Mechanisms for Enhancing Spectrum Utilization in a Spectrum Access System

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Abstract

Multi-antenna systems with resource allocation based on transmit and receive precoding matrices have proven to enhance the spectral efficiency of cellular systems. In this thesis, we extend these concepts to a spectrum sharing system with primary users and secondary users. The spectrum sharing area is modeled as an array of transmit and receive antennas, with the transmit power constraint defined as a function of the interference threshold of the primary user. The area covered by a database enabled spectrum access system is represented as spatial bins, which are regions of predefined sizes. Each bin is assumed to have a single secondary user base station and all the resources of that bin (i.e., available frequencies, transmit power, etc.) are consumed by this secondary user in that bin. With these assumptions, the service area of the database can be represented by a grid of secondary users. Such a grid of secondary users forms a array of transmit antennas with secondary users in each bin. Furthermore, the set of bins with its secondary users at the edge of the exclusion zone of the primary user are assumed to create an array of receive antennas. These receive antennas act as sensors that will measure the interference power at the edge of the exclusion zone of the primary users. So the overall system of secondary user base station transmit and receive antennas can be modeled as a multi-element antenna array system.

A regulatory interference threshold (I_{th}) is defined for protection of the primary user at the edge of exclusion zones. This interference threshold is used by the resource allocation algorithms in the spectrum access system to calculate the transmit and receive precoding matrices for the secondary user antenna array. Using multiple-input multiple-output theory, the receive antenna array will measure the interference from the transmit antenna array and a feedback mechanism will update the resource allocation to keep the power at the receive array below the interference threshold of the primary user. For each array, the transmit/receive matrix is a beamforming vector which consists of a set of weights, one for each antenna. Furthermore, a codebook-based strategy is used by the spectrum access system database to choose a transmit matrix from the codebook which minimizes the interference at the primary user.

The overall spectrum sharing system can be represented by a model based on four design parameters, namely, $\Delta = (I_{th}, P, V, B)$, where P is the transmit power constraint, V are the transmit and receive beamforming matrices, and B is the matrix with active secondary user base stations of the antenna array or the quality of service level of the secondary users. The Δ parameter is called the *system index* of the spectrum sharing system. We apply the multi-antenna model to the challenging problem of spectrum sharing where the primary users operational parameters, such as transmit power levels, waveform types, and service modes, can change with time. Moreover, there are several types of primary users in different bands. Most of these users are federal government systems and their operational parameters are not available to the spectrum access system database. Our framework is useful in sharing spectrum with federal primary users, since only the interference threshold is needed for sharing their bands. Furthermore, we quantify the uncertainty in the availability of these bands for secondary users and the variations in achievable capacity with sharing spectrum in these bands.

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Public Abstract

The goal of this thesis is to build a Protected Shared Access Model (PSAM) [1] through database enabled Spectrum Access System (SAS). A model for the SAS is proposed, which is based on our vision for the SAS as a more dynamic and responsive architecture as a geolocation database than the current TVWS database. Major functions and capabilities of the model include, calculations of exclusion zone (EZ) of primary users with different operational parameters, use interference estimation techniques for predicting interference levels that will be generated by the new secondary users (SUs) and existing systems operating in the database service area, allocate location based transmit power levels and provide an algorithm for communications among the PUs, SUs, and the SAS to implement management and authorization framework of spectrum resources to different types of SUs.

The selection of a propagation model is of utmost importance in spectrum sharing studies. Existing literature on EZs with simplified propagation models does not consider the effect of LOS interference between the PU to SU link and SU to PU link on peak points in the terrain area around the PU. The use of a terrain profile based model captures the essence of propagation over irregular terrain. Terrain regions that are far away from the PU may have a LOS between the PU and SU. So its not only the nearest area where the PU/SU can get interference, but interference is present from areas further away on high grounds having a direct LOS with the PU antenna. The exclusion zone computation with terrain profile based propagation model captures this effect, and it is the same effect that makes the shape of the exclusion zone irregular. So the propagation model used in spectrum sharing studies must be able to use the terrain for the specific geographical area for precise propagation calculations, and provide statistical reliability parameters for the computed propagation values for area of interest.

For a multi-tier shared access model with incumbent access (IA) users, priority access (PA) users and general authorized access (GAA) users. The SU interference tolerance thresholds varies by the type of SU's i-e., PA users like public safety systems and mission critical users have low tolerance for interference and hence need to

operate further from the PU. While GAA users like commercial broadband systems have higher interference tolerances and can operate closer to the PU. This multi-tier shared access model requires varying levels of interference protection from PU, that can be provided with multiple exclusion zones [2] defined for different types of SU's.

We propose the concept of *differential spectrum access hierarchy*, and define it in the context of a multi-tiered EZs that are based on quantiles of tolerable interference levels for different tiers of SUs. We also quantify and show the gain in SU capacity (or throughput) obtained by using multi-tiered EZs for different tiers of SUs. Using simulation results, we show that the size of EZs can be significantly reduced with the use of a terrain profile-based propagation model that takes into account terrain profile for signal attenuation between PUs and SUs in the P2P link.

The exclusion zones involve the use of interference test points at the circumference of the protection contour of the PU. They are monitoring test points that the SAS uses with a propagation model and locations of SUs to calculate interference [3]. Consider a model of Figure 5.1, the coexistence environment with PU, SU and the SAS with a database. As more SUs enter the system, their transmit powers creates interference for the PUs. In the event of SU interference exceeding a predefined threshold level at any of the test points, the SAS uses an interference based power control algorithm to turnoff the nearest dominant interferer's. Turning off the dominant interferers eliminates interference generated by that node at the PU. This nearest node interference cancellation significantly reduces the outage probability at the PU.

Unlike existing metrics for spectrum utilization efficiency that considers separate metrics for PU interference protection and maximum use of the band for secondary use [4] [5]'we define a new metric for spectrum utilization efficiency. This metric uses utility functions and cost functions to measure the impact of secondary use of the spectrum on PUs as well as the degree of satisfaction SUs can achieve from reuse of such spectrum [6]. The new spectrum utilization metric is used to evaluate tradeoffs between interference protection of PUs and SU spectrum utilization.

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Chapter 1

Introduction

Any wireless communication system requires one fundamental resource for over-the-air information transfer: radio frequency (RF) spectrum. RF spectrum is a precious resource mainly because of physical and technological limitations. As a result, radio frequencies are in heavy demand and a license is needed to transmit in most RF bands to avoid harmful interference to and from other users. Exclusive Use Licenses were given out in the past, but the limited availability and sparse use of spectrum by legacy systems has motivated a new form of spectrum management known as *Spectrum Sharing* allows two or more systems to access a pool of frequencies based on certain rules and regulations, which vary with location and frequency. In order to make more RF spectrum available for wireless communications, the FCC has issued many Notices of Proposed Rule Making (NPRM) to facilitate better spectral efficiency in many different spectrum bands. One such rule making is for the 3.5 GHz band, the citizen broadband radio services (CBRS) band [8]. For this band FCC proposes the use of small cells and spectrum sharing. The FCCs plans for the CBRS band include the use of a Spectrum Access System (SAS). The SAS is a dynamic spectrum management system that is capable of a number of unique capabilities such as real-time assessment of spectrum availability, adjustment of the Exclusion Zones (EZs) around the Primary Users (PUs), interference protection, operational privacy [9], enforcement of regulatory policies, and other interference mitigation [3] and coexistence techniques [10]. The SAS will ensure that the CBRS users operate only in areas where they would not cause harmful interference to the PUs, and could also help manage interference protection among different tiers of the CBRS users [11]. The three tiers of service, as proposed in the FCCs NPRM [8] are: Incumbent Access (IA), Priority Access (PA) and General Authorized Access (GAA). IA users have exclusive rights to the spectrum whereas GAA users are the lowest priority users in accessing the shared band.

For shared use of spectrum there are several types of PUs in different spectrum bands, i.e., PUs with extremely high transmit powers and a larger signal coverage area and PUs with relatively smaller transmit power and a smaller signal coverage area. Existing techniques require case-by-case sharing arrangements in different spectrum bands [10] [12]. Such case-by-case solutions result in inefficient methods for calculations of the available spectrum for the SUs and interference to the PUs. In the case of EZs of the PUs with high transmit powers and a substantial interference area, the minimum distance between a PU and SUs is large. In this scenario, the transmission power discrepancy between the two is sufficiently sizeable such that interference from SUs to a PU is negligible [13]. For PUs with relatively low transmit power and smaller signal coverage area, interference from SUs to PUs is effective and the size of EZ depends on interference tolerance of the PU. Changing PU parameters causes considerable uncertainity in the availability of spectrum resources for the SUs [14]. In order to make sharing viable and economically feasible we need to provide certain QoS protection to the SUs and guarantee interference protection to the PU.

Multiple antenna systems with resource allocation based on beamforming matrices have proven to enhance the spectral efficiency of cellular systems. In this paper, we extend these concepts to a spectrum sharing system with primary and secondary users. We model the interactions among the PU and all the SU base stations operating in the analysis area using a graph theoretic framework. This framework allows effective definition of interference statistics that account for all the users in the network. These statistics are then used to define constrained beamformers (BFs) for the SUs to enhance their spectral efficiency. The constrained BF ensures that both the PU as well as SUs' interference constraints are satisfied. These constraints are dependent on the size of the EZs of the PU and cell sizes of the SUs. The role of the SAS is to model the overall system with PUs and SUs as a single system with a specific set of parameters affecting both systems. These parameters are discretized to become the system index Δ_i, and are used by the SAS to generate aggregate beamformers for all the SUs in the network.

The set of parameters for the overall system can be expressed based on four system design parameters, namely, I_{th}, P, V_i, and B. Γ_{th} is the interference threshold of the PU maintained at the edge of the EZ, P is the transmit power constraint for each SU base station, V_i are the beamforming matrices, and B is the matrix with active SU base stations in each system state. With these system design parameters, the operational characteristics of the SAS can be modeled as states of the system $S_1, ..., S_J$, and the intervals for which the SAS remains in these states are modeled by parameter $T_1, ..., T_J$. Every state of the SAS requires a different set of design parameters. When there is an increase in the interference threshold of the PU, the allowable transmit power increases and a larger number of SU base stations can be allocated spectrum resources.

We apply this SAS model with constrained BFs to the challenging problem of spectrum sharing with different types of PUs whose operational parameters are changing over time [15]. These parameters include transmit power levels, waveform types, and service modes. In each system state, a new set of beamformer matrices are generated based on interference parameters in the asymptotic covariance matrix (ACM). These interference parameters change from symmetric to asymmetric cases based on both PU as well as SU base station parameters. This technique allows the spectrum manager to adaptively control the resource allocation process for ensuring interference protection of the PU and adapting parameters of the SUs. The proposed SAS model with constrained BFs addresses this problem and enhances the spectral efficiency of the overall system.

Chapter 2

Contributions and Research Objectives

2.1 Contribution 1: A model for the Spectrum Access System

Our model for the Spectrum Access System is based on a more dynamic and responsive architecture than the current TV whitespace (TVWS) database approach to spectrum sharing. Major functions and capabilities of the model include, calculations of EZs of primary users with different operational parameters, use interference estimation techniques for predicting interference levels that will be generated by the new secondary users and existing systems operating in the database service area, allocate location based transmit power levels to the secondary users based on their estimated interference to the primary users and provide an algorithm for communications among the PUs, SUs, and the SAS to implement management and authorization framework of spectrum resources to different types of secondary users.

The following are some of the contributions for this research objective.

- Develop requirements, features, and a data model for the new functionalities of the SAS as a geolocation database (GDB). These functionalities are inline with the FCC requirements as mentioned in [16].

Along with an outline for the main functional components of the SAS with a block diagram and details of each component with its data model.

- Develop a centralized SAS controller as the main component of the overall Spectrum Access System. It has algorithms for optimizing utility or cost functions and providing instructions to the SU base stations.
- Achieve fairness, responsiveness, and fullfill heterogeneous service requirements of multi-tier networks.
- Efficiently handle network congestion and mitigate interference from dominant interferers through controlling the SU beamforming.

2.2 Contribution 2: Multi-Tier Exclusion Zones for Spectrum Sharing

Reducing the size of EZs using propagation models is vital for efficient utilization of fallow spectrum as well as for the economic viability of spectrum sharing itself. In this dissertation, we explore two approaches for reducing the size of EZs. We show that multi-tiered EZs can be used to improve spectrum utilization efficiency by implementing the concept of differential spectrum access hierarchy. Also, we provide quantitative results that show the impact of using a point-to-point mode terrain profile in calculating an EZ's contour. Such a terrain profile captures the effects of propagation losses due to area-specific topography, which are not considered by the F-curves, a common method of calculating an EZ's boundary. Our results indicate that the use of such a terrain profile results in a noticeable decrease in the size of an EZ compared to simple propagation models.

The core contributions of this chapter are summarized below:

- Propose the concept of *differential spectrum access hierarchy*, and define it in the context of a multi-tiered EZs that are based on quantiles of tolerable interference levels for different tiers of SUs. We also quantify and show the gain in SU capacity (or throughput) obtained by using multi-tiered EZs for different tiers of SUs.

- Using simulation results, we show that the size of EZs can be significantly reduced with the use of a terrain-based propagation model that considers terrain profile for signal attenuation between PUs and SUs in the P2P link.

2.3 Contribution 3: Terrain Enabled Propagation Models

The selection of a propagation model is of utmost importance in spectrum sharing studies. Existing literature on exclusion zones with simplified propagation models [14] does not consider the effect of LOS interference between the PU to SU link and SU to PU link on peak points in the terrain area around the PU location. The use of a point-to-point model captures the essence of propagation over irregular terrain. Terrain regions that are far away from the PU location may have a LOS between the PU and SU. So its not only the nearest area where the PU/SU can get interference, but interference is present from areas further away on high grounds having a direct LOS with the PU antenna. The EZ computation with terrain profile based propagation model captures this effect, and it is the same effect that makes the shape of the EZ irregular. So the propagation model used in spectrum sharing studies must be able to use of the terrain for the specific geographical area for precise propagation calculations, provide statistical reliability parameters for the computed propagation values for area of interest, must have strong analytical background for explanation of the propagation results, and an opportunity for further development of the model.

The contribution of this research objective are the following.

- Motivation for selection of ITS-Irregular Terrain Model for propagation analysis in spec- trum sharing with use of P2P mode with terrain profiles and area-based mode without terrain profiles.
- Impact of the propagation model on availability of spectrum for secondary use through classification of area around PU into different regions based on interference between primary users and secondary users.

2.4 Contribution 4: Resource Allocation using Multiantenna Systems for Database Enabled Spectrum Management

This contribution develops a framework for database oriented resource sharing among the secondary users (SUs) based on the primary users' (PU) parameters. This problem has been analyzed in recent literature for (a) protecting the PU from RF interference with (b) improving the operating conditions for SUs. Our work addresses the gap of providing protection to the PU while also maximizing the spectrum opportunities and efficiency of SU access systems using MIMO beamforming in dynamic mode. We formulate the spectrum management problem as a constrained beamforming optimization problem and solve it using Lagrangian duality with subgradient based methods. Furthermore, a parametric model for a Spectrum Access System (SAS) is defined, that has four parameters $-$ interference thresholds (Γ), transmit power (P), aggregate beamformers (V_i), and active SU base stations (B) $-$ that allow configuring the spectrum sharing system to the given scenario. The SAS model allows for developing new innovative solutions for spectrum sharing not only among primary and secondary users but also among secondary users. The SAS ensures the trustworthiness in the use of the shared spectrum through MIMO beamformers with interference constraints among all the users in the network. Our results show significant improvement in both the protection of PU as well as enhancing the reliability in QoS for the SUs.

Contributions of this paper are the following.

- A spectrum management framework based on constrained BFs that takes into account both PU as well as SU interference constraints. Using a graph theoretic framework an asymptotic covariance matrix is defined that contains the interference constraints based on physical locations of all the users in the network.
- Address the problem of aggregate interference from a system level perspective.
- Generate resource allocation policies with regulatory constraints for different adaptation modes of the spectrum sharing system using a dynamic SAS. These policies are in the form of system index (Δ) used for resource allocation. The system index comprises a set of design parameters (Γ_{th}, P, V_i, and

B) where the aggregate beamformers V_i can be adapted for different applications and scenarios.

- Apply the SAS model based on constrained BFs to characterize the sum capacity of the SUs when the operational modes of the PU as well as SUs change with time.

2.5 List of Publications

The following is a list of published, submitted and in preparation papers from this research effort.

1. **A. Ullah**, S. Bhattarai , J.-M. Park , J. Reed , D. Gurney, "Multi-Tier Exclusion Zones for Spectrum Sharing.," in IEEE International Conference on Communications (ICC), 2015
2. **Abid et. al.**, "Resource Allocation using Multiantenna Systems for Database Enabled Spectrum Management," submitted to *IEEE Transactions on Wireless Communications, 2017*
3. **Abid et. al.**, "Optimization of Training Sequences for Radio Environment Estimation in Database Enabled Spectrum Access System," to be submitted to *IEEE Transactions on Wireless Communications, 2017*
4. B. Bahrak, S. Bhattarai, **A. Ullah**, J.-M. Park, J. Reed, and D. Gurney, "Protecting the primary users operational privacy in spectrum sharing," in IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN), 2014
5. Dudley, S.M. Headley, W.C. and Lichtman, M. and Imana, E.Y. and Xiaofu Ma and Abdelbar, M. and Padaki, A. and **Ullah, A**. and Sohul, M.M. and Taeyoung Yang and Reed, J.H. "Practical Issues for Spectrum Management With Cognitive Radios", Proceedings of the IEEE, March, 2014
6. S. Bhattarai and **A. Ullah** and J. M. J. Park and J. H. Reed and D. Gurney and B. Gao "Defining incumbent protection zones on the fly: Dynamic boundaries for spectrum sharing " Proceedings of IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN) 2015

Chapter 3

A Review of Spectrum Access System Concepts

The Federal Communications Commission (FCC), in its Notice of Proposed Rule Making (NPRM) [8] for the 3.5 GHz band, proposed the use of small cells and spectrum sharing in the newly created Citizens Broadband Radio Service (CBRS) band. The FCC's plan for the CBRS band include the use of Spectrum Access System (SAS) for managing spectrum sharing. SAS is a dynamic database system that is capable of a number of unique capabilities such as real-time assessment of spectrum availability, adjustment of the *Exclusion Zones* (EZs) of the Primary Users (PUs), interference protection, operational privacy [17], enforcement of regulatory policies, and other interference mitigation and coexistence techniques [18]. It will ensure that the CBRS users operate only in areas where they would not cause harmful interference to the PUs, and could also help manage interference protection among different tiers of CBRS users. The three tiers of service, as proposed in the FCC's NPRM are as follows; Incumbent Access (IA), Priority Access (PA) and General Authorized Access (GAA). IA users have exclusive rights to the spectrum while GAA users are the lowest priority users in accessing the shared band.

To support spectrum sharing inside the PU protection zones, some important information from the SAS must be disseminated among the PA-SU and the GAA-SU for efficient operation. The type of information of interest may vary with the situations and includes allowable SU transmit power, antenna beam steering directions, etc. A monitoring system with measurement test points (MTPs) is optimally placed around the PU to estimate the interference generated by the SUs in different directions. A statistical analysis may also be introduced to determine how often the SAS needs to be updated and the weight for each parameter for which the information should be used in the decision process.

In order to provide differing QoS to SUs in the primary-secondary sharing paradigm, access to spectrum is allowed through some licensing mechanism. Multiple tiers of SUs are defined through the licensing parameter Ψ_i, which allows differing levels of spectrum rights among the users. The network performs such licensing through the assignment of a parameter Ψ_i to the license holders and SUs. The power allocation policy will assign unlimited spectrum rights to the PU with guaranteed QoS protection. While the level of the SU license will depend upon the assigned licensing parameter Ψ_i. The SUs will not be able to change their licensing parameter Ψ_i without an authorization from the SAS database. Such a mechanism will entitle the PUs exclusive acces to the spectrum, and must satisfy their QoS requirements. While the PA-SUs will have a higher licensing parameter Ψ_i and will be entitled to interference protection from both IA-SUs as well as GAA-SUs.

Furthermore, the SAS uses measurement test points (MTPs) for estimating the interference at the circumference of the protection contour of the PU. They are real/hypothetical test points that the SAS uses with a propagation model and locations of SUs to calculate interference. In the event of SU interference exceeding beyond a predefined threshold level at any of the test points, the SAS uses interference based dynamic control parameters Δ to turnoff the dominant interferer's. Turning off the dominant interferers eliminates interference generated by these SUs at the PU. The SU interference elimination process significantly reduces the outage probability at the PU receiver. Outage probability scales down exponentially with the number of eliminated interferer's, showing the significant potential of this technique.

The SAS database in this case will act as a local licensing server (LLS) as mentioned in [19], but the difference between our work and [19] is that the SAS will be coordinating the admission, priority level and the license parameters of the SUs. The SAS will admit as many SUs as possible until the interference threshold at any of the test points exceeds beyond the threshold limit. The monitoring system will convey an interference distress request to the SAS. The SAS will broadcast the Δ parameter to instruct the SUs to reduce their transmit power in the particular area.

3.1 Outline of the Architecture

3.1.1 Push vs Pull Approach

Most of the existing database enabled spectrum sharing techniques like in the TV whitespace uses a polling based approach for information dissemination. In this approach, each SU must query the SAS-database to receive spectrum information in the database response. This query-response technique is called a pull-based approach for the transfer of information from the SAS to SUs initiated by a SU request. In contrast, the information dissemination that involves sending information to a large number of SUs before any specific request is known as push-based approach, since information transfer is initiated by a SAS-push.

The trade-offs between SAS-push and SU-pull techniqus, revolves around the context of the application for which they are used and depends on the costs of initiating the transfer of data. A pull-based approach requires the use of a back channel for each database query. Furthermore, the SAS must be interrupted continuously to deal with such requests and has limited flexibility in scheduling the order of data delivery. Also, the information that the SUs can obtain from a SAS-database is limited to that which the SUs know to ask for. Thus, new data items or updates to existing data items may go unnoticed at SUs unless they periodically query the SAS-database.

A SAS initiated information push-based approaches, in contrast, avoid the issues identified for the SU-query, but have the problem of deciding which data to send to SUs in the absence of specific requests. Clearly, sending irrelevant data to SUs is a waste of resources. A more serious problem, however, is that in the absence of requests it is possible that the SAS will not deliver the specific data that are needed by the SUs in a timely manner. Thus, the usefulness of the SAS-initiated push is dependent on the ability of a monitoring system to accurately predict the changes needed in parameters of the SUs to mitigate interference to PU. A solution to this problem is to allow the SUs to provide a set of their operational parameters to the SAS in the initial license/registration. A popular approach for providing such information is through the IETF PAWS protocol. Using this approach the SUs subscribe to given set of information by providing a set of expressions that describe the parameters of interest. These subscriptions form a profile the SAS database then adaptively make changes to this profile based on PU and SU parameters.

3.1.2 Information dissemination schemes

The control information for the SUs from the SAS can be disseminated by periodically broadcasting control information into the entire network via plain flooding. This technique is straight forward but costly in terms of energy and spectrum consumption. Extension of the optimized link state routing protocol (OLSR) for the control information dissemination was evaluated in [20]. OLSR is a proactive protocol and uses link state scheme in an optimized manner to diffuse topology information. But in this thesis we consider a probabilistic broadcasting protocol that disseminates the control parameter throughout the SUs by using local exchanges of information among the SUs. This method reduces the overhead by adaptively controlling the information dissemination based on certain parameters of the PU system like interference threshold measured at different MTPs and the selected information of the SU system like changing antenna tilts or allowable transmit power levels, etc. Furthermore, this algorithm allows the mathematical modelling of the overall system to a discrete time Markov process through the mean-field analysis of individual SUs and all the active SUs together. This technique provides mathematical background to evaluate the efficiency of spectrum use over a period of time and impact of different resource allocation policies and regulatory constraints in the use of the available spectrum. The probabilistic information dissemination algorithms can also be used for a multi base station cellular system in which the UEs are clustered around the cells.

3.1.3 SAS with Real-Time Database System

The SAS in this application acts as an integrated real time database system (RT-DBS), which provides control operations with real time constraints on the operation of the overall system. It provides an efficient repository of data with efficient storage, retrieval and manipulation of information. RT-DBS provides a degree of confidence in meeting the constraints of the overall system. Conventional database systems are not adequate for this type of dynamic application with interference protection of the incumbent and priority access users. A real-time operation of modifying the SUs parameters to address a specific application requirements i.e., reducing interference below the threshold level or abandoning the use of the band due to arrival of a primary user must be completed by its deadline to be of full benefit to the system. RT-DBS differ in the way delayed operations are handled, and this issue is generally referred to as the overload management problem. The RT-DBS are used in the control systems of different processes. These systems can be either, 1. hard real time systems (i.e., power plant control system) or soft real time systems (i.e., stock trading), etc. RT-DBS suffers from the execution delays of database operations due to information dissemination among the SUs. Moreover, difficulties exists for the RT-DBS systems to be useful for spectrum sharing systems. But specialized protocols with scheduling and pre-analyzed evaluations of different situations in spectrum sharing can be used to address the drawbacks related to real-time system control.

3.2 Model for the Spectrum Access System

3.2.1 Introduction

The FCC released its National Broadband Plan (NBP) [21] citing the exponentially growing demand for mobile data services and the critical need to utilize the radio spectrum efficiently. Moreover, in the President's Council of Advisors on Science and Technology (PCAST) report [7] emphasized the role of the spectrum as an important economic growth mechanism. The PCAST report proposed a shared spectrum access model, wherein a heterogeneous mix of wireless systems of differing access priorities, QoS requirements, and transmission characteristics need to coexist without causing harmful interference to each other. In this spectrum sharing model, SUs identify unused spectrum by accessing a geolocation database that is constantly updated with the PUs spectrum utilization information. The PCAST report defines a three-tier hierarchy for access to federal spectrum bands. The federal PUs have an exclusive right to use the spectrum when they deploy their networks or systems. The SUs are allocated short term rights for operation in a specific geographical area. They are assured of interference protection with priority over opportunistic users. Any spectrum resources that are left over from the first and second tier users are made available to the general authorized access (GAA) users. They opportunistically use these spectrum resources with an obligation to clear the spectrum in case of a federal primary or priority access(PA) SUs appears in that spectrum band.

For shared access to federal bands, a Spectrum Access System (SAS) with a geolocation database will be used [7]. Access to spectrum is authorized after successful communication and registration with the database. Unlike the TV whitespace database, the federal SAS [7] has more functional and operational requirements that need to be satisfied. Table 3.1 compares the functional requirements of a TV White space database with those of SAS.

Table 3.1: Comparison of Spectrum Access System Capability [7]

Functionality	White Space in TV Bands	White Space Federal Addition	Spectrum Access System (SAS)
Accept specific interference contours for federal primary access users and specific secondary uses	Yes	Yes	Yes
Automatically determine interference possibilities for any secondary technology	No	No	Yes
Register the location of secondary devices authorized to operate	No	Yes	Yes
Provide deconfliction of secondary spectrum users	No	No	Yes
Provide real time input of PU operating locations and periods	No	Yes	Yes
Provide marketplace for leasing of spectrum and revenue to treasury	No	No	Yes
Provide the Spectrum Management Team (SMT) metrics [7] and advanced features like time to live (TTL)	No	No	Yes

3.2.2 Requirements

For an effective operational system [12], the SAS must fulfill the requirements of both the PUs and SUs in the shared spectrum bands. These requirements regarding the protection of PUs include the following.

1. No interference to existing PUs of the spectrum bands.
2. SUs must have the ability to reconfigure for accommodating changes in PU parameters like waveform types, occupancy, and locations, etc.
3. SUs must have backup bands to allow the PUs to reclaim their spectrum at any time.
4. Systems must have mechanisms for enforcement of spectrum rules to track down interference events quickly and reliably.
5. System must be protected against any unauthorized/accidental use, and security must be provided against hackers.
6. Efficient system management for operating complex secondary to secondary system to ensure that agreed parameters are not violated.

The requirements regarding SUs spectrum access that the SAS system [22] must fulfill are the following.

1. Interference requirements for the SUs must be reasonable for practical system deployment.
2. Existing broadband system architecture must be supported with minimal changes to existing standards.
3. Secondary QoS requirements, low power operation must be achievable with no harmful interference to the PUs.
4. A fair use policy with reliability and assured access for all SUs must be enforced.
5. System must be secured against any unauthorized/accidental use and security must be provided against hackers.

3.2.3 Features

To fulfill the above-mentioned requirements, the SAS includes many features that are intended for interference protection of PUs and SUs [10]. Along with the ability to accommodate changes in the PUs operational parameters or response to unforeseen interference scenarios. Central entity of the SAS model is the database but sensing, and dynamic frequency selection (DFS) must be used to enhance the spectrum utilization efficiency of the model. These capabilities are incorporated through the operational features defined by the PCAST report and summarized below.

1. *Channel selection* decisions for devices based upon their location, QoS requirements of the application and spectrum access rules specified by the database for that geographic location.
2. *Enforcement* of the spectrum reclaims from the PU by switching off SU communications on certain frequency channels through commands from the database or signal beacons.
3. Database must *validate the equipment* used for secondary access at the time of a spectrum request. Equipment validation can be done through the use of FCC certification identities.
4. The SAS system implemented either as centralized or distributed system must have defined generic terms of use in all the available bands in the SAS database. In other words, from a user perspective, the database must provide a single consistent interface for accessing all geolocation database information and channel allocation methods, like the Internet Domain Naming System (DNS) to facilitate a greater opportunistic use of the spectrum.
5. All the registrations and reservations for use must be time limited and renewed as appropriate. The database must have Time To Live (TTL) mechanisms, that can also be used for enforcement by revoking the SU spectrum authorization.
6. Security must be provided by the SAS for both the database request and the response using a public key cryptographic system. Experience from the Digital Rights Management (DRM) systems can be used in securing the whole operational mechanism.

3.2.4 Data Model

In addition to the above-mentioned requirements, the SAS and the access protocol [7], [22], [23] must have algorithms and data types to support implementation specific details. Some of these requirements are mentioned below.

1. *Radio and Spectrum Regulatory Concepts.* They include channel, co-channel, adjacent channel, modulation, waveform, data rate, type of filtering, block size, device characteristics and attributes (e.g., FCC ID, serial number, transmitter, receiver, detector), Equivalent Isotropically Radiated Power (EIRP), mean EIRP, peak receiver (RX) power, frequency, center frequency, power masks, bandwidth, duty cycle, signal detector [including detection threshold, frequency range, sample rate, precision, Signal to Noise Ratio (SNR), and Received Signal Strength Indicator (RSSI)], and signal type.
2. Support for *signal evidence* like detected signal, sensed frequency intervals, peak sensed power, detected time, scan time/duration, count along with location evidence and time evidence.
3. Support *scalar constraints* like restrictions on frequencies, time and dates.
4. *Security considerations* like the type of encryption, keys, key exchange, credential, security mechanism (e.g., integrity, confidentiality, authentication, authorization), and security/classification level.
5. *Networking concepts* like node identities, network membership, and types of networks i.e., peer 2 peer etc.
6. *Policy authority* for primary and secondary spectrum markets with primary and non-primary users.

3.3 Functional Components

The Spectrum Access System (SAS) is a dynamic database system and consists of many logical and physical components that will allow a number of unique capabilities like real time channel availability from dynamic calculations of the protection contours of stationary and mobile PUs. Interference protection and coexistence capability to calculate the secondary network interference power spectral density (IPSD) at PU location for allowing operations inside the protection zones as well.

The spectrum access system consist of the following components.

1. Spectrum Manager
2. Database Management System
3. Primary Incumbent Update Mechanism

4. Access Mechanism to SAS

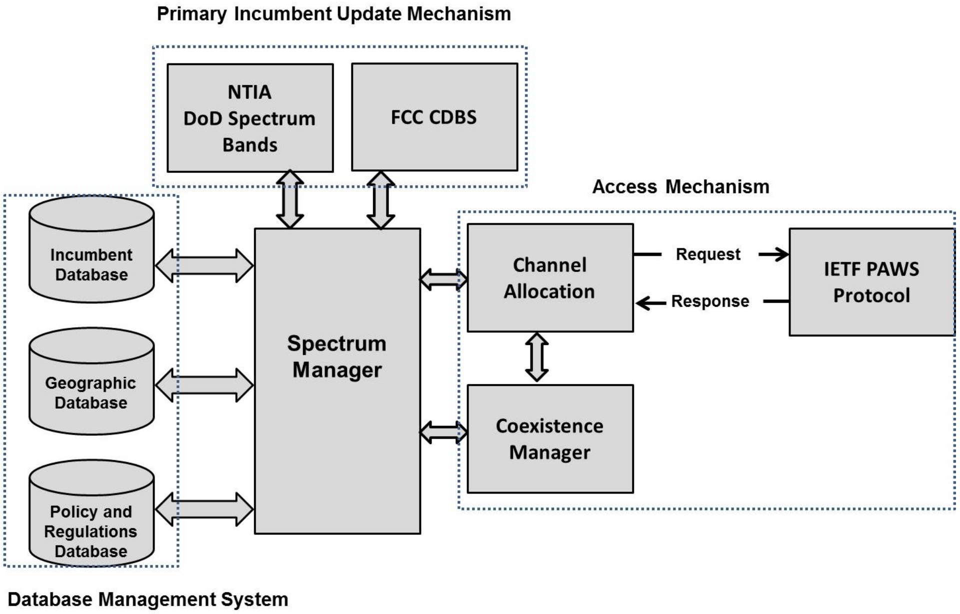


Figure 3.1: Block diagram of Spectrum Access System (SAS) with functional components.

3.3.1 Spectrum Manager

Spectrum manager (SM) is responsible for ensuring the protection of PUs and efficient spectrum utilization while complying with regulatory policies [24]. Following are some of the functions of the spectrum manager.

1. Maintain spectrum availability information
2. Calculations for available channels, spectrum quality ranking and prioritization
3. Association control mechanisms for devices with the SAS
4. Channel set management for prioritized access
5. Enforcing regulatory domain policies
6. Managing spectrum mobility
7. Facilitating the coexistence of multiple wireless services

Spectrum manager has the database management system that it uses for the spectrum availability information through available white-space channel calculations, ranking the spectrum quality, developing the spectrum prioritization and maintaining a channel set for prioritized incumbent user (IU) access, PA user, and GAA users.

3.3.2 Database Management System

The DBMS system will reside inside the spectrum manager and include a number of database entities having information about PUs in different spectrum bands like TV stations (54-72 MHz, 76-88 MHz, 174-216 MHz and 470-806 MHz) [25], Satellite systems (1675-1710 MHz) [10], RADAR systems (3500-3650 MHz) [10], Federal communication networks (1755-1850 MHz) [10], Radio Altimeters(4200-4400 MHz) [10], etc. Each PU has their own database with primary entity parameters, geographical parameters, regulatory protection constraints, and available white-space resources.

3.3.2.1 Entity Parameters

The *entity parameters* of each wireless device will depend on application for the device like the application parameters defined in the FCC CDBS [26] [27]. The entity parameters will include transmitter, receiver, antenna, mobility, and network parameters [23], [24], [28]. The *transmitter parameters* will include but not limited to the device ID, its modulation, bandwidth, transmission power, power spectral density (PSD), spurious emissions, access methodology (periodic/continuous). *Receiver/sensing parameters* will include but not limited to the type of detector, noise estimate, sampling rate, bandwidth, time stamp, location stamp, sensing values, etc. The *antenna parameters* will define the maximum gain, antenna pattern, elevation angle, azimuth angle, Effective Isotropically Radiated Power (EIRP), height of antenna above terrain (HAAT), polarization, beam width, number of sectors, maximum sweep angle, number of elements, and system type. *Mobility parameters* will specify the direction of motion and speed of the device with constructs like speed, velocity, and acceleration, etc. The entity parameters will also include the network parameters to which the device is associated with like Network ID, device role, context parameters, etc.

3.3.2.2 Geographical Parameters

The *geographic parameters* includes the PUs locations, the terrain features of the environment, and the signal propagation conditions. The *PU locations* are used to characterize the geographical features around the incumbents. These parameters are in the form of latitude, longitude and height above the terrain. *Terrain features* specify the administrative/political boundaries and other features like plain flat areas, hilly terrain, mountains, and bodies of water like lakes, rivers and oceans, etc. These terrain features will be generated from publicly available National Elevation Database [29]. The *signal propagation conditions* [30] defines all the parameters that affect the propagation of radio frequency electromagnetic waves. These parameters include but not limited to type of terrain, terrain irregularities, type of built environment, electrical ground constants, radio climatic conditions, and surface refractivity, etc.

3.3.2.3 Regulatory Protection Requirements

The SAS system maintains a database of regulatory protection requirements [7], [10], [22]. The regulatory requirements will specify a framework for sharing the spectrum bands by providing aggregate Interference limits, along with spectrum masks, underlay masks, co-channel and adjacent channel interference limits, etc. The spectrum manager using the regulatory protection requirements [12], establish the following.

1. Utilize the regulatory-approved interference prediction model, associated input parameters and aggregate interference distributions for authorizing access to commercial within and out of PU protection zones.
2. Evaluate the interference limits of the SU network on the PUs, to facilitate coordination among primary and SUs for authorizing the use of spectrum bands within the protection areas.
3. Use the spectrum sensing functionality for collecting real time spectrum use data to enforce the aggregate interference limits in the geographical area of its operation.

The regulatory protection database has constructs for implementing the above-mentioned capabilities along with the ability for sharing and acquisition with the regulatory update mechanisms of the FCC CDBS and NTIA databases.

3.3.2.4 Available White-Spaces

The spectrum manager will use the entity parameters from the databases, the geographical parameters and calculate the available white-space channels through calculation‘s methods [31], [32], [33], [34], [35] by taking into account the regulatory protection requirements. Most of these channel calculation algorithms use the entity parameters, antenna patterns, geographic locations, terrain databases for calculating the EZs around the PUs like TV transmitters, CMRS/PLMRS, Wireless Microphones, Radio Astronomy sites, RADAR systems, satellite earth stations, etc, through propagation models [36], [30], [37] defined by these standards.

The protection contours are overlaid in the form of channel power plots [31] to calculate the available channels for white space devices (WSD) in a geographical area. The WSD channel availability is specified through minimum allowed transmit power level for the SUs link. The transmit power levels for SUs varies across a region, due to high spatial variability of the PU protected service areas. This leads to fewer high powered channels and more lower powered channels making the spectrum availability highly dynamic across a region.

3.3.3 Database Update Mechanism

The PUs information is updated in the geolocation database from regulatory databases of FCC Consolidated Database Systems (CDBS), and the NTIA database of DoD PU systems. This mechanism ensures reliability of information in the geolocation databases for proper operations. The *database administrators* must ensure the accuracy of their PUs information by regular updates of their information about the PUs locations, access patterns (i.e., periodic or continuous), regulatory interference protection levels, spectrum availability for open spectrum markets, etc from the FCC Consolidated Database Systems (CDBS) [26], and NTIA Federal Spectrum Management System (FSMS) [38].

These *regulatory databases* are designed as license databases not as spectrum management databases [39]. The SAS will fulfill this gap and provide all the necessary functionality to promote technological innovations. The *database administrators* provide web-based interfaces for registration of PUs (DTV stations, Wireless microphones, etc.) and the recent FCC rules require these PUs to update their database registrations daily.

3.3.4 Access Mechanism to SAS

The access mechanism for the SAS includes a generalized database access protocol with a data model that can support the implementation of the objectives mentioned in the Table 3.1. The white space allocation of channels from the database is analogous to the *Internet Domain Naming System (DNS)*, which maps the symbolic names to the IP addresses and is transparent to the Internet users. The SAS access protocol must map the user spectrum requirements to a database query and perform all the necessary protocol related operations like secure database discovery, determining essential query parameters, and exchanging messages with the database for desired frequency channels of operation. This ease of access would enable greater opportunistic use of the RF spectrum.

The *Internet Engineering Task Force (IETF)* is currently working on development of a *Protocol for Access to Whitespace Spectrum (PAWS)*, that will be used to request resources from the geolocation database. The protocol support spectrum queries agnostic of the spectrum bands, and takes in user device description (type, ID, capabilities), location, antenna characteristics, etc. These parameters are sent in the query message to the geolocation database asking for available spectrum. The database responds back with a set of available channels, time schedule for use of the spectrum, rule set for that area, and maximum allowable location change after which the spectrum lease needs to be renewed.

The current implementation of the IETF PAWS does not support enforcement of spectrum rules, coexistence mechanisms, dynamic interference protection. But provides flexible and extensible data structures to implement the SAS functionalities with extended constructs for enforcement, coexistence and interference assessment.

3.4 Standardization Activities

3.4.1 FCC 3.5 GHz NPRM and CBRS Database

FCC released a Notice of Proposed Rule Making (FCC NPRM- 12-148) [40] to create a new Citizens Broadband Radio Service in the 3550-3650 MHz band (3.5 GHz Band) currently used for military and satellite operations. It will promote two major advances that enable more efficient use of the radio spectrum: small cells and spectrum sharing.

The 3.5 GHz Band was identified by the NTIA for shared federal and non-federal use in the *2010 Fast Track Report* [10]. Current FCC's proposal builds on experience with spectrum sharing in the television white spaces (TVWS), and prepares ideas for the new notice of Inquiry on Dynamic Spectrum Access technologies, and broadly reflects recommendations made in a recent report by the *Presidents Council of Advisors on Science and Technology (PCAST)* [7].

Moreover, these proposed new and flexible rules can be extended to the neighboring 3650-3700 MHz band, which is already used for commercial broadband services. Together, these proposals would make up to 150 megahertz of a contiguous spectrum available for innovative mobile and fixed wireless broadband services without displacing mission-critical incumbent systems.

3.4.2 European Communication Commission and Ofcom Efforts

Efficient use of the radio spectrum is a global regulatory goal from Europe, to Canada or Singapore with a primary focus on what spectrum sharing can add to existing spectrum management options. European Commissions recent release [41] on promoting the shared use of radio spectrum and the interest from regulators such as the UKs Ofcom [42] and Singapore‘s IDA [43] in trials and commercial pilots of the White Spaces technology, ensures that a significant portion of spectrum is available for license-exempt sharing on a nationwide basis, increasing the amount of such spectrum in the urbanized areas within these countries.

The reason is simple: the number of wireless devices is growing exponentially. According to the European

Commission statistics [44], by 2015 there will be 7.1 billion phones, tablets and other mobile devices connected to the Internet globally. Five years further down the line, the number of smart devices connected to the Internet is going to be staggeringly larger particularly when wireless sensors and other machine-to-machine communication devices are counted. Unfortunately, the way spectrum is managed today, does not readily allow the flexibility to adapt to meet that projected demand. Gaps in coverage and network overload in busy areas are already resulting in poor service for end-users.

These problems can be alleviated through spectrum sharing, as proposed in the European Commissions Communication [41]. Fortunately, the technology is now ready to make this happen. A Commission funded project called COGEU [45], which brings together research institutes and private companies from Portugal, France, Ireland, Germany, Poland, Slovakia, Greece and Cyprus, has lately set out to quantify the white spaces sharing opportunities in key central European states. In August, Europe‘s another commercially-authorized TV White Space geolocation database established in Finland [46]. Ireland is on the cusp of launching its own White Spaces initiative [47], and the French regulator has recently granted a TV white space test license.

With this growing interest and investment in White Spaces technology, it has become increasingly clear that its benefits can be much broader than just ensuring good wireless broadband services. Trials and pilots have explored a range of solutions from increasing the affordability of the Internet and enabling a machine to machine (M2M) communication, to turn a highly populated metropolitan area into a leading Smart City with substantial long-term environmental benefits. A popular use case is looking at how spectrum resources can help overcome inadequate Internet access in remote rural areas.

3.5 IEEE Standardization Activities

IEEE standards are key drivers for standardization and implementation of novel communications system concepts. A number of IEEE standards have incorporated the use of geolocation database as a source of available white space channels for operation. Some of these standards are summarized below.

3.5.0.1 IEEE 802.11af Standard

IEEE 802.11af working group [48] has been set up to define a standard to implement WiFi technology within the TV unused spectrum, or TV white space. Research and standardization groups around the world are taking a more flexible approach to spectrum allocations, the idea of low power systems that are able to work within portions of RF spectrum that may need to be kept clear of high-power transmitters to ensure coverage areas do not overlap are being seriously investigated. IEEE 802.11af that use TV white space, the overall system must not cause interference to the primary users. There are many benefits from a system such as IEEE 802.11af from using TV white space.

Propagation characteristics In view of the fact that the 802.11af WiFi system operating the TV white spaces would use frequencies below one GHz. This would allow for greater distances to be achieved. Current Wi-Fi systems use frequencies in the ISM bands - the lowest band is 2.4 GHz and here signals are easily absorbed.

Additional bandwidth is one of the advantages of using TV white space is that unused frequencies can be accessed. However, it will be necessary to aggregate several TV channels to provide the bandwidths that Wi-Fi uses on 2.4 and 5.6 GHz, to achieve the required data throughput rates. IEEE 802.11 af uses many new technological concepts of cognitive radio and dynamic spectrum access with sensing and database access technologies.

Cognitive Radio utilizes the available spectrum as efficiently as possible, there is a need to utilize radio technology that can sense the environment and configure itself accordingly - Cognitive Radio. The technology is heavily dependent upon Software Defined Radio technology as the radio needs to be configurable according to the prevailing radio environment.

Database Access: The IEEE 802.11af systems have provisions for accessing the geolocation database to get available spectrum for use with the available channel powers mentioned in the spectrum response.

3.5.0.2 IEEE P1900 Standard

The IEEE P1900 standard gives a complete overview of a cognitive radio network (CRN). The standard provides basic definitions and interconnection between cognitive radio and cognitive radio network concepts. For example, information tables and diagrams explain the relationships of CRs, software-controlled radios, intelligent radios, and adaptive radios. The P1900.1 definitions and terminology are categorized into (1) definitions of advanced radio system concepts, (2) definitions of radio system functional capabilities, (3) definitions of network technologies that support advanced radio system technology (4) spectrum management definitions, and (5) a glossary of ancillary definitions.

The P1900 committee objective is to develop supporting standards dealing with new technologies and techniques being developed for next-generation radio and advanced spectrum management The different tasks [49] for the working groups are defined below.

1. IEEE P1900.1: Terminology and Concepts for Next-Generation Radio Systems and Spectrum Management,
   http://grouper.ieee.org/groups/dyspan/1/index.htm
2. IEEE P1900.2: Recommended Practice for Interference and Coexistence Analysis,
   http://grouper.ieee.org/groups/dyspan/2/index.htm
3. IEEE P1900.3: Recommended Practice for Conformance Evaluation of Radio (SDR) Software Modules,
   http://grouper.ieee.org/groups/dyspan/3/index.htm
4. IEEE P1900.4: Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks,
   http://grouper.ieee.org/groups/dyspan/4/index.htm
5. IEEE P1900.5: Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications,
   http://grouper.ieee.org/groups/dyspan/5/index.htm
6. IEEE 1900.6 Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems,

http://grouper.ieee.org/groups/dyspan/6/index.htm

7. IEEE 1900.7 White Space Radio Working Group,
   http://grouper.ieee.org/groups/dyspan/7/index.htm

3.5.0.3 IEEE 802.22 Standard

The IEEE 802.22 WG was formed to use the frequencies in the TV-band between 54 MHz and 862 MHz at 6, 7, or 8 MHz bandwidths. The standard defines a cognitive radio based wide-area regional network (WRAN) that contains cognitive radio devices that can sense the immediate spectrum. The 802.22 WRAN is the first IEEE standard [50] to define how cognition in radios can be used in the base station and user terminals in a regional area network.

Communications between fixed point-to-multipoint environment with specific use of television channels and guard bands was considered in the WG specifications. Specifically, the primary goal was to develop a standard for a CR-based PHY/MAC air interface for use in license-exempt wireless communication devices on a non-interfering basis with a TV broadcast spectrum. Moreover, deployment in different geographic areas, including sparsely populated rural areas, while preventing harmful interference to incumbent licensed services in the TV broadcast bands. A secondary objective for the 802.22 standard is to serve dense population areas where spectrum is available. The 802.22 standard have the capability for accessing the geolocation database for available specrum in its operational area. The specification defines protocol for accessing the database from the base station perspective as well as the individual CPE device.

Chapter 4

Multi-Tier EZs and the Impact of Propagation Models

4.1 Introduction

Reducing the size of exclusion zones (EZs) in spectrum sharing is vital for efficient utilization of fallow spectrum as well as for the economic viability of spectrum sharing itself. In this paper, we explore two approaches for reducing the size of EZs. We show that multi-tiered EZs can be used to improve spectrum utilization efficiency by implementing the concept of differential spectrum access hierarchy. Also, we provide quantitative results that show the impact of using a point-to-point mode terrain profile in calculating an EZ's contour. Such a terrain profile captures the effects of propagation losses due to area-specific topography, which are not considered by the F-curves, a common method of calculating an EZ's boundary. Our results indicate that the use of such a terrain profile results in a noticeable decrease in the size of an EZ.

EZs are static spatial separation regions around the PU where secondary users (SUs) are not allowed to operate [10]. EZ boundaries are based on interference threshold at which the receiver's performance starts to degrade, for both primary and secondary receivers [8]. Existing techniques for computing PU EZ either use statistical pathloss models or models that have very limited usage of the terrain [10], [51]. This leads to conservatively large EZ boundaries as the model has to ensure that receivers do not suffer from interference even in the worst-case scenario (flat terrain), where the pathloss is relatively low. For example, to account for possible deep fades, the 802.22 working group specifications require detectors to have a sensitivity of -116 dBm which corresponds to a safety margin of roughly 20 dB (equivalent to an increased radius of the EZ by 110 km) [52]. In most situations, detectors do not face such severe fading, and hence the SUs are unnecessarily prohibited from using the band even though they do not cause interference to the PUs.

Shrinking the size of EZs can greatly increase the economic benefits of spectrum sharing, as the following example shows. Based on NTIA's EZ calculations for shipborne radar systems in 3.5 GHz band, it is estimated that approximately 60% of the United States population fall within the EZs [2]. This implies that a reduction in EZ size by x (in percent) enables $x \times$ (60% of 308.745 million) = 185.247x million of potential users to use the CBS band, assuming a uniform population density. Here, the US population of 308.745 million is taken from the US census 2010 [53]. Since the spectrum price is inversely proportional to the square of the frequency [54], and the 700 MHz band is currently priced at \$1.50 per MHz/POP (\$1.28 from 2008 auction adjusted for inflation) [55], sharing the CBS bandwidth of 150 MHz results in an increased revenue of 1.67x billion dollars, assuming that a licensed-like scheme will be implemented. Note that this increased revenue is apart from the revenue collected by sharing the band outside the current EZs.

To overcome the underutilization of the precious spectrum, terrain details can be incorporated to capture the actual propagation environment between the PUs and SUs. For contour estimation over irregular terrain, the terrain profile of a particular area needs to be taken into account for estimating the pathloss [56]. The terrain profiles between two points in any geographical area can be extracted from the publicly available terrain databases such as Global Land One-km Base Elevation (GLOBE) [57], Shuttle Radar Topographic Mission (SRTM) [58], National Elevation Dataset (NED) [59], etc. It may vary from a simple curved earth profile to a highly irregular mountainous profile. The presence of scattering due to trees, buildings, and other obstacles must also be taken into account. These realistic propagation effects make the EZ irregular shaped and significantly smaller in size.

Propagation models like the Irregular Terrain Model (ITM) in *point-to-point (P2P)* mode includes the terrain details in the pathloss computation [60]. It is often argued that sophisticated propagation models like the ITM are computationally expensive, and they cannot be implemented in real-time. However, since the EZs are static in nature (for stationary PUs), advanced geolocation databases like the SAS can pre-compute the pathloss over the entire service area. The pathloss computations can be coarse in less populated areas while it can be done with fine resolution in highly populated areas for maximizing the spectrum utilization. These pre-computed pathloss values can then be used to compute spectrum availability information in real-time and provided to the requesting SUs.

There are several types of PUs in the CBS band, but in this dissertation, we limit our discussions to the analysis of EZs of large-scale PUs. They have high transmit powers and the size of their EZ spans over a substantial geographic area. On the other hand, SUs (PA/GAA users) are small cell technologies and they transmit with relatively low power [8]. In this scenario, the minimum distance between a PU and SUs is large enough and the transmission power discrepency between the two is sufficiently large such that interference from SUs to a PU is negligible. In order to increase spectrum utilization, we propose to divide a EZ into multi-tiered EZs, where the boundary between two tiers is defined based on the interference tolerance threshold, I_{th}, of SUs. SUs with larger I_{th} (GAA users) will be able to operate closer to PUs as compared to SUs with smaller I_{th} (PA users). This approach is in line with the NPRM's proposed-idea of differential spectrum access hierarchy for distinct tiers of SUs that are in the vicinity of PU. Our proposed interference based multi-tier EZs are smaller than conventional EZs, and offer improved SU spectrum utilization by allowing more area for SU usage around the PU location.

We define spectrum utilization in terms of area sum capacity (ASC), which is the summation of channel capacity values of each coexisting SU in its tier within the considered SAS service area. The SU's ASC depends on its spectral efficiency (bps/Hz), the channel bandwidth (W_s) and the number of SU cells in the geographical area.

4.2 Terrain Enabled Propagation Model

In this section, we evaluate Irregular Terrain Model (ITM) for the protected shared access model (PSAM) [1] in SAS. Specifically, we study the Institute for Telecommunication Sciences (ITS) Irregular Terrain Model (ITM) for propagation analysis over terrain derived from publicly available terrain databases such as Global Land One-km Base Elevation (GLOBE) [57], Shuttle Radar Topographic Mission (SRTM) [58], National Elevation Dataset (NED) [59], etc. The Irregular Terrain Model is a theoretical-empirical propagation model that can be used in a number of scenarios and modes to study propagation losses over irregular terrain. The model is based on electromagnetic theory and on statistical analysis of both terrain features and radio measurements. It is used to predict the median attenuation of signal propagation as a function of distance and the variability of the signal in time and in space. The model uses details about environmental parameters of the region around the PUs and SUs. In this chapter, the ITM is used for computation of exclusion zones of PU's based on interference thresholds of SUs. The ITM is used in two ways for propagation analysis; one is the area-based mode, and the other one is the point-to-point mode. Details of the two operational modes are given below.

4.2.1 Area Based Mode

The area-based mode of the model is used when details of the path profile for signal propagation are not available, and the model has to predict signal attenuation with a certain statistical reliability between a transmitter and receiver. In the area mode, terrain irregularity parameter (Δh) specifies the inter-decile range of terrain elevations that separates the two SUs. In the area prediction mode, the model requires input parameters of transmit frequency (f), separation distance (d), antenna heights (h_{tx}, h_{rx}), polarization, terrain irregularity parameter (Δ h), electrical ground constants (Z_g), surface refractivity (N_s), radio climate, siting criteria (random, with care, with great care), and required statistical parameters of reliability and confidence levels, etc.

4.2.2 Point-to-Point Mode

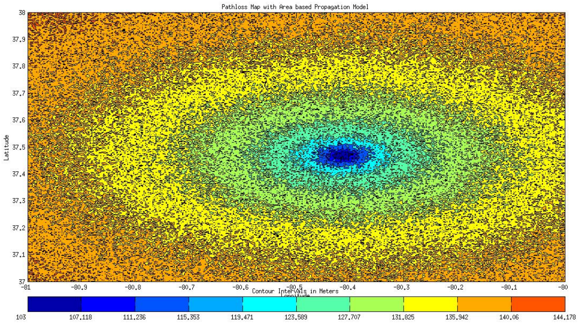
The point-to-point profile based propagation model classifies the topography of the desired service area into terrain categories based on ground profile information. The topographic database of an area is in the form of a three dimensional array with latitude, longitude, and elevation above the sea level for each point on the service area. The profile between the transmitter and receiver is constructed from the map of the service area. The algorithm makes a decision about the type of terrain based on information in the ground profile. Terrain is classified into the following categories.

- Line-of-Sight (LOS)
- LOS, but with inadequate first fresnel-zone clearance.
- Single diffraction edge
- Greater than one diffraction edges

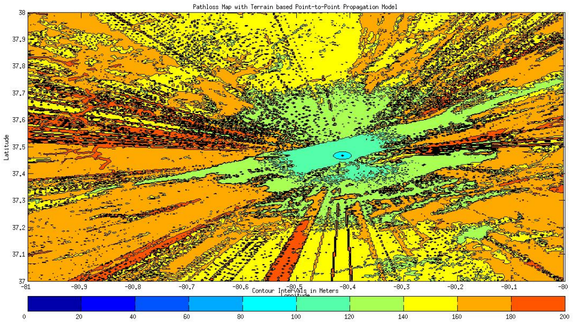
The ITS-Irregular Terrain model is used in the point-to-point mode for propagation calculations over different types of terrain. The ITM calculates median transmission loss based on path geometry of the terrain profile and refractivity of the troposphere. Two ray ground reflection model is used to predict signal strengths within the radio horizon. Fresnel-Kirchoff knife edge model is used for estimating the diffraction losses over isolated obstacles. Topospheric scatter is predicted using forward scatter theory. This model can estimate propagation losses over irregular terrain for frequencies between 20 MHz and 10 GHz. For the point-to-point profile mode the model takes in path profile parameters such as horizon distance of the antennas (d_{L1}, d_{L2}), horizon elevation angle (θ_{e1}, θ_{e2}), terrain irregularity (δh), and other specific parameters.

4.2.3 Shape of Exclusion Zones

Existing literature on exclusion zones with simplified propagation models [61] does not consider the effect of LOS interference to distant SU on peak points in the terrain area around the PU location. The use of a point-to-point model captures the essence of propagation over irregular terrain. Terrain regions that are far away from the PU location may have a LOS between the PU and SU. So its not only the nearest area where the SU can get interference but the PU interference is present further away on high grounds having



(a) Area mode



(b) Point-to-point mode

Figure 4.1: Example Pathloss maps from Irregular Terrain Model (ITM)

a direct LOS with the PU antenna. The exclusion zone computation with point-to-point propagation model captures this effect and it is the same effect that makes the shape of exclusion zone irregular. An example scenario for exclusion zone of a hypothetical PU in the Blacksburg area is shown in the Figure 4.2. As the interference tolerance of SU increases, so the effect of terrain becomes dominant and the shape of exclusion zone becomes irregular.

In the irregular terrain model (ITM), the reference attenuation is computed as a function of the distance d from the piece-wise formula:

$$A_{ref} = \begin{cases} max[0, A_{el} + K_1 d + K_2 ln\left(\dfrac{d}{d_{LS}}\right) & d \leq d_{LS} \\ A_{ed} + m_d d & d_{LS} \leq d \leq d_x \\ A_{es} + m_s d & d_x \leq d \end{cases} \tag{4.1}$$

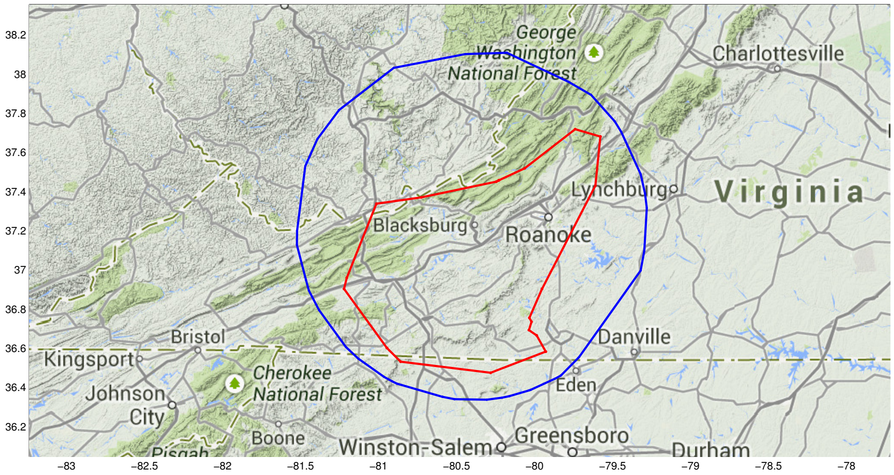


Figure 4.2: Multiple EZs around the PU on top of Durham Hall in Blacksbrug area

where the coefficients $A_{el}, K_1, K_2, A_{ed}, m_d, A_{es}, m_s$ and the distance d_x are calculated using the ITM algorithms. The above three intervals are called the line-of-sight d_{LS}, diffraction d_{diff}, and scatter regions d_{sc}. The total pathloss is the sum of A_{ref} and free space pathloss which also depends on the frequency:

$$L_d = A_{ref} + 20log_{10}\left(\frac{4\pi df}{C}\right) \tag{4.2}$$

If the interference tolerance of SU is very low then the required propagation loss for the PU signal is high. So the distance between the PU and SU for spectrum reuse needs to be large. In this case, most of the exclusion zone radii $r_1, r_2, ..., r_n$ in different sectors lies in the far away scatter regions and the contour formed is circular in shape. But if the interference tolerance of SU is high as for the GAA users. The required propagation loss is achieved at a distance that lies in the diffraction region where the effect of terrain is dominant. Terrain dominance causes the irregular shape of the exclusion zone.

4.3 Exclusion Zones with Terrain Profiles

The contour of an EZ is defined by the surrounding area around a PU's location. EZs depend on the interference from PU to SU and are calculated based on the I_{th} of the SUs [10] to maintain a desired QoS level. The QoS is defined as the required signal to interference and noise ratio (SINR), ρ_s, to achieve the desired throughput between the secondary base station/access point and user equipment. The SINR depends on secondary transmit power P_{ts} and interference power I_{rs} from the PU. I_{rs} at the secondary receiver is calculated as $I_{rs} = P_{tp}G_{tp}G_{rs}/L_r$, where P_{tp} is the PU transmit power, G_{tp} is the primary transmitter antenna gain, G_{rs} is the SU receiver antenna gain and L_r is the required propagation loss between the PU and SU. If SU I_{th} is known for a certain SINR level, then the minimum propagation loss required to prevent non-negligible interference from a PU to the SU is given by $L_r = P_{tp}G_{tp}G_{rs}/I_{rs}$. The required propagation loss L_r is then used to determine the minimum separation distance between the PU and the SU.

A terrain enabled propagation model like ITS-ITM [60] is used in the P2P mode for propagation calculations over different types of terrain. The model classifies the topography of the desired service area into terrain categories based on ground profile information. It creates a propagation map of the desired service area around the PU location. The characteristics of the propagation environment significantly affects the pathloss map of the desired area [56]. The distance at which the SUs can reuse the PUs' bands depends on a required propagation loss for the desired SU I_{th}. It varies significantly based on the ground profile between the transmitter and the receiver. For instance, when there is a clear line-of-sight (LOS) between the transmitter and the receiver, a larger distance is required in order for the propagation loss to be sufficiently large to enable coexistence of a PU and SUs.

As mentioned earlier, L_r is the required propagation loss used to determine the minimum separation distance between the PU transmitter and the SU. It is calculated using the ITS-ITM model [60], as shown below

$$L_r = 32.44 + 20log(f) + 20log(r) + A_{ref} \tag{4.3}$$

$$r = P_{tp} + G_{tp} + G_{rs} - I_{th} - 20log(f) - 32.44 - A_{ref} \tag{4.4}$$

where f is the channel frequency, $G_{tp} + G_{rs}$ depends on the antenna coupling between the transmitter and receiver. The antenna coupling is calculated from the main beam gains and azimuth orientation of the two antennas, their location dependent relative orientation and statistical antenna gain model. From these parameters the antenna gain is calculated as a function of the off-axis angle for the given main beam angle. The minimum separation distance r establishes the radius of the EZs around the PUs. The EZ radius is calculated for the whole 2π radians around the PU location. Due to variability in the attenuation factor, A_{ref}, for each measurement degree, the EZ contour may have different radius in each different direction. Hence the propagation loss can be defined as,

$$L_r = \begin{cases} L_{r_1}, & r_1 \\ L_{r_2}, & r_2 \\ ... \\ L_{r_n}, & r_n \end{cases} \tag{4.5}$$

where L_{r_i} is the required propagation loss with exclusion radius r_i for $i = 1, 2, 3, ..., n$. The EZ contour is formed by connecting the points of location with the required propagation loss, calculated from the PU transmitter. Due to variation in the radii $r_1, r_2, ..., r_n$, the contour formed is irregular in shape.

Furthermore, the EZ contour is calculated by segmenting the area around the PU location. The segmentation of the area can be done by using the transmitter antenna gain pattern, which divides the area into a number of segments, each with its own angular sector θ_i. The contour estimation algorithm takes the transmitter antenna gain pattern and calculates the edge of the EZ in each sector. The total area of the EZ is the summation of the area of each segment, which can be calculated through the following equation:

$$A_{EZ} = \sum_{i}^{n} \frac{\pi r_i^2 \theta_i}{360} \tag{4.6}$$

where θ_i is the angular resolution factor and n is the number of segments in the EZ contour. The angular resolution, θ_i, determines the granularity in estimating the EZ's area, A_{EZ}. Angular resolution of the contour estimation has a dominant impact on SU area sum capacity (ASC). ASC is the sum of the channel capacities of all the SUs that are operating outside the PU EZ within a considered geographical area (The precise definition is given in Equation (4.15)). If the angular resolution, θ_i, is reduced, then an EZ's area increase and vice versa.

A polygonal approximation algorithm is used for estimating the EZ contour around the PU with different radii in each direction [62]. It takes an array of points $r_n : (x_1, y_1), ..., (x_n, y_n)$ and generates a small number of vertices on the contour formed around these points. The number of points in the contour radii depends on the PU antenna gain pattern, granularity of the contour estimation and dynamics of the terrain.

4.4 Multi-Tiered Secondary Users

Unlike other databases that only protect PUs from potential interference [61], the SAS provides interference protection to the SUs operating in the same frequency band. For this purpose, the SAS defines *differential spectrum access hierarchy* [11] through multiple EZs for different tiers of SUs operating around the PU location [2] [11].

A SU's I_{th} is defined according to its desired QoS. We consider k threshold values $I_{th}^{(1)}, ..., I_{th}^{(k)}$ to identify k different tiers of SUs. The PU's EZs for these SUs are calculated based on the terrain profile between the PU and SUs in the P2P link. The area for secondary spectrum reuse depends on the performance of the propagation model in predicting the interference region of the PU. The authors in [63] introduced the concept of quantiles of received PU power on radials around the PU location. We build on that concept for defining spatial interference quantiles for different tiers of SUs. The quantile model is used for classification of area around the PU into distinct EZs. A hypothesis test is performed at every grid location with multiple thresholds $I_{th}^{(i)}$ for $i = 1, 2, 3, ..., k$ of PU received interference calculated through the terrain enabled propagation model in P2P mode. The channel at the location is considered available if the propagation model predicts the received interference from PU to be below the threshold limit $I_{th}^{(i)}$ defined for that EZ. We denote the output of the hypothesis test by D_i for each grid location. The symbol D_i represents if the grid location loc_i is inside the PU's i^{th} EZ denoted by $\Re_i^2$. The indicator function is used to denote spectrum opportunity at each grid point $x = loc_i$ [63].

$$\mathbf{1}_{D_i(x)} = \begin{cases} 1 & \text{if}\, x \in D_i \not\subset \Re_i^2 \\ \\ 0 & \text{if}\, x \in D_i \subset \Re_i^2 \end{cases} \tag{4.7}$$

We compute the quantiles of received signal interference in the geographic area around the PU location [64]. The quantile is a set consisting of the interference distributions defined by the influence function ψ and is a function of grid point location loc_i; denoted by $Q(loc_i, \psi)$. The influence function ψ depends on the application of the quantile model. In [63], it is estimated based on uncertainity and desired performance, while in [65] it is defined by the Huber's ψ function. In our case, we define the influence function as the *Gaussian erf* function. Let $\mathbf{F}$ be the set of all the distributions that the PU interference can take over a given geographical area. The interference distribution at the grid point loc_i is denoted by, $F_{loc_i} \in \mathbf{F}$ and is calculated as,

$$P_{f_{loc_i}}(I_{rs} < Q(loc_i, \psi)) = \chi, \tag{4.8}$$

where I_{rs} is the average power of the PU interference at the SU receiver and $0 \leq \chi \leq 1$. For a set of k threshold values for different tiers of SUs, a $k-$quantile model with a set of distributions $\mathbf{F}$ of interference is defined by a set of numbers $(\chi_1 < \chi_2 < ...\chi_k)$ with a corresponding list of functions $Q_1(loc_1, \psi_1), ..., Q_k(loc_k, \psi_k)$. A distribution $F_{loc_i} \in \mathbf{F}$ iff $\forall i \leq k$.

$$P_{f_{loc_i}}(I_{rs} < Q_i(loc_i, \psi_i)) = \chi_i \tag{4.9}$$

In this paper, the quantiles are chosen based on the $I_{th}^{(i)}$ limits of different tiers of SUs.

A hypothesis test is used to classify the area around the PU into multiple EZs based on SU interference threshold levels. For the test, the test statistic $T(I)$ is the received interference as predicted by the propagation model over the geographical area for an interference threshold limit of $I_{th}^{(i)}$. From [60], the test statistic is distributed normally with different mean values, and a multiple hypothesis testing problem is formulated for the area classification, as shown below.

$$T(I) \sim \begin{cases} \aleph(I_{th}^{(0)}, \sigma_0^2) & \text{when } H_0 \\ \aleph(I_{th}^{(1)}, \sigma_1^2) & \text{when } H_1 \\ ... & \\ \aleph(I_{th}^{(k)}, \sigma_k^2) & \text{when } H_k \end{cases} \tag{4.10}$$

where $I_{th}^{(k)} < ... < I_{th}^{(1)} < I_{th}^{(0)}$. The PU interference is classified based on mean value of the Gaussian statistic, which changes value in different regions around the PU location. In this case $I_{th}^{(0)}$ is the mean value of PU interference inside the forbidden area, while $I_{th}^{(1)}, I_{th}^{(2)}, ..., I_{th}^{(k)}$ are the mean interference values for different EZs around the PU.

The hypothesis testing is used to find the decision function $\delta(I) \in (1, 2, ..., k)$ such that $\delta(I) = EZ_i$ if the test decides that hypothesis H_i holds when $I = I_{th}^{(i)}$, where I is the PU interference predicted by the propagation model at the test grid. The decision function $\delta(I)$ specifies a k-fold partition $I = \cup_{i=1}^{k} I_{th}^{(i)}$ with $I_{th}^{(i)} \cap I_{th}^{(j)} = \phi$ for $i \neq j$. As the PU interference is distributed normally, the maximum likelihood decision function $\delta(I)$ is given by the following equation.

$$\delta(I) = \arg\ \min(I - I_{th}^{(i)})^T K^{-1} (I - I_{th}^{(i)}) \tag{4.11}$$

where K is the covariance matrix of the gaussian interference functions. The decision function $\delta(I)$ partitions the area around the PU into multiple EZs based on the SU interference thresholds $I_{th}^{(i)}$. It is used to generate a set of all the points $loc_i = (x_i, y_i)$ that are within the boundry of each EZ defined by its corresponding I_{th}.

4.5 Spectrum Utilization Efficiency

We consider a deterministic model for SU distribution outside the PU EZs. The model distributes SUs along a grid with a distance of d between their centers. The goal of the analysis is to estimate the spatial spectrum utilization of the multi-tier EZs. We define spectrum utilization in terms of ASC, which is the summation of channel capacity values of each coexisting SU in its tier within the considered SAS service area. The SU's ASC depends on its spectral efficiency (bps/Hz), the channel bandwidth (W_s) and the number of SU cells in the geographical area.

As the size of EZ is substantial due to the huge discrepency between the PU and SU transmit power levels, the interference from SUs to PU is negligible. In this case, the SUs can use the maximum power level of P_{max} as recommended by the FCC CBS NPRM [8]. So, the maximum transmit power (MTP) function is given by,

$$P_{ts} = P_{max} \quad \text{mWatt} \tag{4.12}$$

From the MTP function, the SU's SINR ρ_s is calculated [51], which determines the secondary achievable data rates.

$$\rho_s = \frac{P_{ts}/L_s(r_{cell})}{n_s W_s + I_{P2S} + I_{S2S}} \tag{4.13}$$

where, $L_s(r_{cell})$ is the path loss between the SU transmitter and receiver in the cell with radius r_{cell}, n_s is the background noise power spectral density at the secondary receiver, W_s is the bandwidth per SU, I_{P2S} is the primary to secondary interference, and I_{S2S} is the secondary to secondary interference.

From the SINR (ρ_s), the achieved capacity by each SU is calculated through the Shannon capacity formula.

$$C_{SU} = W_s log_2(1 + \rho_s) \tag{4.14}$$

The EZs are defined for PA-SU and GAA-SU with parameters given in the Table 5.1. For a given analysis area, N_k represents the total number of SU cells that are within the area defined for the tier-k SUs. Assuming that each cell has a single user, the SU ASC for a single k^{th} tier, C_k, is given by equation (4.15).

$$C_k = W_s \sum_{i=1}^{N_k} log_2(1 + \rho_s(loc_i)), \tag{4.15}$$

where, $\rho_s(loc_i)$ is the SINR at SU location loc_i. The Equation (4.15), takes into account the impact of location dependent interference from PU to SU (I_{P2S}) through the SU SINR ($\rho_s(loc_i)$), as well as the number of SU cells (N_k) operating in the k^{th} tier. The total SU ASC in a given area can be obtained by summing C_k for all k tiers.

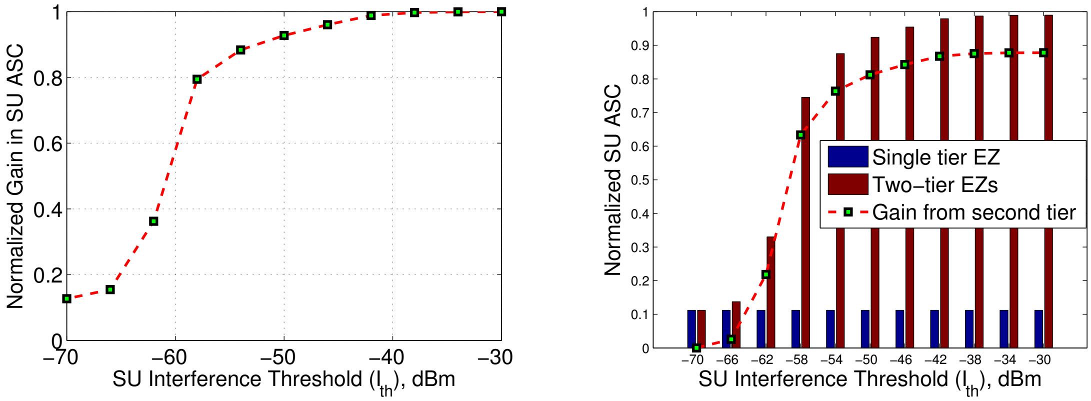
4.6 Simulation Results

In this section, we present the simulation results for EZ computation using ITM area based mode and P2P mode, and compare the SU ASC achieved by them. We also show the resulting gain in total SU ASC when multi-tier EZs are used.

Table 4.1: Sample parameters for simulations

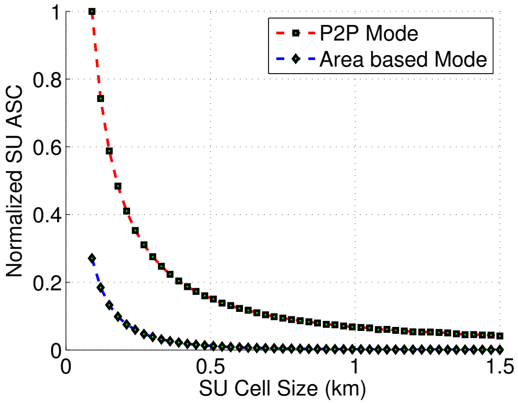
Size of analysis area	$200km \times 200km$
Transmitter Location	(37.4667, -80.4139)
Frequency Channel	3500MHz
Effective Radiated Power	100 kWatt
Antenna Height Above Average Terrain	684m
Omni Directional Antenna	Uniform Radiation
Propagation Model	ITM with Terrain
Terrain detail	SRTM-3 (30m)
GAA-SU	$I_{th}^{(1)}$ = -40 dBm
PA-SU	$I_{th}^{(2)}$ = -70 dBm
Channel bandwidth (W_s)	5MHz

Let us consider a database coverage area with a single PU transmitter at the center. To study the effect of SU I_{th} on the size of EZs, we consider a two-tier SU model. The detailed operating parameters of the PU as well as the two tier SUs are listed in Table 5.1. The database coverage area is divided into $m \times n$ grids/cells depending on the granularity of the terrain database. The interference from PU is calculated using the ITM model for each grid in the area. The ITM is used in P2P mode with terrain profile of the area between the two systems from the SRTM-3 terrain database. For the area based mode, a terrain irregularity factor, Δh, of 90 m is used. The area around the PU is divided into two EZs based on the I_{th}s of the two tiers of SUs. In [66], it is shown that secondary LTE networks can tolerate a vast range of interference from PUs. Based on their analysis, we choose two I_{th} values for the SUs (see Table 5.1). The inner EZ is referred to as tier-3 EZ and outer EZ is referred to as the tier-2 EZ. Tier-3 EZ is based on higher $I_{th}^{(1)}$ of GAA users.



(a) Gain in SU ASC obtained by using P2P mode as compared to the area based mode

(b) ASC of single tier EZ and multi-tier EZs



(c) SU ASC for two different propagation models with different SU cell sizes

Figure 4.3: Performance of the proposed schemes

Figure 4.3(a) shows a significant gain in SUs' ASC when ITM in *P2P mode* is used as compared to the *area based mode*. This gain is a direct consequence of the accurate pathloss computations by the ITM in *P2P mode*. The *P2P mode* takes into account terrain obstructions, which causes diffraction and scattering of signals resulting in higher propagation losses compared to the *area-based mode* which only considers the terrain irregularity factor Δh of the area. Note that the normalized plot is generated by using the SU ASC over the analysis area as a normalizing constant assuming there is no PU and all the area is used by the SUs.

Figure 4.3(b) shows the gain in SU ASC when the SAS uses multi-tier EZs as compared to a single monolithic EZ. For these simulations, we fix tier-3 EZ boundary at $I_{th}^{(2)} = -70$ dBm and vary the tier-2 EZ threshold from $I_{th}^{(2)}$ to $I_{th}^{(1)} = -30$ dBm. We use ITM in P2P mode for this analysis. The gain in SU ASC is recorded for each threshold value. The result is that the total SU ASC starts to saturate as the SU I_{th} is increased. This saturation comes from two major effects. First is that the capacity in the area gained by increasing I_{th} beyond -40 dBm is negligible due to interference from PU to SU, I_{P2S}, which reduces the SINR in Equation (4.15), second is that the gain in the area made at higher I_{th} is smaller compared to the gain made at lower I_{th}.

Figure 4.3(c) shows the effect of SU cell size on the SU ASC for the ITM P2P and the area based modes. For these set of simulations, we consider a single tier EZ defined by $I_{th} = -62$ dBm. It is evident from the figure that SU ASC is increased when small cells are used in combination with a terrain enabled ITM P2P model. Figure 4.3(c) shows another important result: the SU ASC gain from P2P mode is higher for small SU cell size, and it decreases as the SU cell size increases. This is because ASC is directly proportional to the number of cells where each cell reuses the same bandwidth. As the SU cell size decreases, the number of cells that can be packed into a given area increases; hence the result. Terrain features affect the size of EZs, which tends to be greater for flat areas while hilly and mountainous terrains have smaller EZs due to greater propagation losses due to the terrain. Hence, the difference in the SU ASC values calculated from P2P and area-based modes of the propagation model will vary based on the type of terrain being considered in the analysis.

4.7 Conclusion

This chapter explored the concept of multi-tiered EZs. We have shown that the concept of differential spectrum access hierarchy can be implemented for different tiers of SUs by assigning SUs with different interference thresholds to different EZ tiers. In addition, we have provided quantitative results that show the gain in SU's ASC due to employment of P2P terrain profiles in computing EZ boundaries.

Chapter 5

Resource Allocation using Multiantenna Systems for Database Enabled Spectrum Management

5.1 Introduction

This chapter develops a framework for database oriented resource sharing among the secondary users (SUs) based on the primary users' (PU) parameters. This problem has been analyzed in recent literature for (a) protecting the PU from RF interference with (b) improving the operating conditions for SUs. Our work addresses the gap of providing protection to the PU while also maximizing the spectrum opportunities and efficiency of SU access systems by using dynamic MIMO beamforming. We formulate the problem as a constrained beamforming optimization and solve it using Lagrangian duality with subgradient based methods. Furthermore, a parametric model for a Spectrum Access System (SAS) is defined, that has four parameters $-$ interference thresholds (Γ), transmit power (P), aggregate beamformers (V_i), and active SU base stations (B) $-$ that allow configuring the spectrum sharing system to the given scenario. The SAS model allows for developing new innovative solutions for spectrum sharing not only among the primary and secondary users but also among the secondary users. The SAS ensures the trustworthiness in the use of the shared spectrum through MIMO beamformers with interference constraint matrix among all the users in the network. Our results show significant improvement in both the protection of PU as well as enhancing the reliability in QoS for the SUs.

Contributions of this paper are the following.

- A spectrum management framework based on constrained BFs that takes into account both PU as well as SU interference constraints. Using graph theoretic framework an asymptotic covariance matrix is defined that contains the interference constraints based on physical locations of all the users in the network.
- Address the problem of aggregate interference through system level perspective.
- A dynamic SAS model that generates resource allocation policies with regulatory constraints for different adaptation modes of the spectrum sharing system. These policies are in the form of system index (Δ) used for resource allocation. The system index comprises a set of design parameters (Γ_{th}, P, V_i, and B) where the aggregate beamformers V_i can be adapted for different applications and scenarios.
- Application of the SAS model based on constrained BFs for characterization of the sum capacity of the SUs when the operational modes of the PU as well as SUs are changing with time.

This chapter is organized as follows. Section 5.2 outlines the related work on SAS, cooperative beamforming and interference coefficients. Section 5.3 gives the signal model for the downlink transmission in a cooperative multi-cell system, and presents the problem formulation for the sum-rate maximization with the conventional and constrained ZF beamforming. Section 5.4 derives the optimal interference coefficients for both PUs and other SUBSs taking into account the presence of an EZ around the PU. Section 5.5 gives the solution for coordinated BF problem with interference constraints, and characterizes the optimal solution for the cases of asymmetric, symmetric, and dynamic network layouts. Also optimum interference coefficients using optimization of per link coefficients using constraints in Section 5.4 as upper-bounds for sum capacity maximization. Section 5.6 provides numerical examples on the performance of the proposed optimal and suboptimal schemes. Finally, Section 5.7 concludes the paper.

Notations: Lower-case letters are for scalers, bold-face lower-case letters are for vectors, and bold-face upper-case letters denote matrices. For a square matrix $\mathbf{S}$, $\text{Tr}(\mathbf{S})$, $\mid \mathbf{S} \mid$, $\mathbf{S}^{-1}$, and $\mathbf{S}^{1/2}$ are the trace, determinant, inverse, and square root of $\mathbf{S}$, respectively. While for arbitrary size matrix W, W^H, W^T, Rank(W), and $W^\dagger$ denote the conjugate transpose, rank, and pseudo inverse of W, respectively.

5.2 Related Work

5.2.1 Role of the SAS

Most of the existing database enabled spectrum sharing techniques like in the TV whitespace uses a polling based approach for information dissemination. In this approach, each SU must query the SAS -database and receive spectrum allocation in the database response [11] [8]. This query-response technique is called a pull-based approach for the transfer of information from the SAS to a SU initiated by the SU request. In contrast, the information dissemination that involves sending information to a large number of SUs before any specific request is known as push-based approach, since information transfer is initiated by the SAS.

The trade-offs between SAS-push and SU-pull techniques, revolves around the context of the application for which they are used and depends on the costs of initiating the transfer of data. A pull-based approach requires the use of a back channel for each database query. Furthermore, the SAS must be interrupted continuously to deal with such requests and has limited flexibility in scheduling the order of data delivery. Also, the information that the SUs can obtain from a SAS-database is limited to what the SUs have asked for. Thus, new data items or updates to existing data items may go unnoticed at SUs unless they periodically query the SAS-database. A SAS initiated information push avoids the issues identified for the SU-query, but has the problem of deciding which data to send to the SUs in the absence of specific requests.

A solution to this problem is to allow the SUs to provide a set of their operational parameters to the SAS in the initial license/registration [15] [67]. A popular approach for providing such information is through the IETF PAWS protocol [68]. Using this approach the SUs subscribe to given classes of information by providing a set of expressions that describe the parameters of interest. These subscriptions form a profile and are in effect, a continuous query to the SAS-database. Without loss of generality in this paper, the SAS based push approach is used as the profile of the SU parameters are modified based on the requirements of the PU as well as other SUs operating in the same spectrum band.

5.2.2 Cooperative Beamforming for MIMO Systems

Multiantenna based beamforming have previously been used for sharing spectrum bands among the SUs and PUs. Reference [69] proves that BF is optimal for SUs when there is an interference constraint that needs to be maintained for the PUs. In MIMO literature the transmit power and interference temperature constraints are defined as multiple linear transmit covariance constraints [70]. Here the constraint matrix determines if sum power, per antenna transmit power or interference related constraints are used in the sum capacity optimization problem. In [70] [71], the authors consider MIMO-BC and MISO-BC with single and multiple linear transmit covariance constraints and analyze the MIMO MAC and MIMO-BC duality with these constraints. A subgradient based method was used with these constraints for optimizing the beamforming matrices.

5.2.3 Utility of Interference Coefficients

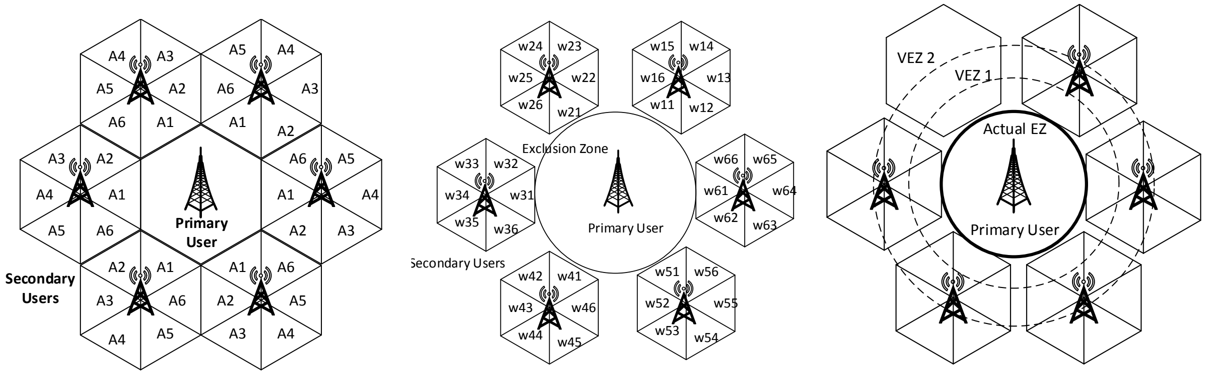
The authors in [72] discuss the maximum interference coefficient among different users for coexistence on the same channel. They prove that FDMA is sum rate optimal when interference coefficint goes beyond a threshold level [73]. Etkin, et. al [74] show how dissimilar systems can coexist in the same spectrum band if their interference coefficients are kept below a certain threshold. The authors consider asymmetries and selfish behaviors when multiple systems coexist and interfere with each other and propose a punishment based mechanism to achieve optimal operating points that ensure fairness among the users.

In this paper, we introduce a new concept of SAS-enabled control of SU resource allocation to ensure interference protection of PU while maximizing SU spectrum utilization. With our model, SAS optimally estimates the interference statistics among the PU-SU and SU-SU links. Based on regulatory interference protection ratios for both the PU as well as SUs and their interference statistics, the SAS generates constrained BFs for all the SU base stations in the network. Our framework offers an enhanced control over the use of shared spectrum. The proposed SAS maintains global statistics of channels and interference among all users and ensures reliability and trustworthiness for the PUs willing to share their spectrum and provides QoS protection for the SUs as well.

5.3 System Model

We consider the primary user (PU) of a frequency band to be a satellite earth station (SES) or a public safety base station as shown in Figure 5.1(a). The diagram shows PU and other secondary user (SU) base stations that are seeking to share spectrum within the PU operational area. Each PU typically updates a policy in a SAS database with any changes in its protected contours and transmit/receive parameters, etc. Similarly, each SU or a cluster of SU base stations are configured to communicate with a SAS for requesting spectrum resources for operation. The SAS comprises of a computational system that evaluates the protected contour of the PU, as well as the characteristics of the SUs to determine the aggregate interference levels to both the PU as well as the SUs. The aggregate interference levels are used by the SAS to determine the allowable transmit power and the BF for the SUs. The SAS maintains the system characteristics of all the SUs and updates them based on the discrete time instances of the PU operational parameters. The SUs operates in accordance with the transmit characteristics provided by the SAS database.

We consider a multibase station MIMO network with a total of A BS each with K users distributed in the cell edge of its coverage region. Each BS has N_t transmit antenna, while N_r antennas at each user. We consider the downlink of the network with the channel between the ith user and the BS writes as H_i, where H_i models the small scale and large-scale fading process accounting for the pathloss and shadowing parameters. We assume that the lth PU in each type of network is equipped with L antennas, $L \geq 1$. These antennas are distributed as sensors in each subspace around the PU. We use the G_{il} to denote the channel from the ith SU to the lth PU, and F_{ij} to denote the channel from the ith SU to the jth SU on the same



(a) Symmetric Network (b) Asymmetric Network (c) Dynamic Network

Figure 5.1: A Multicell MIMO Network with PU and SU Base Stations

channel.

For a system of K SU base stations and end users distributed around them as shown in the Figure 5.1(a), the received signal y_i at a user is given by

$$y_i = h_{ii}^H v_i s_i + \sum_{j=1, j\neq i}^{K} h_{ij}^H v_j s_j + \sum_l h_{il} s_l + n_i^{'} \tag{5.1}$$

where s_i and v_i are the vectors of signals and beamformers at the antenna elements of the ith BS, h_{ii} is the channel from the desired BS to the ith user. The additive noise has a noise power $E[|n_i^{'}|^2] = \sigma_i^2$ and includes the PU signal as an increase in the noise floor of each SU, such that $n_i = n_i^{'} + \sum_l h_{il} s_l$. The first term in (5.1) represents the desired signal and the second term is the sum of interference from $K-1$ undesired transmitters. The achieveable capacity or mutual information with beamformers $v_1, ..., v_K$ for a given set of subspaces $(A_1, ..., A_K)$ around each SUBS is given by

$$C_i(v_1, ..., v_K) = log_2 \left(1 + \frac{|h_{ii}^H v_i|^2}{\sigma_i^2 + \sum_{j\neq i} |h_{ij}^H v_j|^2} \right) \tag{5.2}$$

The sum capacity is the rate of all the SUBS with beamformers given by (5.2) having transmit power constraints P_i. The overall capacity C is the sum of the rate-tuples that can be achieved by all the BS with $C = \sum_{i=1}^{K} (C_i(v_i))$.

For PU-SU network with spectrum sharing, multiple interference constraint are used to protect both the PU as well as other SUs from mutual interference generated by each others transmission [69]. These constraints requires the interference power received at each user from all other users to be below a predefined threshold, known as interference limit Γ. In case of PU, this interference limit is divided among all the SUBS, such that each SUBS can contribute an interference level equal to a leakage factor of $w_l = \Gamma/K$ in the channel subspace towards the PU. We assume that there are L sensors around the primary users in the network and g_{il} represents the channel from the secondary BS to the lth PU. Let G_l be the equivalent channel matrix from the SUBS to the lth PU sensor obtained by stacking all $g_{il}, l = 1, ..., L$, into G_l. Each PU-sensor has an interference power constraint, which can be expressed as

$$g_{il} v_i v_i^H g_{il}^H \leq w_{il}, \;\; i = 1, ..., N, \;\; l = 1, ..., L, \tag{5.3}$$

where Γ_l is the interference-power constraint applied to each PU. Each SUBS has a component of the channel g_{il} towards the PU, where its interference leakage needs to be minimized. The interference leakage w_l of each BS depends on its propagation loss towards the PU, interference threshold Γ_l, and number of SUBS sharing the spectrum band with the PU. The interference power threshold of the PU (Γ) is maintained at the edge of the EZ of the PU. We assume an optimized EZ (5.16) as given in [13], [15], [75] around the PU. The size of this EZ changes based on the parameters of the PU, (i.e., antenna tilting of a satellite earth station) [76]. We therefore discretize the operational states of the PU based on its interference coupling parameters into different states of the system operation. In each of these states there is a different interference threshold $(\Gamma_1, ..., \Gamma_J)$ maintained at the edge of the optimized EZ. This threshold is used as PU interference constraints in designing the aggregate beamformers for all the SUBS operating in the vicinity of the PU. The changing interference threshold of the PU causes a virtual movement of the EZ by changing the interference constraints in the constrained subspaces of the PU [75].

In MISO multicell network, the interference to the undesired receivers of both PU sensor and Su base stations can be completely eliminated by using ZF coordinated beamforming at each SUBS, solving the following optimization problem

$$v_i^* = arg \max_{v_i \in C^N} log \left(1 + \frac{|h_{ii}^H v_i|^2}{\sigma_i^2}\right) \tag{5.4}$$

$$subject\ to\ |g_{il}^H v_i|^2 = 0\ \ \forall l \neq i \tag{5.5}$$

$$|f_{ij}^H v_i|^2 = 0\ \ \forall j \neq i \tag{5.6}$$

$$and\ \ ||v_i||^2 \leq P_i \tag{5.7}$$

The zero-forcing constraint at the ith SUBS for the lth PU sensor and adjacent SUBS are given by $|g_{il}^H v_i|^2 = 0$, and $|f_{ij}^H v_i|^2 = 0$. ZF is a conceptually ideal BF and due to presence of certain noise level at each receiver [77]. With signal fading through propagation effects, a leakage level of w_{li} can be allowed for better system performance [78]. So the constraints (5.4) can be written as

$$|g_{il}^H v_i|^2 \leq w_{il}\sigma_l^2 \quad \forall i, l \neq i \tag{5.8}$$

$$|f_{ij}^H v_i|^2 \leq w_{ij}\sigma_j^2 \quad \forall i, j \neq i \tag{5.9}$$

where $(w_{il} \geq 0, w_{ij} \geq 0)$ are constants that controls the allowed level of interference leakage from the ith SUBS to the lth PU sensor and jth adjacent SUBS relative to their thermal noise level σ_l^2 and σ_j^2 [79].

Based on the channel definitions and interference constraints, we define a set of transmit covariance matrix optimization problems [78], each for one of the K BSs in the MISO-IC expressed as

$$\max_{S_i} \log \left(1 + \frac{h_{ii}^H S_i h_{ii}}{\sum_{i \neq j} h_{ij}^H S_j h_{ij} + \sigma_j^2}\right) \tag{5.10}$$

$$g_{il}^H S_i g_{il} \leq w_{il}, \forall l \neq i \tag{5.11}$$

$$f_{ij}^H S_i f_{ij} \leq w_{ij}, \forall j \neq i \tag{5.12}$$

$$Tr(S_i) \leq P_i,\ S_i \geq 0 \tag{5.13}$$

where $i \in 1, ..., K$, and the above problem for a given Γ_l and Γ_j is fixed with an optimal value of $C_i(S_i)$.

The transmit covariance matrix is defined as $S_i = v_i^H v_i$. The interference-temperatures Γ_l and Γ_j in the above problem are intended to protect the PU as well as the SU from their mutual interference given by $\Gamma_l = g_{il}^H S_i g_{il} \ \ \forall l \neq i$ and $\Gamma_j = f_{ij}^H S_i f_{ij} \ \ \forall j \neq i$.

5.4 Interference Relaxation Parameters

The system policies Δ_i defines the threshold interference level in the protected region, maximum level of transmit power, available frequencies, etc. The acceptable interference levels can be computed by the interference coupling between the PU and other SUBS. The interference coupling is based on spatial layout of the BS and signal propagation characteristics. The aggregate interference levels from multiple BS need to be considered when designing the transmit BFs. The interference coupling among a set of BS with end users distributed in each subspace is shown in Figure 5.1(a). It can be modeled by a directed graph [80], where each BS is represented by a node. The nodes are connected by directed edges which are given by the positive entries of the link gain matrix H (if $H_{il} > 0$). The spectrum sharing graph is strongly connected, if for each pair of nodes [80] there is a sequence of directed edges leading from ith to jth BS. A connected graph is mathematically expressed by the notion of irreducibility which requires at least one node to be interfering with every other node.

5.4.1 Interference Graph

In the spectrum sharing model, Figure 5.1(a),5.1(b), 5.1(c), all the interfering links do not effect the desired user performance. Dominant interfering links with small pathloss and shadowing contribute to high interference while other interfering BSs that are further apart with higher propagation losses do not cause any interference to the desired users. So the CSI of the dominant interfering links should be used in the BF design algorithm. The constraints for the BF matrices only considers dominant interferers for each SUBS by generating clusters of BS with effective interference to the desired SUBS. The set of cells that have interference effect on a desired i th user whose serving cell i is defined as

$$M_i = \left(j \mid \frac{H_{ii}P_i}{H_{ij}P_j} \leq \Xi \right) \tag{5.14}$$

The clustering equation depends on the threshold parameter (Ξ), transmit power constraint (P_s) and channel statistics. A PU system with higher interference sensitivity uses a larger threshold parameter (Ξ). This results in a bigger interference cluster of BSs and systems with more interference tolerance have smaller (Ξ) with few BSs in the interference cluster.

We consider the system as interference coupled if the Ξ is above threshold Ξ_{th}. In this case the $D_I(\Xi) = 1$ for a given transmit/receive pairs

$$D_I(\Xi) = \begin{cases} 1 & I_k(\Xi) > 0 \\ 0 & otherwise \end{cases} \tag{5.15}$$

where the matrix D is called the dependency matrix. The non-zero entries in the matrix D mark the transmit/receive pairs, which are coupled by interference. A zero-entry means no interference is received. We assume D to be an irreducible matrix, which implies that each BS is interfered by atleast one other BS. Irreducibility of D is equivalent to strong connectivity of the graph $G(D)$, where $G(D)$ is defined to be the directed graph of K BSs, in which there is a direct edge leading from BS $i \in K$ to $j \in K$ if and only if $D_{j,i} > 0$. Now the dependency set $L_i = \{j \in K | [D]_{j,i} = 1\}$ for the ith BS is the set of users that are connected to the jth BS in the interference graph. They are the set of transmitters which have an impact on the kth BS. For a hexagonal layout of the Figure 5.1(a) 5.1(b) the dependency set is the set of subspaces $A_1, A_2, ..., A_k$, one towards each edge of the SU cell. These subspaces are divided into constrained PU and SU along with unconstrained (U) subspaces $A_1^{(PU)} A_2^{(SU)} A_3^{(U)} A_4^{(U)} A_5^{(U)} A_6^{(SU)}$.

5.4.2 Effect of PU Exclusion Zone

The interference coefficients in the PU subspaces are calculated through the regulatory protection ratios that need to be maintained at the edge of the exclusion zone of the PU. Most of the existing analysis assume a single emitter analysis model (SEAM) for estimation of interference and allowable transmit power levels at the boundary of the EZs of the PUs [3] [81]. These models do not consider varying channel conditions and interference aggregation effects due to multiple SUs in different directions. In this paper we extend the single emitter analysis model to multiple emitter analysis model (MEAM) by incorporating the interference aggregation effects due to multiple users from different directions. A MEAM is more conservative and hence more protective for the PU due to division of the interference threshold among the multiple subspaces of the SUBS. In this paper we only consider the aggregate interference effects with similar channel conditions using a propagation model for computation of the EZ of the PU [76]. The size of this EZ is given by (5.16), where P_t is the transmit power of the PU, G_r is the antenna gain of the PU receiver, P_r is the minimum detectable received power at the PU receiver, and h_t/h_r are the transmitter and receiver antenna heights. We use this technique for the EZ computation based on the concept of bi-directional interference between PU and SU.

$$\log(d) \quad = \quad \frac{P_t + G_r - P_r - 26.16\log(f) + 13.82\log(h_t) + 1.1log(f) - 0.7)h_r - (15.6\log(f) - 0.8)}{44.9 - 6.55\log(h_t)} \tag{5.16}$$

Generally, interference is bi-directional due to reciprocity of the wireless channel. So the quantity of interference that the PU is causing to the SU (P_r), the same quantity can be caused by the SU to the PU [3]. So if there is a regulatory interference threshold that needs to be maintained for the PU protection, that threshold is equally divided among all the SU base stations subspaces that are pointing towards the PU. In this way the aggregate interference from the SUs is maintained below the PU protection ratio [82]. The interference coefficients in the PU subspaces can be mathematically calculated using the following equation

$$w_k^{(PU)} = \min_{1 \leq k \leq K} \frac{I_{th}^{max}/K}{L_k} \tag{5.17}$$

where I_{th}^{max} is the interference threshold of the PU that is equally divided into K parts and L_k is the propagation loss of the SU from the interference measurement point. This framework allows for an optimized EZ as the total interference threshold Γ_l of the PU is divided among all the subspaces of the SUBS that are pointing towards the PU. In this way the effective $\Gamma_{th}^{(e)} = \Gamma_l/K$ which is smaller that the total Γ_{th} allows for an extra layer of protection from the aggregate interference of the SUs [69].

5.4.3 Asymptotic Covariance Matrix

The utility function for the SUs in this case strongly depends on the interference coupling among these BS. Utility of SU depends on the interference function $I_k(v)$, which gives the interference power experienced by the kth SU, from the transmission of other SUs and the PU. With K-SUs simultaneously transmitting on the same channel, the interference power at the K-th SU can be written as

$$I_k(v) = \sum_{k \neq i} h_{ik}^H v_k^H v_k h_{ik} + \sigma_i^2, \tag{5.18}$$

where the coupling coefficient of interference among the SUs is given by $w_{ik} = h_{ik}^H v_k^H v_k h_{ik}$. For the linear interference model with transmit powers p, the interference in the system is determined by the $K \times K$ coupling matrix $W = [w_1, w_2, ..., w_K]^T$. Here by w_k we denote the coefficient vector associated with kth user and all coefficients are collected in a matrix W, with $\sum_i w_{ik} = \Gamma \ \ \forall k \in K$. In this paper we define the matrix W as the asymptotic covariance matrix (ACM) of interference coupling among all the users in the network.The W is maintained by the SAS with channel and interference statistics of all the users.

Now consider the multiple sets of subspaces $A_1, A_2, ..., A_k$, defined based on the dependency sets of each BS. The vector of interference coefficients of each SUBS in Figure5.1(a) is given by

$$w_k = \left[w_{11}^{(PU)} w_{12}^{(SU)} w_{13}^{(U)} w_{14}^{(U)} w_{15}^{(U)} w_{16}^{(SU)} \right]^T \tag{5.19}$$

The above vector of interference coefficients is for a single SUBS with $w_{li}^{(PU)}$ and $w_{ij}^{(SU)}$ as the interference coefficients towards the constrained PU and SUs, while $w_{ij}^{(U)}$ are the interference coefficients for the unconstrained subspaces. The threshold values of each subspace is at its lowest value to maintain target interference limits [79]. It is given by .

$$w_{ij}^{(SU)} = \frac{\| h_{ij}^H h_{ii} \|^2 \ P_i}{\| h_{ii} \|^2} \tag{5.20}$$

and corresponds to the case of using maximum transmit power with MRT beamforming for the ith SUBS. For ZF BFs the SUBSs have to satisfy the constraints (5.4), i.e., no interference towards the PU subspace. In this case the interference coefficients ($w_{li}^{(PU)} = \sigma_l^2$) have only noise terms.

5.5 Coordinated Beamformers

As mentioned earlier, each SUBS or clusters of SUBSs are configured to communicate with the SAS for receiving updates on spectrum resources for operation. These BSs send their long term channel statistics to the SAS. Based on the channel statistics the SAS generates coordinated beamformers by defining an optimization problem which is solved through lagrangian dual functions. The lagrangian function properly weights each subspace around a SUBS through its interference constraints in the ACM. The lagrangian weights allows the SAS to generate transmit power allocation for the precoding matices of each BS through waterfilling technique. The SAS then sends the precoding matrices, allocated transmit power, indices of coordinating BS and the selected subspaces for transmission. Subspace selection is based on the allowable transmit power and channel characteristics by using a prioritized eigen-mode beamforming.

For a coordinated multicell system, the S_k depends on the interference constraints defined in the ACM (5.30). The objective function is to optimize the S_k for the overall network sum capacity.

$$\max_{S_k \geq 0, \forall k} U(S_1, S_2, ..., S_K) \tag{5.21}$$

$$\sum_{k=1}^{K} Tr(S_k) \leq P \tag{5.22}$$

$$\sum_{l=1}^{L} Tr\left(G_{kl} S_k G_{kl}^H\right) \leq \Gamma \tag{5.23}$$

where S_k is the transmit covariance matrix of the k^{th} SUBS, and $\Gamma = \sum_{l=1}^{L} w_{kl}$ is the aggregate interference temperature constraint to limit the total interference power from the K-SUBS.

The SAS uses the local channel statistics H of the SUBS and uses the coordinated BF design technique. In this technique, the S of all the SUs are designed using an iterative technique, which requires the SAS to have complete channel statistics of all the SU operating in the proximity of the PU. The S_i of one BS in (5.21) depends on the other BS S_k $k = 1, 2, ..., K$ due to interefernce coefficients in the asymptotic covariance matrix W. The algorithm designs the S_k of one SU based on local channel statistics and interference constraints while keeping all the other BSs constant. We compare this technique with BFs that are independently generated by the SU without requiring the existence of a spectrum manager providing the interference constraints for W. Based on the interference coefficients in the ACM (W), the SAS designs the BFs for all the BS in the network. These BFs depends on the behavior of the network interference which is defined in the interference coefficients. These interference coefficients needs to be optimized to reduce interference and enhance the network sum capacity.

The constrained optimization problem in (5.21) is solved through projected gradient with ellipsoidal method using a control sequence on the constrain set of the optimization problem. The control sequence prioritizes the different subspaces of the beam design algorithm into PU and other SU subspaces. The control sequence is useful in dynamic scenarios with varying PU parameters or mobile PUs where the constrained subspace changes over time and the corresponding BFs are optimized for discrete system states. We define a control sequence $\omega_i, i = 0, 1, ..., K$ as a sequence of indices according to which individual sets ω_i are chosen for the execution of the iterative power allocation algorithm. The control sequence in this case represents the optimal partitioning of subspaces into PU and other SU subspaces with their interference relaxation parameters. The permutation sequence of subspaces can be different or the same based on the location of the BS relative to the PU.

When the SUBSs feedback their local channel statistics, SAS combines the channel statistics with the interference constraints defined in the ACM and generates the lagrangian dual function of the optimization problem (5.21).

$$\min_{\nu \geq 0, \delta \geq 0} d(\nu, \delta) \tag{5.24}$$

where ν and δ denotes a vector of dual variables for the (5.21) with ν associated with the transmit power constraint, and δ_l associated with the interference constraints for $l = 1, 2, ..., L$. The dual function is defined as follows

$$d(\nu,\delta) = \max_{S\geq 0} U(S) - \nu(Tr(S) - P) - \sum_{l=1}^{L} \delta_l (Tr(G_l S G_l^H) - \Gamma_l) \tag{5.25}$$

where $U(S) = \log det\left(I + HSH^H\right)$ and since (5.21) is convex with no duality gap between the (5.21) and (5.25) as explained in [69]. The parameters ν and δ weights the different subspaces based on their interference constraints. Now with the lagrangian dual function, SAS redefines the optimization problem as

$$\max_{S\geq 0} \log det\left(I + \frac{HSH^H}{\sum_{j\neq k}\Gamma_{jk} + \sigma_k^2}\right) - Tr(TS) \tag{5.26}$$

where the noise covariance matrix $T = \nu I + \sum_{l=1}^{L} \delta_l (G_l^H G_l)$ and $T \geq 0$ is a constant matrix for a given (ν, δ). The transmit power (ν) and interference weights (δ) depends on the spatial layout of the SU network. The matrix T in this case is defined as the spatial weighting matrix for transmit power allocation. In order for the above problem to have a bounded objective value the interference graph should be fully connected. Based on structure of the matrix T, the following cases can be defined for the multibase station network.

5.5.1 Asymmetric Network

This case corresponds to a large scale PU like a satellite earth station or a TV station. In this scenario the distance statistics among the PU-SU link and the SU-SU link are considerably different. These statistics generates different signal propagation effects with channel gain regions of H_{ii}, H_{ij} and G_{ik} denoted by $g_{ii}^{(s_1)}$, $g_{ij}^{(s_2)}$, and $g_{ik}^{(s_2)}$. These channel regions determine the interference coefficients (w_k) in W which are asymmetric due to different channel gains and interference tolerance levels.

In this case a SUBS does not cause interference to all of its neighbors. The weighting matrix T is rank-deficient since the interference graph is not fully connected. The optimal transmit covariance matrix is defined as $S_k = q_k v_k v_k^H$ with $q_k > 0$ and $v_k \in C^{M_k \times 1}$ and satisfies $\parallel v_k \parallel = 1$ and $Tv_k = 0$. The objective value of the problem becomes

$$\log\left(1 + \frac{q_k \parallel h_{kk}^H v_k \parallel^2}{\sum_{j\neq k}\Gamma_{jk} + \sigma_k^2}\right) \tag{5.27}$$

This problem is solved through standard waterfilling solution. The SAS in this case prioritizes the eigen-modes $(\lambda_1, \lambda_2, ..., \lambda_K)$ based on the control sequence ω_i of the constrained PU and SU subspaces. The subspace that generates the minimum interference to both PU and other SUBSs is selected for transmission. The optimal beamformers for the problem (5.27) is given by

$$v_k = \varphi^{'} \left(\frac{1}{ln2} - \frac{\sum_{j \neq k} \Gamma_{jk} + \sigma_k^2}{\psi^{'}} \right) \tag{5.28}$$

with the $\varphi^{'}$ and $\psi^{'}$ given by (5.48) and (5.49), respectively. The joint BFs are based on closed form solution with different Lagrangian multipliers in each subspace.

5.5.2 Symmetric Network

This case corresponds to a small scale PU like a public safety base station, where both the PU and SUs have similar system characteristics (as shown in the Figure 5.1(a)). The channel gain regions for the three channels are almost the same due to similar distance statistics. The channel states of H_{ii}, H_{ij} and G_{ik} are denoted by $g_{ii}^{(s_1)}$, $g_{ij}^{(s_1)}$, and $g_{ik}^{(s_1)}$. The interference coefficients (w_k) in the three subspaces are asymmetric with extremely low $\Gamma_{th}^{(PU)}$, while relatively moderate $\Gamma_{th}^{(SU)}$ in the SU subspaces and $\Gamma_{th}^{(Un)}$ in the unconstrained subspaces. The sum capacity optimization in this case is a convex function where both PU as well as SU interference constraints are effective. The SAS uses the gradient projection algorithm along with the closed form solution based technique to generate BFs for all the SUBSs in the network. The threshold parameter for SUBS clustering (Ξ) is maintained at a value such that only the first tier of users are selected in the interference graph. In this case the interference graph is irreducible and the joint BFs for the SUBS achieves pareto optimality as mentioned in [80].

When the network is symmetric then its interference graph is irreducible and by the KKT optimality conditions the weighting matrix T is of full rank with either the transmit power or the interference temperature constraints tight for the constrained and unconstrained subspaces. When the transmit power constraint of the k^{th} SUBS is tight, then the corresponding lagrangian multiplier is $\nu > 0$. When the transmit power constraints are loose, $\nu = 0$, but the interference temperature constraints are tight in atleast $M_k \delta_{kj} \;\; j \neq k$ with $\delta_{kj} > 0$. In this case the ZF constraints $M_k \leq k - 1$ must be satisfied and (i) $\delta_{kj}^{(PU)} > 0$ is tight when the $w_l^{(PU)} > 0$, (ii) $\delta_{kj}^{(SU)} > 0$ is tight when the $w_j^{(SU)} > 0$, and (iii) $\delta_{kj}^{(U)} = 0$ is loose and the maximum transmit power can be used in this subspace. The SAS in this case prioritizes the eigen-modes $(\lambda_1, \lambda_2, ..., \lambda_K)$ based on the control sequence ω_i of the constrained PU and SU subspaces. The subspace that generates the minimum interference is selected for transmission.

The optimal beamformers for the problem (5.26) in the constrained and unconstrained subspaces is given by

$$v_k = \varphi \left(\frac{1}{ln2} - \frac{\sum_{j \neq k} \Gamma_{jk} + \sigma_k^2}{\psi} \right) \tag{5.29}$$

with the φ and ψ given by (5.45) and (5.46), respectively

5.5.3 Dynamic Network

In the adaptive BF framework, at time instant t_0, the PU EZ is in state EZ_0 for a PU interference tolerance level of $\Gamma_{th}^{(PU)}$ and SU interference tolerance of $\Gamma_{th}^{(SU)}$. Based on both PU and SU interference thresholds, the joint BFs for the whole system are denoted as V_0 and given by (5.10). With the state instance of $S_1, S_2, ..., S_J$, the virtual EZ of PU moves from state $VEZ_1, VEZ_2, ..., VEZ_J$ with the change in interference threshold denoted by parameter x in $\Gamma_{th}^{(PU)}$. Also the change in SU interference threshold $\Gamma_{th}^{(SU)}$ is denoted by parameter y. In this case the boundary of the actual EZ remains fixed but only the interference threshold of the SUBS changes for the design of the BF matrices. In this case the SAS for each system state $S_1, ..., S_J$

generates $W_1, ..., W_J$ for the joint BFs $V_1, ..., V_J$.

$$W = \begin{pmatrix} w_{11}+x & w_{12}+y & w_{13} & w_{14} & w_{15} & w_{16}+y \\ w_{21}+x & w_{22}+y & w_{23} & w_{24} & w_{25} & w_{26}+y \\ w_{31}+x & w_{32}+y & w_{33} & w_{34} & w_{35} & w_{36}+y \\ w_{41}+x & w_{42}+y & w_{43} & w_{44} & w_{45} & w_{46}+y \\ w_{51}+x & w_{52}+y & w_{53} & w_{54} & w_{55} & w_{56}+y \\ w_{61}+x & w_{62}+y & w_{63} & w_{64} & w_{65} & w_{66}+y \end{pmatrix} \tag{5.30}$$

A dynamic network is evaluated in which the two constraints sets changes with time and the BFs for the SU base stations are designed for J discrete time intervals. It is assumed that in each of these intervals the SAS knows channel statistics of all the users in the network. The beamformer design to maximize the sum capacity of the SU network is formulated as follows

$$\max_{S_k(j)\geq 0, \forall k,j} C(S_k(j)) \tag{5.31}$$

$$\sum_{k=1}^{K} Tr(S_k(j)) \leq P_k \tag{5.32}$$

$$\sum_{l=1}^{L} Tr\left(G_{kl}(j)S_k(j)G_{kl}^H(j)\right) \leq \Gamma_l(j) \tag{5.33}$$

where Γ_j denotes the average interference power constraint for the lth PU to limit the total interference power from the K SUs, which is averaged over the J discrete time intervals. Where $S_k(j)$ denotes the set of transmit covariance matrices for the $k = 1, 2, ..., K$ SUBS for the state instants of $j = 1, 2, ..., J$ maximizing the sum capacity utility function $C(S_k(j))$. We assume that the utility function $C(S_k(j))$ is separable over each discrete time instant j,

$$C(S_k(j)) = U_j(S_1(j), ..., S_k(j)) \tag{5.34}$$

with U_j denoting the individual utility function in the jth time interval. This problem can be solved using the lagrangian dual decomposition technique.

As the transmit power and interference constraints in the J discrete time intervals involve the transmit covariance matrices $S_k(j)$. The lagrangian dual decomposition method for optimization over the K parallel dimensions requires dual variables, ν_k's and δ_k's for each transmit power and interference constraint respectively. The lagrangian optimization problem can be written as (5.35). The dual problem can be efficiently solved by the ellipsoidal method using the subgradients of the dual function $d(\nu, \delta)$. The above problem can be solved for any given set of ν and δ. It is interesting to observe that this maximization problem can be decomposed into J parallel subproblems having the same structure and solvable by using the same algorithm using the dual decomposition method.

So each subproblem can be written as

$$\max_{S_k \geq 0, \forall k} U(S_1, ..., S_k) - \sum_{k=1}^{K} Tr\left(B_k(\nu, \delta) S_k\right) \tag{5.35}$$

where $B_k(\nu_k, \delta) = \nu_k I + \sum_{l=1}^{L} \delta_l G_{kl}^H G_{kl}$ is a constant matrix for the given ν and δ, $k = 1, 2, ..., K$. In this case the S_k is time variant with changing interference constraints with each system state. In each system state, SAS selects the subspace for transmission based on joint weighting from both the lagrangian multipliers as well as the control sequence ω_i for PU and SU constrained subspaces.

The beamformers are in the form of a vector $V = v_k^{(1)}, v_k^{(2)}, ..., v_k^{(N)}$ with N as the number of states of the multibase station network.

$$v_k^{(n)} = \varphi^{(n)} \left(\frac{1}{ln2} - \frac{\sum_{j \neq k} \Gamma_{jk}^{(n)} + \sigma_k^2}{\psi^{(n)}} \right) \tag{5.36}$$

with the φ and ψ given by (5.45) and (5.46), respectively

5.5.4 Network Capacity Optimization

The interference coupling matrices used for the BF design in (5.10) depends on the interference coefficients in the asymptotic covariance matrix (W). For each system state the SAS generates a new W based on the new PU and SU interference constraints. For each SU as well as for the PU, W divides the sets of subspaces with one interference coefficient ($w_{lk}^{(C)}$) and another set of subspaces with another interference coefficient ($w_{ik}^{(UC)}$). It carries the interference coeffcients defined for a specific transmit power threshold and is used for the low and high interference scenarios as depicted in the Figure 5.1(a),5.1(b).

Now consider the interference relaxation parameter w_{ij} as the design variable. A centralized approach is developed to determine w_{ji} with the aim of maximizing the achievable rate tuple. We consider an iterative algorithm for updating the interference relaxation parameter to achieve an optimal sum capacity of the following optimization problem.

$$\max_{S_k \geq 0, \forall k} U(S_1, S_2, ..., S_K) \tag{5.37}$$

$$W_l^{(L)} \leq \sum_{l=1}^{L} Tr\left(h_{kl} S_k h_{kl}^H\right) \leq W_l^{(U)} \tag{5.38}$$

$$\sum_{k=1}^{K} Tr(S_k) \leq P \tag{5.39}$$

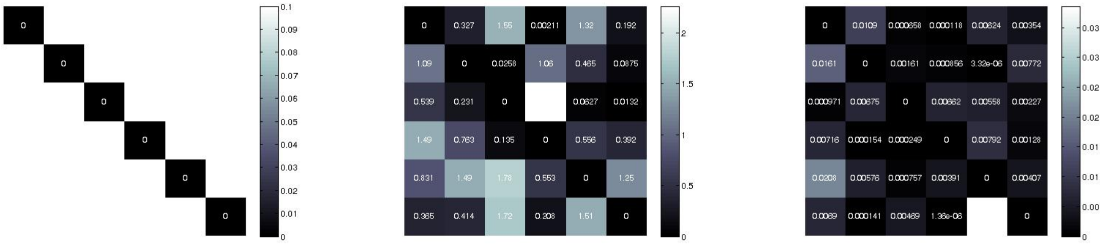
where $U(S_1, S_2, ..., S_K)$ is the desired utility function for the sum rate of the multi-base station network, with $W_l^{(L)}$ and $W_l^{(U)}$ as the lower and upper bounds on the interference constraints in the ACM. The optimization can be solved by an alternating technique, i.e., we fix all other w_{ij} except one interference relaxation parameter and update the next w_{ij} is picked for update, the process continues untill all parameters are updated.

For a given utility function $U(S_1, S_2, ..., S_K)$, the RZF beam vectors v_i can be obtained as functions of w_{ij} by the beam-design technique and the achievable capacity can be computed as a function of v_i and finally the utility function value can be computed as a function of $U(S_1, S_2, ..., S_K)$. Thus the utility value as a function of w_{ij} can be computed very efficiently by the centralized algorithm. The algorithm makes its easier to apply a numerical optimization method such as interior point method to the per-iteration optimization.

5.6 Simulation Results

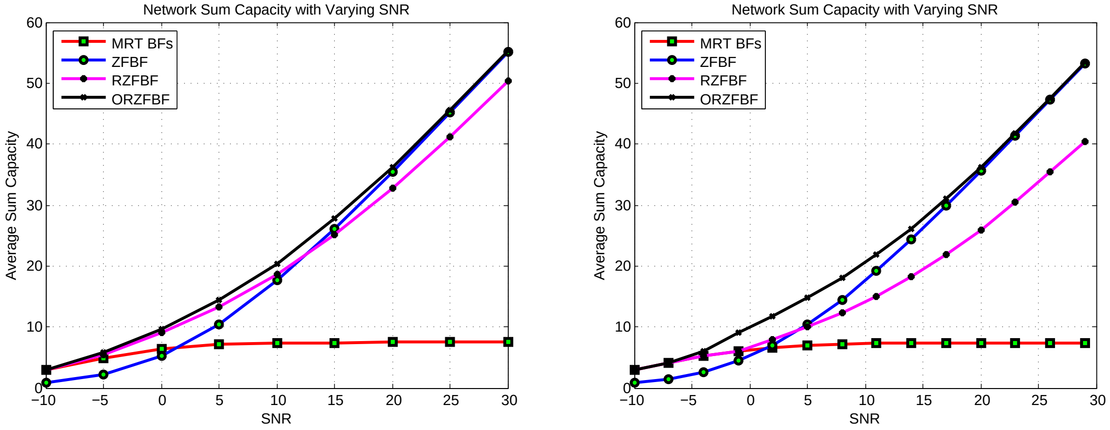
A multicell MIMO network is defined with PU and other SUBSs as shown in Figure 5.1. Figure 5.2(a), 5.2(b) and 5.2(c) show the heatmaps of the interference coefficients in the symmetric network, asymmetric network, and the optimal interference coefficient obtained through the network optimization function (5.37). In the symmetric network the interference coefficients are the same among the neighboring SUBSs due to similar channel conditions as well as the interference thresholds and similar system characteristics for both the PU and SUs. In the asymmetric case the channel conditions, interference thresholds and type of systems for the PU and SUs are considerably different. Hence the interference coefficients are different among the different subspaces for the same base station (row in the ACM). These two cases represents the maximum interference coefficients given by (5.17) and (5.20). Figure 5.2(c) gives the interference coefficients when each link in the ACM matrix is optimized for the sum capacity using (5.20) as the upper bounds. Elements in the ACM are considerably smaller in 5.2(c) w.r.t to 5.2(b) because of the optimization technique.

Figure 5.3(a) and 5.3(b) show the average spectral efficiency of different beamforming techniques for the symmetric and asymmetric networks for different SNR levels. Figure 5.3(a) shows that both the RZF and ORZF are better than MRT and ZF beamformers at low SNRs whereas ZFBF approaches the two in the high SNR region. Because of the similar channel characteristics (channel rank) in the symmetric network, the slopes of the sum capacity curves are almost the same with minimal differences in the spectral efficiency curves. In the asymmetric network case ORZF is good at both low and high SNRs. RZF is better than ZF at low SNR but worse than ZF at higher SNR. The 3dB improvement in spectral efficiency among the BFs is considerably larger then the symmetric case for the channel conditions among the PU and SUs.



(a) Symmetric Interference coefficients (b) Asymmetric Interference coefficients (c) Optimal Interference coefficients

Figure 5.2: Intensity of Interference Coefficients



(a) Symmetric Network

(b) Asymmetric Network

Figure 5.3: Sum Capacity of Coordinated/Uncoordinated BFs in Spectrum Sharing

5.6.1 Dynamic Networks

For a SUBS deployment model of Figure 5.1(c), the SAS defines N system states for the spectrum sharing system. These states are divided into static and dynamic states. In the static state (as shown in Figure 5.1(a) and 5.1(b)) a fixed point operation is defined with BFs that remain the same for a longer period of time. This state does not take into account any variations in the interference environment between the PU and SUs [13]. While in the dynamic states the SAS takes into account any changes in PU parameters (i.e., antenna tilting of a satellite earth station) [15] or SU parameters like cell sizes, etc. In this case the system operates in J different states. With a similar coordinated BF optimization problem (5.31) in each system state and a different ACM of the system. The ACM is based on interference coefficients with maximum interference threshold used for deriving the matrix. An optimization function (5.37) is used for optimum values of the ACM with optimum defined either based on maximum sum capacity or minimum network interference among the users. This technique iteratively updates the parameters for optimization of each link while keeping all other links constant. The optimization function maximizes the capacity of each link which also minimizes the interference coefficients as well. This optimum matrix generates the ORZF beamformer with the maximum sum capacity among all the techniques in Figure 5.3, 5.4 and 5.5.

For a multi-state system, the SAS dynamically adapts the interference limits Γ_j $(j = 1, 2, ..., J)$ of each

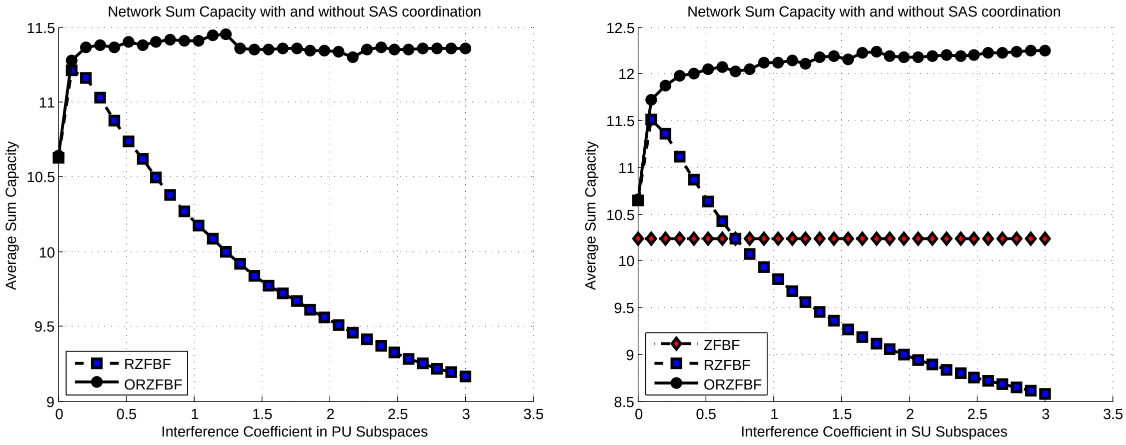


Figure 5.4: Performance of the beamforming techniques in network congestion

system state based on the analytical model developed in section 5.5.3 5.5.4, that relates to the estimated change in interference function and interference coefficients. For a given change in PU interference function, the interference limits Γ_j are set in each time interval $t_j \quad j = 1, 2, ..., J$ such as to maintain interference coefficients of all the SU below their threshold values. The threshold values of each subspace is at its lowest value to maintain target interference limits.

The SAS makes Δ selection based on their interference levels in the matrix W. The SAS selects the control parameter Δ based on interference-limits at PU and SU base stations. The adjustment of the interference control is based on discrete states of parameters for both PU and SUs. Using interference at different users, the control parameter is quantized into $\Delta_1, \Delta_2, ..., \Delta_J$, based on N different combinations of PU and SUs interference levels in the ACM W. The J-adaptation control modes $(\Delta_1, \Delta_2, ..., \Delta_J)$ are defined based on interference limits. Δ_1 is the pure adaptation mode for any change in the SUs interference levels, while that of Δ_2 is the adaptation mode for any change in the PUs interference levels. While all other Δ_k (for $k \geq 3$) are mixed PU and SU adaptation modes. The SAS selects the adaptation control mode based on the current interference levels in the matrix W.

The analysis in Figure 5.4, uses interference coefficients with a multiplication factor for increasing the coefficients of a uniform ACM for the network. This case shows that as the interference in the network is increasing ZF sum capacity remains the same but that of RZF starts to gradually decrease due to more interference in the network. But the ORZF keeps on increasing due to optimization of the ACM for minimum interference and maximum sum capacity of the network.

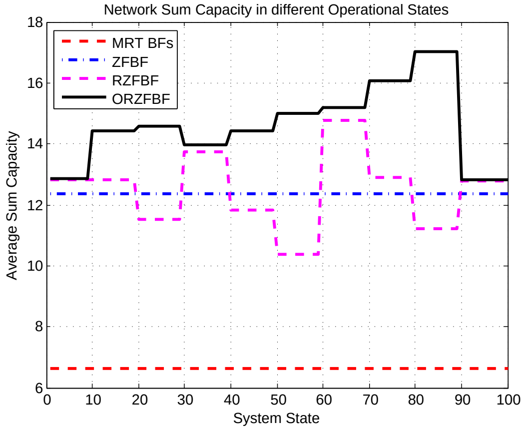


Figure 5.5: Sum Capacity in different System Operational States

The same behavior (as in Figure 5.4) is observed in Figure 5.5 when either the parameters of PUs are changing or those of the SUs are changing or both are changing at the same time (5.30). With change in those parameters the sum capacity of the network changes in each system state. In this case the performance of the ORZF is the best among all the BFs as SAS in this case uses the optimum ACM for the SUBSs.

5.7 Conclusions

In this paper, we have studied a SAS enabled control of the optimal beamforming techniques that enhance the spectrum utilization for the SUs while ensuring reliable interference protection for the PUs of a spectrum band. Our analysis and simulation results show that the ZFBF with interference coefficients is sum rate optimum while maintaining the interference protection ratios for the PUs of a spectrum band. We solve the optimal BFs for a static layout of SUs around the PU through Lagrangian dual decomposition method with ellipsoidal updates. Then we extend the problem to a dynamic network case where the interference constraints in distinct subspaces' changes with time. A discrete system model is proposed with four system design parameters to allow the spectrum sharing system to adopt to different scenarios while maintaining the PU interference protection constraints. Multiple scenarios are defined based on SU layout and factors

Table 5.1: Parameters for Analysis and Simulations

Number of SUBS	6
Number of PUs	1
Channel bandwidth	5MHz
Interference graph Ξ	First tier
transmit power SUBSs	-10 to 30dBm
$w_{il}^{(PU)}$ $w_{ij}^{(SU)}$	3, 0 3, 0
t_j for System State (Δ_j)	10
Step Sizes (x) of $w_{il}^{(PU)}$	0.0003,1,3
Step Sizes of (y) $w_{il}^{(SU)}$	0.01,1,3
initial Lagrangian multipliers	0.1
tol for Lagrangian multipliers	10^{-7}
Noise Variance	1
w_{ij}^{max}	3
w_{ij}^{min}	0.001
type of beamformers	Prioritized eigen-mode beamforming
Intra-cell/Intercell propagation parameter	Rayleighfading

affecting both sum rate capacity and network interference are evaluated through numerical simulations. The results show superior performance of ORZFBFs for both sum rate as well as interference protection in all layouts of the network.

Appendix A

In order to solve (5.26), we introduce an auxiliary variable $\tilde{S} = T^{1/2}ST^{1/2}$. We can express (5.25) in terms of the auxiliary variable $\tilde{S}$ as follows

$$\max_{\tilde{S}\geq 0} \log det \left(I + \frac{HT^{-1/2}\tilde{S}T^{-1/2}H^H}{\sum_{j\neq k}\Gamma_{jk} + \sigma_k^2} \right) - Tr(\tilde{S}) \tag{5.40}$$

The above problem can be shown equivalent to the standard multiantenna capacity optimization problem with a single sum-power constraint. Its solution can be expressed as the eigen-value decomposition given as: $\tilde{S}_k^* = V_k \Theta_k V_k^H$, where $v_k = v_{k_1}, ..., v_{k_M} \in C^{M_k \times M_k}$ is unitary and $\Theta_k = Diag([\theta_{k_1}, ..., \theta_{k_M}]) \geq 0$.

Remark: The rank of the spatial weighting matrix T depends on the SNR level of the SUBSs in the network. A spatial multiplexing function $M(p)$ is defined, that contains the eigenvalues of the transmit covariance matrix $\tilde{S}$

$$M(p) = \max_{\Lambda=(\lambda_1,...,\lambda_m)} (k : \lambda_k(p) \geq 0) \tag{5.41}$$

The multiplexing function provides the necessary and sufficient number of transmit covariance matrix eigen values which are greater then zero. These eigenvalues depends on the transmit power (SNR) level and can be classified into the following cases.

- At low SNR beamforming is optimal with $Rank(\tilde{S}_k) \leq 1$. In this case SAS uses the control sequence to ensure that the selected transmit subspace causes minimum interference and maximum capacity.
- At high SNR, the multiplexing function $M(p)$ has m parallel subspaces with their eigenvalues $(\lambda_1, \lambda_2, ..., \lambda_m)$. In this case, SAS uses the control sequnce as a scoring function and selects the eigenvalues of the subspace that causes minimum interference and maximum capacity.

Now with the eigen value decomposition we can write (5.40) as $HT^{-1/2} = U\Sigma V^H$, with $\Sigma = Diag([\sigma_1, ..., \sigma_T])$ follows the standard water-filling solution: $\sigma_i = \max(0, 1/\ln(2) - 1/\theta_i^2)$ $i = 1, ..., T$. Thus, the solution of (5.26) for a given (ν, δ) can be expressed as $S^* = T^{-1/2} V \Sigma V^H T^{-1/2}$.

The solution of the optimal beamformers for the problem (5.40) in the constrained and unconstrained subspaces is given by

$$v_k = \frac{h_{kk}\sqrt{P_k}}{\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H} \tag{5.42}$$

where ν and δ_l are the lagrangian dual variables for the kth BS transmit power constraint and the interference temperature constraints in the PU and SU constrained subspaces, respectively.

- **Case 1:** We can write for the beamformer in equation (5.42) for K SUBS is follows

$$v_k = \frac{\left(h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right)}{\| \left(h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right) \|} \left(\frac{1}{ln2} - \frac{\sum_{j\neq k} \Gamma_{jk} + \sigma_k^2}{\| \left(h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right) \|^2} \right) \tag{5.43}$$

$$v_k = \varphi \left(\frac{1}{ln2} - \frac{\sum_{j\neq k} \Gamma_{jk} + \sigma_k^2}{\psi} \right) \tag{5.44}$$

with

$$\varphi = \frac{\left(h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right)}{\| \left(h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right) \|^2} \tag{5.45}$$

and

$$\psi = \| h_{kk}/(\nu I + \sum_{j\neq k} \delta_l h_{kj} h_{kj}^H) \|^2 \tag{5.46}$$

- **Case 2:** In this case we can write for the beamformer in equation (5.42) for K SUBS is follows

$$v_k = \varphi^{'} \left(\frac{1}{ln2} - \frac{\sum_{j\neq k} \Gamma_{jk} + \sigma_k^2}{\psi'} \right) \tag{5.47}$$

with

$$\varphi^{'} = \frac{\left(h_{kk}/(\sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right)}{\| \left(h_{kk}/(\sum_{j\neq k} \delta_l h_{kj} h_{kj}^H)\right) \|^2} \tag{5.48}$$

and

$$\psi^{'} = \| h_{kk}/(\sum_{j\neq k} \delta_l h_{kj} h_{kj}^H) \|^2 \tag{5.49}$$

- **Case 3:** In this case the w_k is time variant with changing interference constraints with time. The beamformers are in the form of a vector $W = w_k^{(1)}, w_k^{(2)}, ..., w_k^{(N)}$ with N as the number of states of the multibase station network.

$$v_k^{(n)} = \varphi^{(n)} \left(\frac{1}{ln2} - \frac{\sum_{j\neq k} \Gamma_{jk}^{(n)} + \sigma_k^2}{\psi^{(n)}} \right) \tag{5.50}$$

with the φ and ψ given by (5.45) and (5.46), respectively.

Chapter 6

Summary and Future Work

This dissertation uses a dynamic SAS as a spectrum manager for sharing spectrum with PUs having multiple sets of parameters that vary with time. In TV bands, the PU parameters such as location, frequency bands, transmit power, antenna parameters, etc are combined with a propagation model and a geographical coordinate system to compute PU exclusion zones and operational rules for SU devices. However, in case of federal systems precise information about PUs may not be available. Spectrum sharing scenarios with *incomplete and imprecise data*, where true location of the PU and its in service parameters like maximum transmit EIRP, antenna parameters; periods of operation, etc are generally not present. In this case, the SAS controller makes selection of the resource allocation policy based on the interference levels in the asymptotic covariance matrix W. The controller selects the control parameter Δ based on interference-limits at PU and SU base stations. The adjustment of the interference control parameters is based on discrete sets of parameters for both PU and SUs. Using interference at different users, the control parameter is quantized into $M_1, M_2, ..., M_J$, based on J different combinations of PU and SUs interference levels in the ACM W. The J-adaptation control modes $(\Delta_1, \Delta_2, ..., \Delta_j)$ are defined based on interference limits. Δ_1 is the pure adaptation mode for any change in the SUs interference levels, while that of Δ_2 is the adaptation mode for any change in the PUs interference levels. While all other Δ_k (for $k \geq 3$) are mixed PU and SU adaptation modes. The SAS selects the adaptation control mode based on the current interference levels in the matrix

W.

Our analysis and simulation results show that the ORZFBF with interference factors is sum rate optimal while maintaining the interference protection ratios for the PUs of a spectrum band. We solve the optimal BFs for a static layout of SUs around the PU through Lagrangian dual decomposition method with ellipsoidal updates and its comparison with constrained BFs that are a combination of both MRT and ZF beamformers. Then we extend the problem to a dynamic network case where the interference constraints in distinct subspaces' changes with time. A discrete system model is proposed with four system design parameters to allow the spectrum sharing system to adopt to different scenarios while maintaining the PU interference protection constraints. Multiple scenarios are defined based on SU layout and factors affecting both sum rate capacity and network interference are evaluated through numerical simulations. The results show superior performance of ORZFBFs for both sum rate as well as interference protection in all spectrum sharing scenarios.

As a future work, the above system can also be modelled as a Markov Decision Process (MDP) or a Partially Observable Markov Decision Process (POMDP). When the state of the PU is changing over a period of time then the resource allocation problem in SAS can be modelled as a MDP. A simple MDP can be described by a tuple $\{S, A, R, P\}$, where

- S: set of states (parameter settings of the PUs)
- $A = \cup_{i \in s} A(i)$ is the set of all actions with $A(i)$ as the set of actions in state i.
- $R = \{r(i, a)\}_{i \in S,\ a \in A(i)}$ defines the reward function i.e., area sum capacity
- $P = \left\{p_{i,j(a)}\right\}_{i,j \in S,\ a \in A(i)}$ transition probability function - giving the probability of transition to state j from state i after performing the action $a \in A$ while in the state $s \in S$
- Policy function: defines the probability that action a is executed when the PU is in state s

The operational modes of the PUs can be interpreted as the maximum number of states of the MDP. As the PU can only be in one operational mode at a time. Therefore, we define the set of states as $S = S_1, S_2, S_3$, and the current state is equivalent to the current operational mode in which the PU is transmitting.The SAS have to adaptively change the parameters of spectrum availablity for the SUs based on operational mode of the PUs. The decisions that the SAS controller have to make corresponds to the actions in each state. In each state the SAS controller have to decide about the number of SU base stations and their resource allocation parameters, etc.

The set of actions are the number of multiple SU base stations with allocation strategies from the SAS controller that maintains interference protection of the PUs.

1. Allow the tier-1 SUs to operate with maximum allowable transmit power level for the beamformers. In this case the geographical separation between PU and SU is large enough that interference from SUs is ineffective.
2. Allow tier-2 and tier-3 with energy efficient power allocation to the SU base stations with maximum interference protection for the PUs.
3. Allow all the SU base stations to operate using the energy efficient power allocation techniques.

The reward function is the spatial spectrum utilization of the spectrum bands that the SAS controller is managing in its service area with minimum interference to the PUs. In this case the reward of action a_i in state S_i is the area sum capacity of the SU base stations operating outside the EZs in the analysis area. The state value function V^{π} maps each state to a real value, describing relative performance to being in this state and then following the policy π. Finding the optimal policy π^* and the optimal state value function $V^*(s)$ with reinforcement learning algorithms follows the idea of generalized policy iteration. Policy is adapted according to current state-value function which evaluates the adopted policy.

The framework proposed for SAS in this dissertation can also be used for managing 5G cellular systems, mmWave, and satellitle communication systems. The resource allocation based on the asymptotic covariance matrix (ACM) W can be extended for spectrum sharing with UAV's. In this case the interference coefficients in W will adaptively change for different base stations based on the UAV location. Another application of the proposed framework is for green networks using optimization of the interference coefficients in W. An optimum W allows for reduction in the overall energy consumption and reduces the interference among the SU base stations.

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