deployment of wireless technologies by reusing the under-utilized pre-allocated spectrum channels, all with minimal impact on existing primary users. Cognitive radio addresses the underutilization problem of the spectrum licensed to different organizations, and it supports dynamic spectrum access. In a dynamic spectrum access system primary users have higher priority in using the licensed channels. Therefore, whenever a primary user is detected, secondary users must vacate the relevant channels or decrease their transmitted power to reduce the interference on primary users. In the context of spectrum sharing, depending on the operational status of the primary user, secondary users may suffer degraded quality of service due to temporal connection loss and undesirable interference situation. Without any prior information about the availability and duration of spectrum opportunities, the secondary user operations need to continuously monitor the spectrum blocks under consideration in order to identify the opportunities and also detect the return of the primary user operations. This continuous monitoring results in significant consumption of time, energy, and spectrum resources. These adversities can be significantly compensated if the secondary users have knowledge about the duration of the spectrum opportunities, and use that knowledge to either avoid or take additional measures while using these opportunities. The fundamental difference between shared and dedicated spectrum systems, as a consequence of dissimilar spectrum usage rights, is the lack of knowledge about the availability and duration of spectrum opportunities. The existing spectrum sharing approaches do not offer any flexibility to the involved parties from which to decide on or choose the sharing mechanisms. These approaches do not involve the cooperation between the resource owner and the opportunistic user who wants to share the resource. Therefore, offering assurances about the availability and duration of spectrum opportunity through primary-secondary cooperation will significantly improve the overall spectrum sharing experience.

In this submission, we proposed a cooperation approach that involves information exchange between the primary and secondary user operations and thus allows the system to improve the spectrum sharing performance. Spectrum occupancy prediction provides cognitive radio secondary users with proactive ability to exploit spectrum opportunities. Through this cooperation approach, we enable the secondary users with access to information about the availability and duration of spectrum opportunities for the spectrum sharing channels. We looked into the important aspect of successful secondary user operation in the shared band and analyze the achievable Quality of Service (QoS) out of the shared spectrum. In Chapter II, we discussed these efforts towards a dynamic spectrum sharing system in the U.S. context. In order to support the dynamic management of the 3.5

GHz band, it is imperative to explore the required SAS composition and functionalities. We presented an example SAS architecture and identified its functionalities, corresponding technical tasks, Information requirement, intra-module interactions, related technical challenges. We also analyzed the position of the Commission on different aspect of the Citizen Broadband Radio Services (CBRS) through the 3.5 GHz R&O and the Second R&O in order to address the criticism of the proposed 3-tier system. We presented a summary of a survey of the stakeholder's comments in response to the 3.5 GHz FNPRM. Our analysis yielded a number of important issues which are required to be addressed for successful operation of the proposed CBRS. We identified the required functionalities, technical capabilities, and composition of the SAS to support the dynamic spectrum management approach envisioned in the CBRS. We hope the discussion presented in Chapter II will help the readers understand the policy and regulatory aspects of the spectrum sharing initiatives and will initiate further awareness and more informed discussions and research towards an efficient dynamic spectrum sharing system. Chapter III addressed the generation of a probabilistic assurance about the availability and duration of the available spectrum opportunities – the Spectrum Opportunity Duration assurance (SODA). A method to statistically ensure spectrum availability using Non-Stationary Hidden Markov Models was proposed. We introduced primary user cooperation into the prediction algorithms to improve the prediction accuracy and reduce the computational complexity of the prediction algorithms. The Incumbent SAS, enabled with primary user cooperation, performs the Non-Stationary Hidden Markov Model approach to re-estimate the model parameters and forward it to the Secondary SAS. The Secondary SAS uses the re-estimated model parameters to run the prediction algorithm in real time using the current channel monitoring results received from the Environmental Sensing Capability (ESC) system and/or the secondary users. The Spectrum Opportunity Duration Assurance (SODA) values determined for each of the shared channels helps the spectrum sharing systems to achieve the availability and duration information about spectrum opportunities. We validated the proposed SODA generation method using real life data (collected local police dispatch data for two twenty four (24) hour period, one to train the NS-HMM parameters and the other to evaluate the prediction performance of the proposed prediction algorithm). Without primary user cooperation the Hidden Markov Model based approach provides 74% of prediction accuracy. On the other hand, the Non-Stationary Hidden Markov Model with primary cooperation (model parameter initialization and *Similar Activity Phase Identification*) offers significant improvement in prediction accuracy (96%). Primary user cooperation also improves the performance of the Non-Stationary Hidden Markov Model approach in predicting the duration of the available spectrum opportunities. For a spectrum opportunity with duration of two (2) time slots, the Hidden Markov Model approach without using any cooperation predicts the opportunity duration with a prediction accuracy of ~65%. While the Non-Stationary Hidden Markov Model with primary user cooperation, under the similar context, improves the opportunity duration prediction accuracy up to ~95%. In Chapter IV we explored the impact of primary-secondary cooperation on the dynamic access of spectrum opportunities. We looked in to the ways to efficiently use the primary user cooperation in order to improve the spectrum sharing experience of both primary and secondary operations. The cooperation from primary users in the form of SODA values allowed us to propose spectrum opportunity access schemes based on the principle of interference avoidance. In order to reduce the overhead in frequently generating and accessing this information, we proposed to maximize the utility duration of the SODA information using the concept of "Time Discounted Value of Information". We determined the effective value of the information at any particular time instant within the assured duration and decided whether to improve the assurance by employing sensing techniques or not. In this analysis, we proposed interference avoidance schemes that use channel monitoring based on the time discounted value of the PU cooperation and reduce the number of time slots in collision between the primary and secondary operations. The interference avoidance schemes use a combination of primary user cooperation and channel monitoring techniques to reduce the resource consumption for channel monitoring during the early stage of the assured duration and at the same time reduce the likelihood of interference in the later stage of the duration with the help of channel monitoring. We also analyzed and theoretically modeled the reduction in number of sensing events which is required to achieve a desired interference environment and also the improvement in secondary user throughput as a result of primary user cooperation. The simulation results showed reasonable improvement in the spectrum sharing performance of the secondary user systems. For a spectrum opportunity with high probabilistic assurance, $SODA = 0.7$, the dynamic access scheme $SODA_2$ results in significant reduction in sensing overhead (~5%). Even with low assurance spectrum opportunities (for example with $SODA = 0.2$), the proposed dynamic access schemes cuts the sensing overhead almost down to half ($\sim 25\% - 30\%$). The $SODA$ without sensing scheme resulted in high throughput (~25% more compared to STS scheme even for $SODA$ as low as 0.1) for secondary user systems. But it also significantly increases the collision time compared to any other scheme. For low assurance opportunities (low $SODA$ values), the proposed access scheme performances (~15-20%) closely approximate that of the STS scheme. As the $SODA$ value increases, the performances of the proposed $SODA_1$ and $SODA_2$ schemes ($\sim 65 - 70\%$ for SODA=0.7) gradually approaches that of the $SODA$ without sensing (using primary cooperation only, no sensing employed) scheme (~80% for SODA=0.7). In Chapter V we proposed an auction-based spectrum sharing framework that statistically accounts for the estimates of spectrum opportunity duration. The framework allowed both the primary and the secondary user operations to act on the current auction results to update their bidding packages in order to achieve a price combination that maximizes both the primary and secondary user auction goals. This chapter presented a dynamic and self-adjusting auction scheme for dynamic spectrum access based spectrum sharing systems that accounts for the quality of the available spectrum opportunity in terms of the probabilistic assurance generated by the SAS under the primary-secondary cooperation framework. The proposed dynamic auction for spectrum sharing with time-evolving values of channel qualities maximizes the social equality among the primary and secondary users. The primary-secondary cooperation was manifested in the form of spectrum opportunity duration assurance (SODA) in the auction process. The SODA approach, as opposed to the QoS prediction approach, estimated the effective spectrum opportunity duration for operations with non-deterministic or unknown spectrum reservations or usage patterns. A spectrum opportunity assignment discrepancy of ~65%, for nor primary user cooperation scenario, was cut down to ~20% while the auction process considered primary-secondary cooperation to readjust the channel quality evaluations. The primary-secondary user cooperation also increases the overall spectrum usage from ~55-60% to an impressive ~95%. Also the asking price adjustment by the primary users improves the revenue. By offering a reduction of 80% in asking price, primary user 1 eventually doubled its aggregate revenue. In response primary user 2 reduced its own asking price down to 25 % and lowered the reduction in revenue (as a result if primary user 1's action) by ~35%. Eventually both the primary users ended up with equal revenue earning as a result of primary-secondary cooperation and iterative auction stages. Knowing the realistically achievable QoS considering the uncertainty due to primary user return to the opportunity allowed the secondary user access points to more effectively determine the number of spectrum opportunities for which it will participate in the auction process. The proposed channel quality based dynamic auction scheme allowed the secondary users to take advantage of the predictive models of spectrum availability, prioritize spectrum opportunities accordingly, and bid for their preferred channels to maximize spectrum utilization while minimizing the occurrence of disruptions to primary users.

Through this dissertation, we proposed a primary-secondary cooperation approach that involves information exchange between the licensed owner and the opportunistic user operations and thus improve the overall spectrum sharing experience by taking advantage of the cooperation. Spectrum occupancy prediction provides cognitive radio secondary users with proactive ability to exploit spectrum opportunities. Through this cooperation approach, we intend to avail the information about the availability and duration of spectrum opportunities for the spectrum sharing channels without endangering the operational privacy of the primary user. We looked into the important aspect of successful secondary user operation in the shared band and analyze the achievable Quality of Service (QoS) out of the shared spectrum. The Spectrum Access System (SAS) plays a significant role in our proposed cooperation approach and bridges the primary-secondary interaction. It also acts as an additional layer of abstraction to improve the primary user information privacy. Although the work presented in this dissertation concentrates on the 3.5 GHz band, but the work is applicable to any spectrum sharing use cases. For example one use case could be the coexistence between cellular communication and the radar system, especially in the 5 GHz band [408]. Another application might be the coexistence of 5G mobile service in 31 GHz to 31.3 GHz spectrum with Radio Astronomy Service (RAS), Earth Exploration Satellite Service (EESS), and Space Research Service (SRS) in the adjacent 31.3 to 31.8 GHz spectrum [409, 410]. EESS systems are sensitive and given their orbit, could be given a probabilistic metric for scanning a specific area on the earth. The proposed probabilistic assurance (SODA) approach also has the potential to significantly influence the operational and technological evolution of the next generation Public Safety systems in the D-Block [37]. Network sharing for wireless cellular systems by the network infrastructure owners may become a very interesting and promising use case for the concept and the models of the sharing framework presented in this dissertation. With a myriad of new use cases and application brunching out of the 5G initiatives, it is unlikely that each of these use cases will have their own network infrastructure and resources. For example, these uses cases will be very likely be sharing resources (computation capability, memory capacity, energy supply, available channel assigned to the eNB, etc.) from the same eNodeB to reduces their dependency on high value infrastructure and thus in turn significantly reduce the capital and operational investment.

The successful implementation of the dynamic spectrum management paradigm, using the Spectrum Opportunity Duration Assurance (SODA) metric proposed in this dissertation, will significantly improve the spectrum usage efficiency and influence the management approach of other spectrum bands. The SODA approach for dynamic spectrum management will give the spectrum sharing architectures new flexibility to handle evolutions in technologies, regulations, and the requirements of new bands being transitioned from fixed to share usage. This calls for a coordinated effort from the government, industry, and academia to expedite the development of the dynamic SAS and move forward towards the dynamic spectrum management regime. We hope the discussion presented in this dissertation will help the readers understand the policy, regulatory, and technological aspects of the spectrum sharing initiatives and will initiate further awareness and more informed discussions and research towards an efficient dynamic spectrum sharing system.

We conclude this submission looking forward to the next generations of wireless networks that upholds the vision set by the President's Committee of Advisors on Science and Technology in their report to the President (PCAST Report 2012 [4]):

"Norm for spectrum use should be sharing, not exclusivity."

Chapter 7: References

[1] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, "IEEE 802.11 af: a standard for TV white space spectrum sharing," *IEEE Communications Magazine,* vol. 51, no. 10, pp. 92-100, 2013.

[2] M. M. Sohul, M. Yao, T. Yang, and J. H. Reed, "Spectrum access system for the citizen broadband radio service," *Communications Magazine, IEEE,* vol. 53, no. 7, pp. 18-25, 2015.

[3] FCC. (2012). *GN Docket No. 12-354, FCC NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[4] (2012). *Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth*.

[5] A. Ericsson, "Interim Ericsson Mobility Report, February 2014," ed, 2014.

[6] C. V. N. Index, "Global Mobile Data Traffic Forecast Update, 2016–2021," 2017.

[7] C. V. N. Index, "The zettabyte era–trends and analysis," *Cisco white paper,* 2013.

[8] D. METIS, "D1. 1. Scenarios, requirements and KPIs for 5G mobile and wireless system, May, 2013," ed.

[9] E. Hossain and M. Hasan, "5G cellular: key enabling technologies and research challenges," *IEEE Instrumentation & Measurement Magazine,* vol. 18, no. 3, pp. 11-21, 2015.

[10] Ericsson, "White paper: 5G Radio Access – Research and Vision," ed: Ericsson, June, 2013.

[11] (March 27, 2012). *An Assessment of the Viability of Accommodating Wireless Broadband in the 1755-1850 MHz Band*.

[12] S. C. Jha, K. Sivanesan, R. Vannithamby, and A. T. Koc, "Dual connectivity in LTE small cell networks," in *Globecom Workshops (GC Wkshps), 2014*, 2014, pp. 1205-1210: IEEE.

[13] Z. Shen, A. Papasakellariou, J. Montojo, D. Gerstenberger, and F. Xu, "Overview of 3GPP LTE-advanced carrier aggregation for 4G wireless communications," *IEEE Communications Magazine,* vol. 50, no. 2, 2012.

[14] Q. Wang, D. Jiang, G. Liu, and Z. Yan, "Coordinated multiple points transmission for LTE-advanced systems," in *Wireless Communications, Networking and Mobile Computing, 2009. WiCom'09. 5th International Conference on*, 2009, pp. 1-4: IEEE.

[15] D. Lee *et al.*, "Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges," *IEEE Communications Magazine,* vol. 50, no. 2, 2012.

[16] A. Mukherjee *et al.*, "Licensed-assisted access LTE: Coexistence with IEEE 802.11 and the evolution toward 5G," *IEEE Communications Magazine,* vol. 54, no. 6, pp. 50-57, 2016.

[17] T. Yücek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys & Tutorials, IEEE,* vol. 11, no. 1, pp. 116-130, 2009.

[18] C. R. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. J. Shellhammer, and W. Caldwell, "IEEE 802.22: The first cognitive radio wireless regional area network standard," *IEEE communications magazine,* vol. 47, no. 1, pp. 130-138, 2009.

[19] 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,* vol. 50, no. 13, pp. 2127-2159, 2006.

[20] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *Signal Processing Magazine, IEEE,* vol. 24, no. 3, pp. 79-89, 2007.

[21] (2013). *ETSI TR 103 113, ETSI TR Mobile Broadband Services in the 2300-2400 MHz Frequency Band under Licensed Shared Access Regime*.
[22] (2010). *National broadband plan: Connecting america*.
[23] M. Denkovska, P. Latkoski, and L. Gavrilovska, "Geolocation database approach for secondary spectrum usage of TVWS," in *Telecommunications Forum (TELFOR), 2011 19th*, 2011, pp. 369-372: IEEE.
[24] NTIA, "Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz, and 4380-4400 MHz Bands," ed: Fast Track Evaluation)(Oct. 2010).
[25] (2013). *Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[26] DCC. (2013). *GN Docket No. 12-354, CFP on The Proposed Spectrum Access System for the 3.5 GHz Band*.
[27] (2014). *FNPRM: Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[28] (2015). *GN Docket No. 12-354, Report and Order and Second FNPRM: In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[29] Federal Communications Commission. (2015). *GN Docket No. 12-354, Public Notice: Wireless Telecommunications Bureau Reminds Licensees in the 3650-3700 MHz Band Wireless Broadband Service and 3550-3650 MHz Band Non-Federal Radiolocation Service of Requirements for Construction and Operation*.
[30] Federal Communications Commission. (2015). *GN Docket No. 12-354, Wireless Telecommunications Bureau Seeks comment on an Appropriate Method for Determining the Protected Contours for Grandfathered 3650-3700 MHz Band Licensees*.
[31] Federal Communications Commission. (2015). *GN Docket No. 12-354, GN Docket No. 15-319, Wireless Telecommunications Bureau and Office of Engineering and Technology Establish Procedure and Deadline for Filing Spectrum Access System (SAS) Administrator(s) and Environmental Sensing Capability (ESC) Operator(s) Applications*.
[32] Federal Communications Commission. (2016). *GN Docket No. 12-354, Order on reconsideration and Second Rule and Order in the matter of commercial operations in the 3.5 GHz band*.
[33] B. Benmammar, A. Amraoui, and F. Krief, "A Survey on Dynamic Spectrum Access Techniques in Cognitive Radio Networks," *International Journal of Communication Networks and Information Security (IJCNIS),* vol. 5, no. 2, 2013.
[34] S. Huang, X. Liu, and Z. Ding, "Opportunistic spectrum access in cognitive radio networks," in *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, 2008: IEEE.
[35] C. Xin, M. Song, L. Ma, G. Hsieh, and C.-C. Shen, "On random dynamic spectrum access for cognitive radio networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*, 2010, pp. 1-5: IEEE.
[36] Y. Zhang, "Dynamic spectrum access in cognitive radio wireless networks," in *Communications, 2008. ICC'08. IEEE International Conference on*, 2008, pp. 4927-4932: IEEE.
[37] M. M. Sohul, M. Yao, X. Ma, V. Marojevic, and J. H. Reed, "Next generation public safety networks: A spectrum sharing approach," *IEEE Communications Magazine,* vol. 54, no. 3, pp. 30-36, 16 March 2016 2016.
[38] (2013). *Comments of Qualcomm Inc. In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[39] S. M. Dudley *et al.*, "Practical issues for spectrum management with cognitive radios," *Proceedings of the IEEE,* vol. 102, no. 3, pp. 242-264, 2014.

[40] M. M. Sohul, B. Ramkumar, and T. Bose, "Multiuser automatic modulation classification for cognitive radios using distributed sensing in multipath fading channels," in *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on*, 2012, pp. 71-76: IEEE.

[41] M. M. Sohul, "Performance of Linear Decision Combiner for Primary User Detection in Cognitive Radio," 2011.

[42] M. M. Sohul, X. Ma, T. Yang, and J. H. Reed, "Quality of Service Assurance for Shared Spectrum Systems," in *Military Communications Conference (MILCOM), IEEE*, 2014, pp. 1471-1476.

[43] M. M. Sohul, R. Bettadapura, S. Aman, and J. H. Reed, "Information Assurance of LTE-Advanced Self-Organizing Networks," in *SDR-WInnComm 2014*, 2014: Wireless Innovation Forum.

[44] M. M. Sohul, M. Yao, V. Marojevic, and J. H. Reed, "Quality of Service Assurance-based Auction for Spectrum Sharing Systems," presented at the Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio, SDR WInnComm, March 2016, 2016.

[45] M. M. Sohul, M. Yao, A. S. Abdallah, M. Carrick, V. Marojevic, and J. H. Reed, "Quality of service assurance-based auction for spectrum sharing systems," *Analog Integrated Circuits and Signal Processing,* vol. 91, no. 2, pp. 203-216, 2017.

[46] (2015). *GN Docket No. 12-354, (NTIA Letter) Letter from Paige R. Atkins, Associate Administrator, Office of Spectrum Management, NTIA to Julius P. Knapp, Chief, Office of Engineering and Technology, FCC*.

[47] F. C. Commission, "Title 47 of the Code of Federal Regulations," *Telecommunications. Part,* vol. 80, 2011.

[48] N. O. o. S. Management. (2010). *Federal Spectrum Use Summary: 30 MHz – 3000 GHz (NTIA Federal Spectrum Use Summary)*. Available: http://www.ntia.doc.gov/files/ntia/Spectrum_Use_Summary_Master-06212010.pdf

[49] N. T. a. I. A. Office of Spectrum Management, "Coordinates of the Pre-existing FSS earth stations in the 3650-3700 MHz Band," ed: NTIA, 2010.

[50] (2014). *Comments of Telcordia Technologies Inc. in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[51] (2014). *Reply Comments of Qualcomm Inc. in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[52] (2013). *Comments of T-Mobile USA Inc. to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[53] (2014). *Comments of T-Mobile USA Inc. to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[54] (2014). *Comments of Verizon in response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[55] (2014). *Reply Comments of Verizon in response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[56] (2013). *1, Comment of AT&T to the NPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[57] (2013). *Comments on Alcatel-Lucent to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[58] (2014). *Comments on Alcatel-Lucent to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[59] (2014). *Comments of 4G Americas on the Further Notice of Proposed Rule Making In the matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[60] (2014). *1, Comment of AT&T to the FNPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[61] (2013). *Reply Comments of 4G Americas In the matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[62] (2013). *CTIA Reply Comments to 3.5 GHz PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550–3650 MHz Band*.
[63] (2013). *Comments of Ericsson to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[64] (2013). *Supplimental Comments of Verizon and Verizon Wireless in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[65] (2014). *Reply Comments of The Wireless Infrastructure Association and The HetNet Forum in response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[66] (2013). *Comments of The Wireless Infrastructure Association and The HetNet Forum in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[67] (2013). *Reply Comments of The Wireless Infrastructure Association and The HetNet Forum in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[68] (2013). *Comments of Telecommunications Industry Association to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[69] (2013). *Reply Comments of T-Mobile USA Inc. to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[70] (2014). *Comments of Nokia Solutions and Networks US LLC in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[71] (2014). *Comments of Google Inc. to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[72] (2014). *Reply Comments of Google Inc. to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[73] (2013). *Comments of Spectrum Bridge Inc. to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[74] (2014). *Comments of Spectrum Bridge Inc. in Response to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[75] (2013). *Response of Spectrum Bridge Inc. to Call for Papers on the Proposed Spectrum Access System for the 3.5 GHz Band. Docket No 12-354*.
[76] (2013). *Reply Comments of Google Inc. to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[77] (2013). *2, Reply Comments of AT&T to the NPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[78] (2013). *Comments of the Wireless Innovation Forum on the Public Notice Seeking Comment on Licensing Models and Technical Requirements in the 3556-3650 MHZ Band*.
[79] (2014). *Comments of Wireless Innovation Forum in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[80] (2013). *Comments of Shared Spectrum Company in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[81] (2014). *Comments of Microsoft Corporation to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[82] (2013). *Comments of New America Foundation and Public Knowledge in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[83] (2013). *Comments of Motorola Mobility in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[84] (2013). *Comments of the Wireless Internet Service Providers Association to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.
[85] (2014). *1, Comments of the American Petroleum Institute to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[86] (2014). *2, Reply Comments of the American Petroleum Institute to the FNPRM in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[87] (2014). *Comments of Motorola mobility in response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[88] (2014). *Comments of Utilities Telecom Council to the FNPRM in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[89] (2014). *Reply Comments of Utilities Telecom Council to the FNPRM in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[90] (2014). *Comments of Wireless Internet Service Providers Association in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[91] (2014). *Reply Comments of Wireless Internet Service Providers Association in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[92] (2014). *Comments of InterDigital Inc. in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[93] (2014). *Comments of Shared Spectrum Company in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[94] (2014). *Reply Comments of Shared Spectrum Company in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[95] (2014). *Comments of Wi-Fi Alliance in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[96] (2014). *Reply Comments of Wi-Fi Alliance in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[97] (2013). *Comments of Microsoft Corporation to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.
[98] (2013). *Reply Comments of New America Foundation and Public Knowledge in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.
[99] (2013). *Comments of the Comsumer Electronic Association In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[100] (2013). *Comments of Google Inc. to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[101] (2014). *2, Reply Comments of AT&T to the FNPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[102] (2014). *Reply Comments of Microsoft Corporation to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[103] (2014). *Comments of Federated Wireless LLC to the FNPRM: In the matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[104] (2014). *Reply Comments of Federated Wireless LLC to the FNPRM: In the matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[105] (2014). *Comments of Exelon Corporation to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[106] (2014). *Reply Comments of Nokia Solutions and Networks US LLC in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[107] (2014). *Reply Comments of Telecommunications Industry Association in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[108] (2014). *Comments of Telecommunications Industry Association in Response to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[109] (2014). *Comments of Ericsson to the FNPRM: In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[110] (2014). *Comments of CTIA - The Wireless Association to FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[111] FCC. (2012). *Notice of Proposed Rulemaking on Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*.

[112] (2014). *Comments of Entelec In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[113] (2014). *Comments of Southern Company Services in Reponse to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[114] (2014). *Comments of National Cable and Telecommunications Association to the FNPRM in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[115] (2013). *Comments of Nokia Solutions and Networks US LLC in response to the Public Notice on Licensing Models and Technical Requirements for the 3.5 GHz Band*.

[116] (2013). *Comments of Utilities Telecom Council to the Licensing PN: Commission Seeks Comment on Licensing Models and Technical Requirements in the 3550-3650 MHz Band*.

[117] (2014). *Comments of WiMAX Forum in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[118] (2014). *Comment of Oncor Electric Delivery Company LLC to the FNPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[119] (2014). *Reply Comments of Exelon Corporation to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[120] (2013). *Comments of Cantor Telecom Services to the NPRM In the Matter of Amendment of the Commission's Rules With Regard to Commercial Operations In the 3550-3650 MHz Band*.

[121] (2014). *Comments of Cantor Telecom Services to the FNPRM In the Matter of Amendment of the Commission's Rules With Regard to Commercial Operations In the 3550-3650 MHz Band*.

[122] (2014). *Comments of the Cohere Technologies to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[123] (2013). *Reply Comments of Telecommunications Industry Association in Response to the NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[124] E. Dahlman, S. Parkvall, and J. Skold, *4G: LTE/LTE-advanced for mobile broadband*. Academic press, 2013.

[125] (2014). *Comment of Satellite Industry Association to the FNPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[126] (2014). *Reply Comment of Satellite Industry Association to the FNPRM In the Matter of Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[127] (2014). *Comments of Baron Services to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[128] (2013). *Comments of the Satellite Industry Association on Licensing Models and Technical Requirements in the 3550-3560 MHz Band*.

[129] (2014). *Joint Content Reply Comments to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[130] (2014). *Comments of National Public Radio to the FNPRM in the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[131] (2013). *Joint Content Reply Comments In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[132] R. J. Berger, "Open spectrum: a path to ubiquitous connectivity," *Queue,* vol. 1, no. 3, pp. 60-68, 2003.

[133] M. McHenry, "Spectrum white space measurements," in *New America Foundation Broadband Forum*, 2003, vol. 1.

[134] N. Hoven, R. Tandra, and A. Sahai, "Some fundamental limits on cognitive radio," *Wireless Foundations EECS, Univ. of California, Berkeley,* 2005.

[135] S. M. Mishra, A. Sahai, and R. W. Brodersen, "Cooperative sensing among cognitive radios," in *Communications, 2006. ICC'06. IEEE International conference on*, 2006, vol. 4, pp. 1658-1663: IEEE.

[136] A. Sahai, R. Tandra, and N. Hoven, "Opportunistic spectrum use for sensor networks: the need for local cooperation," *submitted to the,* 2006.

[137] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Signals, systems and computers, 2004. Conference record of the thirty-eighth Asilomar conference on*, 2004, vol. 1, pp. 772-776: Ieee.

[138] K. Challapali, S. Mangold, and Z. Zhong, "Spectrum agile radio: Detecting spectrum opportunities," in *Proc. Intern. Symp. Advanced Radio Technologies., Boulder, CO, USA*, 2004, pp. 61-65.

[139] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 137-143: IEEE.

[140] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 131-136: IEEE.

[141] H. Kim and K. G. Shin, "Adaptive MAC-layer sensing of spectrum availability in cognitive radio networks," *University of Michigan, Tech. Rep. CSE-TR-518-06,* 2006.

[142] D. Willkomm, J. Gross, and A. Wolisz, "Reliable link maintenance in cognitive radio systems," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 371-378: IEEE.

[143] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on,* vol. 23, no. 2, pp. 201-220, 2005.

[144] J. Mitola III, "Wireless architectures for the 21st century," ed, 1999.

[145] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE personal communications,* vol. 6, no. 4, pp. 13-18, 1999.

[146] J. Mitola, "Cognitive radio for flexible mobile multimedia communications," in *Mobile Multimedia Communications, 1999.(MoMuC'99) 1999 IEEE International Workshop on*, 1999, pp. 3-10: IEEE.

[147] J. Mitola, "Cognitive radio---an integrated agent architecture for software defined radio," 2000.

[148] Y. Chen and H.-S. Oh, "A survey of measurement-based spectrum occupancy modeling for cognitive radios," *IEEE Communications Surveys & Tutorials,* vol. 18, no. 1, pp. 848-859, 2016.

[149] X. Xing, T. Jing, W. Cheng, Y. Huo, and X. Cheng, "Spectrum prediction in cognitive radio networks," *IEEE Wireless Communications,* vol. 20, no. 2, pp. 90-96, 2013.

[150] J. M. Peha, "Sharing spectrum through spectrum policy reform and cognitive radio," *Proceedings of the IEEE,* vol. 97, no. 4, pp. 708-719, 2009.

[151] (2009). *Presentation: spectrum with significant federal commitments 225 MHz - 3.7 GHz*.

[152] (May 2000). *Federal Radar Spectrum Requirements, Special Publication 00-40*.

[153] (June 2006). *ET Docket No. 03-122, In the matter of Revision of Parts 2 and 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) devices in the 5 GHz band, MO&O*.

[154] J. M. Peha, "Spectrum sharing in the gray space," *Telecommunications Policy,* vol. 37, no. 2, pp. 167-177, 2013.

[155] R. Saruthirathanaworakun, J. M. Peha, and L. M. Correia, "Opportunistic sharing between rotating radar and cellular," *IEEE Journal on Selected Areas in Communications,* vol. 30, no. 10, pp. 1900-1910, 2012.

[156] (2014). *Comments of Qualcomm Inc. in Response to the FNPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*.

[157] Z. Chen, N. Guo, Z. Hu, and R. C. Qiu, "Channel state prediction in cognitive radio, part ii: Single-user prediction," in *Proceedings of IEEE SoutheastCon*, 2011, pp. 50-54.

[158] I. A. Akbar and W. H. Tranter, "Dynamic spectrum allocation in cognitive radio using hidden Markov models: Poisson distributed case," in *Proceedings 2007 IEEE SoutheastCon*, 2007, pp. 196-201: IEEE.

[159] M. López-Benítez and J. Lehtomäki, "Energy detection based estimation of primary Channel Occupancy Rate in Cognitive Radio," in *2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2016, pp. 355-360.

[160] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proceedings of the IEEE,* vol. 55, no. 4, pp. 523-531, 1967.

[161] F. F. Digham, M.-S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," *IEEE Transactions on communications,* vol. 55, no. 1, pp. 21-24, 2007.

[162] S. Kapoor, S. Rao, and G. Singh, "Opportunistic spectrum sensing by employing matched filter in cognitive radio network," in *Communication Systems and Network Technologies (CSNT), 2011 International Conference on*, 2011, pp. 580-583: IEEE.

[163] X. Zhang, R. Chai, and F. Gao, "Matched filter based spectrum sensing and power level detection for cognitive radio network," in *Signal and Information Processing (GlobalSIP), 2014 IEEE Global Conference on*, 2014, pp. 1267-1270: IEEE.

[164] S. Shobana, R. Saravanan, and R. Muthaiah, "Matched filter based spectrum sensing on cognitive radio for OFDM WLANs," *International Journal of Engineering and Technology (IJET),* vol. 5, no. 1, p. p142, 2013.
[165] S. Enserink and D. Cochran, "A cyclostationary feature detector," in *Signals, Systems and Computers, 1994. 1994 Conference Record of the Twenty-Eighth Asilomar Conference on*, 1994, vol. 2, pp. 806-810: IEEE.
[166] P.-Y. Wu and A. Duel-Hallen, "Multiuser detectors with disjoint Kalman channel estimators for synchronous CDMA mobile radio channels," *IEEE Transactions on Communications,* vol. 48, no. 5, pp. 752-756, 2000.
[167] P. Sharma and K. Chandra, "Prediction of state transitions in Rayleigh fading channels," *IEEE transactions on vehicular technology,* vol. 56, no. 2, pp. 416-425, 2007.
[168] S. Yarkan and H. Arslan, "Binary time series approach to spectrum prediction for cognitive radio," in *2007 IEEE 66th Vehicular Technology Conference*, 2007, pp. 1563-1567: IEEE.
[169] Z. Wen, T. Luo, W. Xiang, S. Majhi, and Y. Ma, "Autoregressive spectrum hole prediction model for cognitive radio systems," in *ICC Workshops-2008 IEEE International Conference on Communications Workshops*, 2008, pp. 154-157: IEEE.
[170] G. Yuan, R. C. Grammenos, Y. Yang, and W. Wang, "Performance analysis of selective opportunistic spectrum access with traffic prediction," *IEEE Transactions on Vehicular Technology,* vol. 59, no. 4, pp. 1949-1959, 2010.
[171] D. Zhao and X. Zhou, "Spectrum sensing using prior probability prediction," in *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*, 2011, pp. 1-4: IEEE.
[172] V. K. Tumuluru, P. Wang, and D. Niyato, "Channel status prediction for cognitive radio networks," *Wireless Communications and Mobile Computing,* vol. 12, no. 10, pp. 862-874, 2012.
[173] P. F. Marshall, "Closed-form analysis of spectrum characteristics for cognitive radio performance analysis," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1-12: IEEE.
[174] C. Ghosh, S. Roy, M. B. Rao, and D. P. Agrawal, "Spectrum occupancy validation and modeling using real-time measurements," in *Proceedings of the 2010 ACM workshop on Cognitive radio networks*, 2010, pp. 25-30: ACM.
[175] A. Ghasemi and E. S. Sousa, "Optimization of spectrum sensing for opportunistic spectrum access in cognitive radio networks," in *Consumer Communications and Networking Conference, 2007. CCNC 2007. 4th IEEE*, 2007, pp. 1022-1026: IEEE.
[176] H. Kim and K. G. Shin, "Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks," *IEEE transactions on mobile computing,* vol. 7, no. 5, pp. 533-545, 2008.
[177] J. Ma, X. Zhou, and G. Y. Li, "Probability-based periodic spectrum sensing during secondary communication," *IEEE Transactions on Communications,* vol. 58, no. 4, 2010.
[178] C. Song and Q. Zhang, "Intelligent dynamic spectrum access assisted by channel usage prediction," in *INFOCOM IEEE Conference on Computer Communications Workshops, 2010*, 2010, pp. 1-6: IEEE.
[179] G. Ganesan and Y. Li, "Agility improvement through cooperative diversity in cognitive radio," in *Global Telecommunications Conference, 2005. GLOBECOM'05. IEEE*, 2005, vol. 5, pp. 5 pp.-2509: IEEE.
[180] C. Sun, W. Zhang, and K. B. Letaief, "Cooperative spectrum sensing for cognitive radios under bandwidth constraints," in *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, 2007, pp. 1-5: IEEE.
[181] E. Peh and Y.-C. Liang, "Optimization for cooperative sensing in cognitive radio networks," in *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, 2007, pp. 27-32: IEEE.

[182] M. Gandetto and C. Regazzoni, "Spectrum sensing: A distributed approach for cognitive terminals," *IEEE Journal on selected areas in communications,* vol. 25, no. 3, 2007.

[183] G. Auer, H. Haas, and P. Omiyi, "Interference aware medium access for dynamic spectrum sharing," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007, pp. 399-402: IEEE.

[184] C.-J. Yu, Y.-Y. He, and T.-F. Quan, "Frequency spectrum prediction method based on EMD and SVR," in *Intelligent Systems Design and Applications, 2008. ISDA'08. Eighth International Conference on*, 2008, vol. 3, pp. 39-44: IEEE.

[185] R. Min, D. Qu, Y. Cao, and G. Zhong, "Interference avoidance based on multi-step-ahead prediction for cognitive radio," in *Communication Systems, 2008. ICCS 2008. 11th IEEE Singapore International Conference on*, 2008, pp. 227-231: IEEE.

[186] T. Clancy and B. Walker, "Predictive dynamic spectrum access," in *Proc. SDR Forum Technical Conference*, 2006.

[187] K. Sithamparanathan and A. Giorgetti, *Cognitive radio techniques: spectrum sensing, interference mitigation, and localization*. Artech house, 2012.

[188] X. Xing, T. Jing, W. Cheng, Y. Huo, X. Cheng, and T. Znati, "Cooperative spectrum prediction in multi-PU multi-SU cognitive radio networks," *Mobile Networks and Applications,* vol. 19, no. 4, pp. 502-511, 2014.

[189] T. A. Weiss and F. K. Jondral, "Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency," *IEEE communications Magazine,* vol. 42, no. 3, pp. S8-14, 2004.

[190] W. XIANG and T. Luo, "From Software Radio to Cognitive Radio: Principle, Algorithm and Testbed [C]," in *Proceedings of Software Defined Radio Technical Conference and Product Exposition: Nov*, 2006, pp. 13-17.

[191] J. Hillenbrand, T. A. Weiss, and F. K. Jondral, "Calculation of detection and false alarm probabilities in spectrum pooling systems," *IEEE Communications letters,* vol. 9, no. 4, pp. 349-351, 2005.

[192] F. F. Digham, A. H. Tewfik, and M.-S. Alouini, "Detection of known and unknown signals, over fading channels," in *Global Telecommunications Conference, 2003. GLOBECOM'03. IEEE*, 2003, vol. 3, pp. 1756-1760: IEEE.

[193] T. K. Chee, C.-C. Lim, and J. Choi, "Channel prediction using lumpable finite-state Markov channels in OFDMA systems," in *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, 2006, vol. 4, pp. 1560-1564: IEEE.

[194] I. Zukerman, D. W. Albrecht, and A. E. Nicholson, "Predicting users' requests on the WWW," in *UM99 User Modeling*: Springer, 1999, pp. 275-284.

[195] T. Luo, T. Jiang, and W. Xiang, "A Subcarriers Allocation Scheme for Multi-carrier Modulation Based Cognitive Radio Systems," *IEEE Trans. Wireless Commun,* vol. 7, no. 9, pp. 3335-40, 2008.

[196] M. Hoyhtya, S. Pollin, and A. Mammela, "Classification-based predictive channel selection for cognitive radios," in *Communications (ICC), 2010 IEEE International Conference on*, 2010, pp. 1-6: IEEE.

[197] H.-P. Tan, O. Colman, and L. Doyle, "FSMA-A Topology-Transparent Scheme for Opportunistic Spectrum Access," in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, 2007, pp. 2890-2894: IEEE.

[198] S. Yin, D. Chen, Q. Zhang, and S. Li, "Prediction-based throughput optimization for dynamic spectrum access," *IEEE transactions on vehicular technology,* vol. 60, no. 3, pp. 1284-1289, 2011.

[199] I. Macaluso, T. K. Forde, L. DaSilva, and L. Doyle, "Impact of cognitive radio: Recognition and informed exploitation of grey spectrum opportunities," *IEEE Vehicular Technology Magazine,* vol. 7, no. 2, pp. 85-90, 2012.

[200] M. Bkassiny, Y. Li, and S. K. Jayaweera, "A survey on machine-learning techniques in cognitive radios," *IEEE Communications Surveys & Tutorials,* vol. 15, no. 3, pp. 1136-1159, 2013.

[201] A. He *et al.*, "A survey of artificial intelligence for cognitive radios," *IEEE Transactions on Vehicular Technology,* vol. 59, no. 4, pp. 1578-1592, 2010.

[202] V. K. Tumuluru, P. Wang, and D. Niyato, "A neural network based spectrum prediction scheme for cognitive radio," in *Communications (ICC), 2010 IEEE International Conference on*, 2010, pp. 1-5: IEEE.

[203] S. Yin, D. Chen, Q. Zhang, M. Liu, and S. Li, "Mining spectrum usage data: a large-scale spectrum measurement study," *IEEE Transactions on Mobile Computing,* vol. 11, no. 6, pp. 1033-1046, 2012.

[204] J. J. Lehtomaki, R. Vuohtoniemi, and K. Umebayashi, "On the measurement of duty cycle and channel occupancy rate," *IEEE Journal on Selected Areas in Communications,* vol. 31, no. 11, pp. 2555-2565, 2013.

[205] T. W. Rondeau, C. J. Rieser, T. M. Gallagher, and C. W. Bostian, "Online modeling of wireless channels with hidden markov models and channel impulse responses for cognitive radios," in *Microwave Symposium Digest, 2004 IEEE MTT-S International*, 2004, vol. 2, pp. 739-742: IEEE.

[206] K. Kim, I. A. Akbar, K. K. Bae, J.-S. Um, C. M. Spooner, and J. H. Reed, "Cyclostationary approaches to signal detection and classification in cognitive radio," in *New frontiers in dynamic spectrum access networks, 2007. DySPAN 2007. 2nd IEEE international symposium on*, 2007, pp. 212-215: IEEE.

[207] C.-H. Park, S.-W. Kim, S.-M. Lim, and M.-S. Song, "HMM based channel status predictor for cognitive radio," in *Microwave Conference, 2007. APMC 2007. Asia-Pacific*, 2007, pp. 1-4: IEEE.

[208] J. Jacob, B. R. Jose, and J. Mathew, "Spectrum prediction in cognitive radio networks: a Bayesian approach," in *Next Generation Mobile Apps, Services and Technologies (NGMAST), 2014 Eighth International Conference on*, 2014, pp. 203-208: IEEE.

[209] S. Y. Zaihong Shuai, Songhwai Oh, Ming-Hsuan Yang, "Traffic modeling and prediction using sensor networks: Who will go where and when?," *ACM Transactions on Sensor Networks (TOSN),* vol. 9, no. 1, November 2012 2012.

[210] L. Rabiner and B. Juang, "An introduction to hidden Markov models," *ieee assp magazine,* vol. 3, no. 1, pp. 4-16, 1986.

[211] C. Ghosh, C. Cordeiro, D. P. Agrawal, and M. B. Rao, "Markov chain existence and hidden Markov models in spectrum sensing," in *Pervasive Computing and Communications, 2009. PerCom 2009. IEEE International Conference on*, 2009, pp. 1-6: IEEE.

[212] J. V. Candy, *Bayesian signal processing: classical, modern, and particle filtering methods*. John Wiley & Sons, 2016.

[213] T. Nguyen, B. L. Mark, and Y. Ephraim, "Spectrum sensing using a hidden bivariate Markov model," *IEEE Transactions on Wireless Communications,* vol. 12, no. 9, pp. 4582-4591, 2013.

[214] S. H. Shon, S. J. Jang, and J. M. Kim, "HMM-based Adaptive Frequency-Hopping Cognitive Radio System to Reduce Interference Time and to Improve Throughput," *TIIS,* vol. 4, no. 4, pp. 475-490, 2010.

[215] X. Chen, H. Zhang, A. B. MacKenzie, and M. Matinmikko, "Predicting spectrum occupancies using a non-stationary hidden Markov model," *IEEE wireless communications letters,* vol. 3, no. 4, pp. 333-336, 2014.

[216] S. D. Barnes and B. Maharaj, "Prediction based channel allocation performance for cognitive radio," *AEU-International Journal of Electronics and Communications,* vol. 68, no. 4, pp. 336-345, 2014.

[217] L. Melián-Gutiérrez, S. Zazo, J. L. Blanco-Murillo, I. Pérez-Álvarez, A. García-Rodríguez, and B. Pérez-Díaz, "HF spectrum activity prediction model based on HMM for cognitive radio applications," *Physical Communication,* vol. 9, pp. 199-211, 2013.

[218] A. J. Goldsmith and P. P. Varaiya, "Capacity, mutual information, and coding for finite-state Markov channels," *IEEE Transactions on Information Theory,* vol. 42, no. 3, pp. 868-886, 1996.

[219] M. Mushkin and I. Bar-David, "Capacity and coding for the Gilbert-Elliott channels," *IEEE Transactions on Information Theory,* vol. 35, no. 6, pp. 1277-1290, 1989.
[220] H. Eltom, S. Kandeepan, B. Moran, and R. J. Evans, "Spectrum occupancy prediction using a hidden markov model," in *Signal Processing and Communication Systems (ICSPCS), 2015 9th International Conference on*, 2015, pp. 1-8: IEEE.
[221] H. Eltom, S. Kandeepan, L. Ying Chang, B. Moran, and R. J. Evans, "HMM based cooperative spectrum occupancy prediction using hard fusion," in *2016 IEEE International Conference on Communications Workshops (ICC)*, 2016, pp. 669-675.
[222] H. Liu, B. Krishnamachari, and Q. Zhao, "Cooperation and learning in multiuser opportunistic spectrum access," in *Communications Workshops, 2008. ICC Workshops' 08. IEEE International Conference on*, 2008, pp. 487-492: IEEE.
[223] U. Berthold, F. Fu, M. van der Schaar, and F. K. Jondral, "Detection of spectral resources in cognitive radios using reinforcement learning," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1-5: IEEE.
[224] L. E. Baum and T. Petrie, "Statistical inference for probabilistic functions of finite state Markov chains," *The annals of mathematical statistics,* vol. 37, no. 6, pp. 1554-1563, 1966.
[225] J. W. Mark and W. Zhuang, "Wireless Communication and Network," ed: Prentice Hall, 2002.
[226] T. Liu, J. Lemeire, and L. Yang, "Proper initialization of Hidden Markov models for industrial applications," in *Signal and Information Processing (ChinaSIP), 2014 IEEE China Summit & International Conference on*, 2014, pp. 490-494: IEEE.
[227] S. E. Levinson, "Continuously variable duration hidden Markov models for automatic speech recognition," *Computer Speech & Language,* vol. 1, no. 1, pp. 29-45, 1986.
[228] L. R. Rabiner, "A tutorial on hidden Markov models and selected applications in speech recognition," *Proceedings of the IEEE,* vol. 77, no. 2, pp. 257-286, 1989.
[229] S.-Z. Yu and H. Kobayashi, "Practical implementation of an efficient forward-backward algorithm for an explicit-duration hidden Markov model," *Signal Processing, IEEE Transactions on,* vol. 54, no. 5, pp. 1947-1951, 2006.
[230] A. B. M. Abdallah S. Abdallah, Vuk Marojevic, Roger B Bacchus, Ali Riaz, Dennis Roberson, Juha Kalliovaara, Juhani Hallio, Reijo Ekman, "Detecting the Impact of Human {Mega-Events} on Spectrum Usage," presented at the 13th IEEE Annual Consumer Communications & Networking Conference (CCNC 2016), 2016.
[231] S. Fine, Y. Singer, and N. Tishby, "The hierarchical hidden Markov model: Analysis and applications," *Machine learning,* vol. 32, no. 1, pp. 41-62, 1998.
[232] M. A. McHenry, "NSF spectrum occupancy measurements project summary," *Shared spectrum company report,* 2005.
[233] R. W. Brodersen, A. Wolisz, D. Cabric, S. M. Mishra, and D. Willkomm, "Corvus: a cognitive radio approach for usage of virtual unlicensed spectrum," *Berkeley Wireless Research Center (BWRC) White paper,* pp. 1-21, 2004.
[234] N. Han, S. Shon, J. H. Chung, and J. M. Kim, "Spectral correlation based signal detection method for spectrum sensing in IEEE 802.22 WRAN systems," in *Advanced Communication Technology, 2006. ICACT 2006. The 8th International Conference*, 2006, vol. 3, pp. 6 pp.-1770: IEEE.
[235] B. Wild and K. Ramchandran, "Detecting primary receivers for cognitive radio applications," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 124-130: IEEE.
[236] H. Chen and L. Trajkovic, "Trunked radio systems: traffic prediction based on user clusters," in *Wireless Communication Systems, 2004, 1st International Symposium on*, 2004, pp. 76-80: IEEE.

[237] F. Kohandani, D. W. McAvoy, and A. K. Khandani, "Wireless airtime traffic estimation using a state space model," in *Communication Networks and Services Research Conference, 2006. CNSR 2006. Proceedings of the 4th Annual*, 2006, pp. 8 pp.-258: IEEE.

[238] Y. Akinaga, S. Kaneda, N. Shinagawa, and A. Miura, "A proposal for a mobile communication traffic forecasting method using time-series analysis for multi-variate data," in *Global Telecommunications Conference, 2005. GLOBECOM'05. IEEE*, 2005, vol. 2, p. 6 pp.: IEEE.

[239] L. Yang, L. Cao, and H. Zheng, "Proactive channel access in dynamic spectrum networks," *Physical communication,* vol. 1, no. 2, pp. 103-111, 2008.

[240] L. Jiao, F. Y. Li, and V. Pla, "Modeling and performance analysis of channel assembling in multichannel cognitive radio networks with spectrum adaptation," *IEEE Transactions on vehicular technology,* vol. 61, no. 6, pp. 2686-2697, 2012.

[241] C. Jiang, Y. Chen, K. R. Liu, and Y. Ren, "Renewal-theoretical dynamic spectrum access in cognitive radio network with unknown primary behavior," *IEEE Journal on Selected Areas in Communications,* vol. 31, no. 3, pp. 406-416, 2013.

[242] P. Kaur, A. Khosla, and M. Uddin, "Spectrum management models for cognitive radios," *Journal of Communications and Networks,* vol. 15, no. 2, pp. 222-227, 2013.

[243] P. A. Kumar Acharya, S. Singh, and H. Zheng, "Reliable open spectrum communications through proactive spectrum access," in *Proceedings of the first international workshop on Technology and policy for accessing spectrum*, 2006, p. 5: ACM.

[244] X. Li and S. Zekavat, "Traffic pattern prediction based spectrum sharing for cognitive radios," *Cognitive radio systems,* pp. 77-95, 2009.

[245] M. Hoyhtya, S. Pollin, and A. Mammela, "Performance improvement with predictive channel selection for cognitive radios," in *Cognitive Radio and Advanced Spectrum Management, 2008. CogART 2008. First International Workshop on*, 2008, pp. 1-5: IEEE.

[246] M. Hoyhtya, T. Chen, and A. Mammela, "Interference management in frequency, time, and space domains for cognitive radios," in *Wireless Telecommunications Symposium, 2009. WTS 2009*, 2009, pp. 1-7: IEEE.

[247] A. Adas, "Traffic models in broadband networks," *IEEE Communications Magazine,* vol. 35, no. 7, pp. 82-89, 1997.

[248] X. Li and S. A. Zekavat, "Traffic pattern prediction and performance investigation for cognitive radio systems," in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, 2008, pp. 894-899: IEEE.

[249] M. Hoyhtya, S. Pollin, and A. Mammela, "Improving the performance of cognitive radios through classification, learning, and predictive channel selection," *Advances in Electronics and Telecommunications,* vol. 2, no. 4, pp. 28-38, 2011.

[250] W. Ren, Q. Zhao, and A. Swami, "Temporal traffic dynamics improve the connectivity of ad hoc cognitive radio networks," *IEEE/ACM Transactions on Networking (TON),* vol. 22, no. 1, pp. 124-136, 2014.

[251] M. Bradonjić and L. Lazos, "Graph-based criteria for spectrum-aware clustering in cognitive radio networks," *Ad Hoc Networks,* vol. 10, no. 1, pp. 75-94, 2012.

[252] A. Singh, M. R. Bhatnagar, and R. K. Mallik, "Performance of an improved energy detector in multihop cognitive radio networks," *IEEE transactions on Vehicular technology,* vol. 65, no. 2, pp. 732-743, 2016.

[253] Q. Wu, G. Ding, J. Wang, and Y.-D. Yao, "Spatial-temporal opportunity detection for spectrum-heterogeneous cognitive radio networks: two-dimensional sensing," *IEEE Transactions on Wireless Communications,* vol. 12, no. 2, pp. 516-526, 2013.

[254] M. Ozger and O. B. Akan, "On the Utilization of Spectrum Opportunity in Cognitive Radio Networks," *IEEE Communications Letters,* vol. 20, no. 1, pp. 157-160, 2016.

[255] R. Kaniezhil and C. Chandrasekar, "Evaluating the probability of channel availability for spectrum sharing using cognitive radio," *International Journal of Engineering Research and Applications (IJERA),* vol. 2, no. 4, pp. 2186-2197, 2012.

[256] M. Timmers, S. Pollin, and F. Catthoor, "On the value of prediction in opportunistic radio systems," in *Communications (ICC), 2011 IEEE International Conference on*, 2011, pp. 1-6: IEEE.

[257] C.-W. Wang and L.-C. Wang, "Modeling and analysis for proactive-decision spectrum handoff in cognitive radio networks," in *Communications, 2009. ICC'09. IEEE International Conference on*, 2009, pp. 1-6: IEEE.

[258] M. Wellens, A. De Baynast, and P. Mahonen, "Performance of dynamic spectrum access based on spectrum occupancy statistics," *IET communications,* vol. 2, no. 6, pp. 772-782, 2008.

[259] Y. Pei, A. T. Hoang, and Y.-C. Liang, "Sensing-throughput tradeoff in cognitive radio networks: How frequently should spectrum sensing be carried out?," in *Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on*, 2007, pp. 1-5: IEEE.

[260] X. Zhou, J. Ma, G. Y. Li, Y. H. Kwon, and A. C. Soong, "Probability-based optimization of inter-sensing duration and power control in cognitive radio," *IEEE Transactions on Wireless Communications,* vol. 8, no. 10, 2009.

[261] W.-Y. Lee and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks," *IEEE Transactions on wireless communications,* vol. 7, no. 10, 2008.

[262] Y. Chen, Q. Zhao, and A. Swami, "Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors," *IEEE Transactions on Information Theory,* vol. 54, no. 5, pp. 2053-2071, 2008.

[263] H. Jiang, L. Lai, R. Fan, and H. V. Poor, "Optimal selection of channel sensing order in cognitive radio," *IEEE Transactions on Wireless Communications,* vol. 8, no. 1, pp. 297-307, 2009.

[264] I. A. M. Balapuwaduge, F. Y. Li, and V. Pla, "System Times and Channel Availability for Secondary Transmissions in CRNs: A Dependability-Theory-Based Analysis," *IEEE Transactions on Vehicular Technology,* vol. 66, no. 3, pp. 2771-2788, 2017.

[265] U. Varshney and A. D. Malloy, "Improving the dependability of wireless networks using design techniques," in *Local Computer Networks, 2001. Proceedings. LCN 2001. 26th Annual IEEE Conference on*, 2001, pp. 122-131: IEEE.

[266] N. Cordeschi, D. Amendola, and E. Baccarelli, "Hard and soft optimal resource allocation for primary and secondary users in infrastructure vehicular networks," in *Consumer Communications and Networking Conference (CCNC), 2015 12th Annual IEEE*, 2015, pp. 708-713: IEEE.

[267] N. Cordeschi, D. Amendola, and E. Baccarelli, "Reliable adaptive resource management for cognitive cloud vehicular networks," *IEEE Transactions on Vehicular Technology,* vol. 64, no. 6, pp. 2528-2537, 2015.

[268] B. Canberk, I. F. Akyildiz, and S. Oktug, "Primary user activity modeling using first-difference filter clustering and correlation in cognitive radio networks," *IEEE/ACM Transactions on Networking (TON),* vol. 19, no. 1, pp. 170-183, 2011.

[269] G. Egeland and P. E. Engelstad, "The availability and reliability of wireless multi-hop networks with stochastic link failures," *IEEE Journal on Selected Areas in Communications,* vol. 27, no. 7, 2009.

[270] H. B. Salameh, "Efficient Resource Allocation for Multicell Heterogeneous Cognitive Networks With Varying Spectrum Availability," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 8, pp. 6628-6635, 2016.

[271] J. Liu, X. Jiang, H. Nishiyama, and N. Kato, "Reliability assessment for wireless mesh networks under probabilistic region failure model," *IEEE Transactions on Vehicular Technology,* vol. 60, no. 5, pp. 2253-2264, 2011.

[272] Y. Zou, B. Champagne, W.-P. Zhu, and L. Hanzo, "Relay-selection improves the security-reliability trade-off in cognitive radio systems," *IEEE Transactions on Communications,* vol. 63, no. 1, pp. 215-228, 2015.
[273] X. Li and S. A. Zekavat, "Cognitive radio based spectrum sharing: Evaluating channel availability via traffic pattern prediction," *Journal of Communications and Networks,* vol. 11, no. 2, pp. 104-114, 2009.
[274] I. A. Balapuwaduge and F. Y. Li, "System times and channel availability analyses in multi-channel cognitive radio networks," in *Communications (ICC), 2014 IEEE International Conference on*, 2014, pp. 1320-1325: IEEE.
[275] A. Azarfar, J.-F. Frigon, and B. Sansò, "Reliability analysis of a channel restoration mechanism for opportunistic spectrum access," *Computer Communications,* vol. 36, no. 8, pp. 947-961, 2013.
[276] A. Azarfar, J.-F. Frigon, and B. Sanso, "Improving the reliability of wireless networks using cognitive radios," *IEEE Communications Surveys & Tutorials,* vol. 14, no. 2, pp. 338-354, 2012.
[277] C. Ghosh, S. Pagadarai, D. P. Agrawal, and A. M. Wyglinski, "Queueing theory representation and modeling of spectrum occupancy employing radio frequency measurements," in *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, 2009, pp. 1-5: IEEE.
[278] B. Canberk and S. Oktug, "A channel availability classification for cognitive radio networks using a monitoring network," in *Computers and Communications (ISCC), 2012 IEEE Symposium on*, 2012, pp. 000690-000695: IEEE.
[279] D. Xu, E. Jung, and X. Liu, "Optimal bandwidth selection in multi-channel cognitive radio networks: How much is too much?," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1-11: IEEE.
[280] C. Ghosh, S. Roy, and M. B. Rao, "Modeling and validation of channel idleness and spectrum availability for cognitive networks," *IEEE Journal on Selected Areas in Communications,* vol. 30, no. 10, pp. 2029-2039, 2012.
[281] F. C. Commission, "Establishment of interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed mobile and satellite frequency bands," *Et Docket,* no. 03-237, 2003.
[282] T. Clancy and W. Arbaugh, "Measuring interference temperature," in *Virginia Tech Symposium on Wireless Personal Communications*, 2006, pp. 1-10.
[283] T. C. Clancy, "Achievable capacity under the interference temperature model," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, 2007, pp. 794-802: IEEE.
[284] Y. Xing, C. N. Mathur, M. A. Haleem, R. Chandramouli, and K. Subbalakshmi, "Dynamic spectrum access with QoS and interference temperature constraints," *IEEE Transactions on mobile computing,* vol. 6, no. 4, 2007.
[285] W. Wang, T. Peng, and W. Wang, "Optimal power control under interference temperature constraints in cognitive radio network," in *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, 2007, pp. 116-120: IEEE.
[286] M. Hong, J. Kim, H. Kim, and Y. Shin, "An adaptive transmission scheme for cognitive radio systems based on interference temperature model," in *Consumer Communications and Networking Conference, 2008. CCNC 2008. 5th IEEE*, 2008, pp. 69-73: IEEE.
[287] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework," *IEEE Journal on selected areas in communications,* vol. 25, no. 3, 2007.
[288] S. Geirhofer, L. Tong, and B. M. Sadler, "Cognitive medium access: constraining interference based on experimental models," *IEEE Journal on Selected Areas in Communications,* vol. 26, no. 1, 2008.

[289] Q. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, "Optimal dynamic spectrum access via periodic channel sensing," in *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, 2007, pp. 33-37: IEEE.

[290] S. Olariu and J. V. Nickerson, "A probabilistic model of integration," *Decision Support Systems,* vol. 45, no. 4, pp. 746-763, 2008.

[291] S. Olariu, S. Mohrehkesh, and M. C. Weigle, "Toward aggregating time-discounted information," in *Proceedings of the 2nd ACM annual international workshop on Mission-oriented wireless sensor networking*, 2013, pp. 57-66: ACM.

[292] S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz, and L. Stibor, "IEEE 802.11 e Wireless LAN for Quality of Service," in *Proc. European Wireless*, 2002, vol. 2, pp. 32-39.

[293] S. P. T. Force, "Spectrum policy task force report," *Federal Communications Commission ET Docket,* vol. 2, p. 135, 2002.

[294] (2003). *United States frequency allocations—The radio spectrum*. Available: http://www.ntia.doc.gov/osmhome/Allochrt.html

[295] T. Erpek, K. Steadman, and D. Jones, "Dublin ireland spectrum occupancy measurements collected on april 16-18, 2007," *The Shared Spectrum Company,* 2007.

[296] T. Erpek, M. Lofquist, and K. Patton, "Spectrum Occupancy Measurements Loring Commerce Centre Limestone, Maine September 18-20, 2007," *The Shared Spectrum Company,* 2007.

[297] M. McHenry and D. McCloskey, "Spectrum Occupancy Measurements: Chicago, Illinois, November 16-18, 2005. Shared Spectrum Company," Technical report2005.

[298] M. Vilimpoc and M. McHenry, "Dupont circle spectrum utilization during peak hours," *The New America Foundation and the Shared Spectrum Company,* 2003.

[299] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on information theory,* vol. 46, no. 2, pp. 388-404, 2000.

[300] A. Yang, "Overview of FCC's New Rules for TV White Space Devices and database updates," in *ITU-R SG1 WP1B workshop: spectrum management issues on the use of white spaces by cognitive radio systems, Geneva*, 2014, vol. 20.

[301] M. Nekovee, "Quantifying the availability of TV white spaces for cognitive radio operation in the UK," in *Communications Workshops, 2009. ICC Workshops 2009. IEEE International Conference on*, 2009, pp. 1-5: IEEE.

[302] E. CEPT, "Report 159—Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the 'White Spaces' of the Frequency Band 470–790 MHz," ed: October, 2010.

[303] F. C. Commission, "FCC NPRM In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band,," Washington, D.C.2012.

[304] F. C. Commission, "FNPRM: Ammendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band," Washington D.C.2014.

[305] B. Benmammar, A. Amraoui, and F. Krief, "A Survey on Dynamic Spectrum Access Techniques in Cognitive Radio Networks," *International Journal of Communication Networks & Information Security,* vol. 5, 2013.

[306] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *Signal Processing Magazine, IEEE,* vol. 24, no. 79-89, 2007.

[307] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *Communications Surveys & Tutorials, IEEE,* vol. 11, pp. 116-130, 2009.

[308] S. Huang, X. Liu, and a. Z. Ding, "Opportunistic spectrum access in cognitive radio networks," in *The 27th Conference on Computer Communications*, 2008.

[309] C. Xin, M. Song, L. Ma, G. Hsieh, and C.-C. Shen, "On random dynamic spectrum access for cognitive radio networks," in *Global Telecommunications Conference*, 2010.

[310] Y. Zhang, "Dynamic spectrum access in cognitive radio wireless networks," in *ICC*, 2008.
[311] V. Krishna, *Auction theory*. Academic press, 2009.
[312] X. Zhou and H. Zheng, "Trust: A general framework for truthful double spectrum auctions," in *Infocom 2009, Ieee*, 2009, pp. 999-1007: IEEE.
[313] Z. Ji and K. R. Liu, "Multi-stage pricing game for collusion-resistant dynamic spectrum allocation," *IEEE Journal on Selected Areas in Communications,* vol. 26, no. 1, pp. 182-191, 2008.
[314] G. S. Kasbekar and S. Sarkar, "Spectrum auction framework for access allocation in cognitive radio networks," *IEEE/ACM Transactions on Networking (TON),* vol. 18, no. 6, pp. 1841-1854, 2010.
[315] J. Huang, R. A. Berry, and M. L. Honig, "Auction-based spectrum sharing," *Mobile Networks and Applications,* vol. 11, no. 3, pp. 405-418, 2006.
[316] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, "A general framework for wireless spectrum auctions," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007, pp. 22-33: IEEE.
[317] Y. Wu, B. Wang, K. R. Liu, and T. C. Clancy, "A scalable collusion-resistant multi-winner cognitive spectrum auction game," *IEEE Transactions on Communications,* vol. 57, no. 12, 2009.
[318] H. Bogucka, M. Parzy, P. Marques, J. W. Mwangoka, and T. Forde, "Secondary spectrum trading in TV white spaces," *IEEE Communications Magazine,* vol. 50, no. 11, pp. 121-129, 2012.
[319] M. Bykowsky, M. Olson, and W. Sharkey, "Modeling the efficiency of spectrum designated to licensed service and unlicensed operations," *FCC Office of Strategic Planning Working Paper Series,* no. 42, 2008.
[320] S. K. Jones and T. Phillips, "Initial evaluation of the performance of prototype TV-band white space devices," *OET Report FCC/OET,* 2007.
[321] M. 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, 2005. WoWMoM 2005. Sixth IEEE International Symposium on a*, 2005, pp. 78-85: Ieee.
[322] S. Bridge, "Secondary Market Licensing & Leasing Primer," *Spectrum Bridge White Papers,* Available: http://udia.spectrumbridge.com/Libraries/White_Papers/The_Secondary_Spectrum_Market_A_Licensing_Leasing_Primer.sflb.ashx
[323] X. Zhou, S. Gandhi, S. Suri, and H. Zheng, "eBay in the sky: Strategy-proof wireless spectrum auctions," in *Proceedings of the 14th ACM international conference on Mobile computing and networking*, 2008, pp. 2-13: ACM.
[324] S. Bridge, "Analysis of FCC Secondary Spectrum Markets Positions, Policies and Comments," *Spectrum Bridge White Papers,* Available: http://udia.spectrumbridge.com/Libraries/White_Papers/Analysis_of_the_FCC_s_Positions_Policies_and_Comments_on_Secondary_Markets.sflb.ashx
[325] M. Felegyhazi and J.-P. Hubaux, "Game theory in wireless networks: A tutorial," 2006.
[326] D. Niyato and E. Hossain, "A game-theoretic approach to competitive spectrum sharing in cognitive radio networks," in *Wireless Communications and Networking Conference, 2007. WCNC 2007. IEEE*, 2007, pp. 16-20: IEEE.
[327] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of nash equilibrium, and collusion," *Selected Areas in Communications, IEEE Journal on,* vol. 26, no. 1, pp. 192-202, 2008.
[328] J. W. Mwangoka, K. B. Letaief, and Z. Cao, "Joint power control and spectrum allocation for cognitive radio networks via pricing," *Physical Communication,* vol. 2, no. 1, pp. 103-115, 2009.
[329] R. E. Ali, K. G. Seddik, M. Nafie, and F. F. Digham, "A Pricing-Based Cooperative Spectrum Sharing Stackelberg Game," *arXiv preprint arXiv:1312.5555,* 2013.

[330] H. S. Mohammadian and B. Abolhassani, "Auction-based spectrum sharing for multiple primary and secondary users in cognitive radio networks," in *Sarnoff Symposium, 2010 IEEE*, 2010, pp. 1-6: IEEE.
[331] A. Al Daoud, T. Alpcan, S. Agarwal, and M. Alanyali, "A stackelberg game for pricing uplink power in wide-band cognitive radio networks," in *Decision and Control, 2008. CDC 2008. 47th IEEE Conference on*, 2008, pp. 1422-1427: IEEE.
[332] J. Sun, E. Modiano, and L. Zheng, "Wireless channel allocation using an auction algorithm," *Selected Areas in Communications, IEEE Journal on,* vol. 24, no. 5, pp. 1085-1096, 2006.
[333] D. R. Brenner, "Comments of Qualcomm Inc. In the Matter of Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band," FCC2013.
[334] M. M. Sohul, X. Ma, T. Yang, and J. H. Reed, "Quality of Service Assurance for Shared Spectrum Systems," in *Military Communications Conference (MILCOM), IEEE*, 2014.
[335] H.-B. Chang and K.-C. Chen, "Auction-based spectrum management of cognitive radio networks," *IEEE Transactions on Vehicular Technology,* vol. 59, no. 4, pp. 1923-1935, 2010.
[336] I. Stanojev, O. Simeone, U. Spagnolini, Y. Bar-Ness, and R. L. Pickholtz, "Cooperative ARQ via auction-based spectrum leasing," *IEEE Transactions on Communications,* vol. 58, no. 6, 2010.
[337] C. Yi and J. Cai, "Multi-item spectrum auction for recall-based cognitive radio networks with multiple heterogeneous secondary users," *IEEE Transactions on Vehicular Technology,* vol. 64, no. 2, pp. 781-792, 2015.
[338] Y. Chen, J. Zhang, K. Wu, and Q. Zhang, "TAMES: A truthful double auction for multi-demand heterogeneous spectrums," *IEEE Transactions on Parallel and Distributed Systems,* vol. 25, no. 11, pp. 3012-3024, 2014.
[339] G. Iosifidis and I. Koutsopoulos, "Challenges in auction theory driven spectrum management," *IEEE Communications Magazine,* vol. 49, no. 8, 2011.
[340] S.-C. Zhan, S.-C. Chang, C.-T. Chou, and Z. Tsai, "Spectrum Sharing Auction platform for Short-term licensed shared access," in *Wireless Days, 2017*, 2017, pp. 184-187: IEEE.
[341] S.-C. Zhan, C.-T. Chou, and S.-C. Chang, "Auction-based spectrum sharing among heterogeneous secondary networks," in *Communications (ICC), 2015 IEEE International Conference on*, 2015, pp. 2160-2165: IEEE.
[342] S. Bridge, "SpecEx: The Online Marketplace for Spectrum," ed.
[343] Ofcom, "Simplifying spectrum trading - spectrum leasing and other market enhancements," June 2011.
[344] M. Matinmikko, H. Okkonen, M. Palola, S. Yrjola, P. Ahokangas, and M. Mustonen, "Spectrum sharing using licensed shared access: the concept and its workflow for LTE-advanced networks," *IEEE Wireless Communications,* vol. 21, no. 2, pp. 72-79, 2014.
[345] M. Abitbol and P.-J. Muller, "“Licensed Shared Access” an innovation in European radio spectrum policy," in *Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on*, 2014, pp. 259-262: IEEE.
[346] T. Lavander, P. Marks, and S. Wongsaroj, "The economic benefits of LSA in 2.3 GHz in Europe," *Rep. Plum Consulting,* 2013.
[347] M. Matinmikko *et al.*, "Cognitive radio trial environment: First live authorized shared access-based spectrum-sharing demonstration," *IEEE Vehicular Technology Magazine,* vol. 8, no. 3, pp. 30-37, 2013.
[348] A. Apostolidis *et al.*, "Intermediate description of the spectrum needs and usage principles," *METIS Deliverable D,* vol. 5, p. 1, 2013.
[349] K. Chatzikokolakis, P. Spapis, A. Kaloxylos, and N. Alonistioti, "Toward spectrum sharing: opportunities and technical enablers," *IEEE Communications Magazine,* vol. 53, no. 7, pp. 26-33, 2015.

[350] L. Amaitis, G. Manning, D. Mylet, and A. Wilkins, "System and method for trading wireless spectrum rights," ed: Google Patents, 2004.
[351] R. C. Chang, "System and method for automated optimization of spectrum allocation," ed: Google Patents, 2011.
[352] P. Ahokangas *et al.*, "Business scenarios for incumbent spectrum users in Licensed Shared Access (LSA)," in *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, 2014, pp. 407-412.
[353] L. Chen, S. Iellamo, M. Coupechoux, and P. Godlewski, "An auction framework for spectrum allocation with interference constraint in cognitive radio networks," in *INFOCOM, 2010 Proceedings IEEE*, 2010, pp. 1-9: IEEE.
[354] Y. Zhang, D. Yang, G. Xue, and J. Tang, "A Spectrum Auction under Physical Interference Model," in *Global Communications Conference (GLOBECOM), 2016 IEEE*, 2016, pp. 1-6: IEEE.
[355] P. Cramton, "Spectrum auctions," 2002.
[356] P. Cramton, Y. Shoham, and R. Steinberg, "Combinatorial auctions," 2006.
[357] M. M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, 2005, pp. 299-307: IEEE.
[358] J. B. Huang, Randall A; Honig, Michael L, "Auction mechanisms for distributed spectrum sharing," presented at the 42nd Annual Allerton Conference on Communication, Control, and Computing, 2004.
[359] A. P. Subramanian, M. Al-Ayyoub, H. Gupta, S. R. Das, and M. M. Buddhikot, "Near-optimal dynamic spectrum allocation in cellular networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, 2008, pp. 1-11: IEEE.
[360] J. Jia, Q. Zhang, Q. Zhang, and M. Liu, "Revenue generation for truthful spectrum auction in dynamic spectrum access," in *Proceedings of the tenth ACM international symposium on Mobile ad hoc networking and computing*, 2009, pp. 3-12: ACM.
[361] A. Ghosh and M. Mahdian, "Externalities in online advertising," in *Proceedings of the 17th international conference on World Wide Web*, 2008, pp. 161-168: ACM.
[362] P. Jehiel, B. Moldovanu, and E. Stacchetti, "How (not) to sell nuclear weapons," *The American Economic Review,* pp. 814-829, 1996.
[363] F. Constantin, M. Rao, C.-C. Huang, and D. C. Parkes, "On expressing value externalities in position auctions," 2011: American Association for Artificial Intelligence.
[364] P. Krysta, T. Michalak, T. Sandholm, and M. Wooldridge, "Combinatorial auctions with externalities," in *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1*, 2010, pp. 1471-1472: International Foundation for Autonomous Agents and Multiagent Systems.
[365] I. A. Kash, R. Murty, and D. C. Parkes, "Enabling spectrum sharing in secondary market auctions," *IEEE Transactions on Mobile Computing,* vol. 13, no. 3, pp. 556-568, 2014.
[366] J. Hsu and X. H. Wang, "On welfare under Cournot and Bertrand competition in differentiated oligopolies," *Review of Industrial Organization,* vol. 27, no. 2, pp. 185-191, 2005.
[367] M. Khaledi and A. A. Abouzeid, "Auction-based spectrum sharing in cognitive radio networks with heterogeneous channels," in *Information Theory and Applications Workshop (ITA), 2013*, 2013, pp. 1-8: IEEE.
[368] L. Gao, Y. Xu, and X. Wang, "Map: Multiauctioneer progressive auction for dynamic spectrum access," *IEEE Transactions on Mobile Computing,* vol. 10, no. 8, pp. 1144-1161, 2011.
[369] L. Gao, X. Wang, Y. Xu, and Q. Zhang, "Spectrum trading in cognitive radio networks: A contract-theoretic modeling approach," *IEEE Journal on Selected Areas in Communications,* vol. 29, no. 4, pp. 843-855, 2011.

[370] A. W. Min, X. Zhang, J. Choi, and K. G. Shin, "Exploiting spectrum heterogeneity in dynamic spectrum market," *IEEE Transactions on Mobile Computing,* vol. 11, no. 12, pp. 2020-2032, 2012.
[371] D. Niyato, E. Hossain, and Z. Han, "Dynamics of multiple-seller and multiple-buyer spectrum trading in cognitive radio networks: A game-theoretic modeling approach," *Mobile Computing, IEEE Transactions on,* vol. 8, no. 8, pp. 1009-1022, 2009.
[372] M. Dong, G. Sun, X. Wang, and Q. Zhang, "Combinatorial auction with time-frequency flexibility in cognitive radio networks," in *INFOCOM, 2012 Proceedings IEEE*, 2012, pp. 2282-2290: IEEE.
[373] H. Zhou, R. A. Berry, M. L. Honig, and R. Vohra, "Spectrum markets with interference complementarities," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2011 International Symposium on*, 2011, pp. 241-248: IEEE.
[374] D. Xu, X. Liu, and Z. Han, "Decentralized bargain: A two-tier market for efficient and flexible dynamic spectrum access," *IEEE Transactions on Mobile Computing,* vol. 12, no. 9, pp. 1697-1711, 2013.
[375] O. Korcak, T. Alpcan, and G. Iosifidis, "Collusion of operators in wireless spectrum markets," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2012 10th International Symposium on*, 2012, pp. 33-40: IEEE.
[376] A. Gopinathan and Z. Li, "Strategyproof auctions for balancing social welfare and fairness in secondary spectrum markets," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 3020-3028: IEEE.
[377] S. H. Chun and R. J. La, "Secondary spectrum trading—auction-based framework for spectrum allocation and profit sharing," *IEEE/ACM Transactions on Networking,* vol. 21, no. 1, pp. 176-189, 2013.
[378] T. Chen and S. Zhong, "Truthful auctions for continuous spectrum with variable bandwidths," *IEEE Transactions on Wireless Communications,* vol. 13, no. 2, pp. 1116-1128, 2014.
[379] M. Khaledi and A. A. Abouzeid, "A reserve price auction for spectrum sharing with heterogeneous channels," in *Computer Communications and Networks (ICCCN), 2013 22nd International Conference on*, 2013, pp. 1-7: IEEE.
[380] X. Feng, Y. Chen, J. Zhang, Q. Zhang, and B. Li, "TAHES: A truthful double auction mechanism for heterogeneous spectrums," *IEEE Transactions on Wireless Communications,* vol. 11, no. 11, pp. 4038-4047, 2012.
[381] L. Deek, X. Zhou, K. Almeroth, and H. Zheng, "To preempt or not: Tackling bid and time-based cheating in online spectrum auctions," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 2219-2227: IEEE.
[382] Y. Yang, J. Wu, C. Long, and B. Li, "Online market clearing in dynamic spectrum auction," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, 2011, pp. 1-5: IEEE.
[383] Z. Han, R. Zheng, and H. V. Poor, "Repeated auctions with Bayesian nonparametric learning for spectrum access in cognitive radio networks," *IEEE Transactions on Wireless Communications,* vol. 10, no. 3, pp. 890-900, 2011.
[384] S. M. Kakade, I. Lobel, and H. Nazerzadeh, "An optimal dynamic mechanism for multi-armed bandit processes," *arXiv preprint arXiv:1001.4598,* 2010.
[385] X. Wang, Y. Ji, H. Zhou, and J. Li, "A Nonmonetary QoS-Aware Auction Framework Toward Secure Communications for Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 7, pp. 5611-5623, 2016.
[386] L. Duan, L. Gao, and J. Huang, "Contract-based cooperative spectrum sharing," in *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, 2011, pp. 399-407: IEEE.
[387] H. Wang, L. Gao, X. Gan, X. Wang, and E. Hossain, "Cooperative spectrum sharing in cognitive radio networks: A game-theoretic approach," in *Communications (ICC), 2010 IEEE International Conference on*, 2010, pp. 1-5: IEEE.

[388] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio, part II: multiuser networks," *IEEE Transactions on wireless communications,* vol. 6, no. 6, pp. 2214-2222, 2007.

[389] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio, part I: Two user networks," *IEEE Transactions on wireless communications,* vol. 6, no. 6, pp. 2204-2213, 2007.

[390] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," *Physical Communication,* vol. 4, no. 1, pp. 40-62, 2011.

[391] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE Journal on Selected Areas in Communications,* vol. 26, no. 1, 2008.

[392] J. Zhang and Q. Zhang, "Stackelberg game for utility-based cooperative cognitiveradio networks," in *Proceedings of the tenth ACM international symposium on Mobile ad hoc networking and computing*, 2009, pp. 23-32: ACM.

[393] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative spectrum sharing via controlled amplify-and-forward relaying," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, 2008, pp. 1-5: IEEE.

[394] Y. Yan, J. Huang, X. Zhong, and J. Wang, "Dynamic spectrum negotiation with asymmetric information," in *International Conference on Game Theory for Networks*, 2011, pp. 516-529: Springer.

[395] D. Niyato and E. Hossain, "A game-theoretic approach to competitive spectrum sharing in cognitive radio networks," in *IEEE Wireless Communications and Networking Conference* 2007.

[396] R. E. Ali, K. G. Seddik, M. Nafie, and F. F. Digham, "A Pricing-Based Cooperative Spectrum Sharing Stackelberg Game," in *arXiv preprint*, 2013.

[397] J. W. Mwangoka, K. B. Letaief, and Z. Cao, "Joint power control and spectrum allocation for cognitive radio networks via pricing," *Physical Communication,* vol. 2, pp. 103-115, 2009.

[398] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of nash equilibrium, and collusion," *Selected Areas in Communications, IEEE Journal on,* vol. 26, pp. 192-202, 2008.

[399] H. S. Mohammadian and B. Abolhassani, "Auction-based spectrum sharing for multiple primary and secondary users in cognitive radio networks," in *Sarnoff Symposium, IEEE*, 2010.

[400] A. A. Daoud, T. Alpcan, S. Agarwal, and M. Alanyali, "A stackelberg game for pricing uplink power in wide-band cognitive radio networks," in *Decision and Control, 47th IEEE Conference on*, 2008.

[401] J. Sun, E. Modiano, and L. Zheng, "Wireless channel allocation using an auction algorithm," *Selected Areas in Communications, IEEE Journal on,* vol. 24, pp. 1085-1096, 2006.

[402] M. Khaledi and A. A. Abouzeid, "Dynamic spectrum sharing auction with time-evolving channel qualities," *IEEE Transactions on Wireless Communications,* vol. 14, no. 11, pp. 5900-5912, 2015.

[403] A. Mahajan and D. Teneketzis, "Multi-armed bandit problems," *Foundations and Applications of Sensor Management,* pp. 121-151, 2008.

[404] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *Communications, IEEE Transactions on,* vol. 45, pp. 1218-1230, 1997.

[405] A. Sengupta, S. Amuru, R. Tandon, R. M. Buehrer, and T. C. Clancy, "Learning distributed caching strategies in small cell networks," in *Wireless Communications Systems (ISWCS), 2014 11th International Symposium o*.

[406] H. R. Varian and C. Harris, "The VCG auction in theory and practice," *The American Economic Review,* vol. 104, no. 5, pp. 442-445, 2014.

[407] D. Bergemann and J. Valimaki, "Efficient dynamic auctions," 2006.

[408] M. Labib, J. H. Reed, A. F. Martone, and A. I. Zaghloul, "Coexistence between radar and LTE-U systems: Survey on the 5 GHz band," in *Radio Science Meeting (USNC-URSI NRSM), 2016 United States National Committee of URSI National*, 2016, pp. 1-2: IEEE.

[409] M. M. Buddhikot, "Understanding dynamic spectrum access: Models, taxonomy and challenges," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*, 2007, pp. 649-663: IEEE.

[410] M. Matinmikko *et al.*, "Overview and comparison of recent spectrum sharing approaches in regulation and research: From opportunistic unlicensed access towards licensed shared access," in *Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on*, 2014, pp. 92-102: IEEE.