SPECTRUM SHARING:
QUANTIFYING THE BENEFITS OF DIFFERENT ENFORCEMENT SCENARIOS

by

Mohammed Altamaimi

Bachelor in Electrical Engineering, King Fahd University, 2003

Master of Communications Technology and Policy, University of Strathclyde, 2005

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SCHOOL OF INFORMATION SCIENCES

This dissertation was presented

by

Mohammed Altamaimi

It was defended on

October 23rd, 2014

and approved by

Dr. David Tipper, Associate Professor, SIS, University of Pittsburgh

Dr. Konstantinos Pelechrinis, Assistant Professor, SIS, University of Pittsburgh

Dr. Douglas Sicker, Professor, EPP, Carnegie Mellon University

Dissertation Advisor: Dr. Martin Weiss, Professor, SIS, University of Pittsburgh

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Mohammed Altamaimi, PhD

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Recent studies have forecasted major growth in mobile broadband traffic. Due to the predicted high growth rate of mobile broadband traffic over the coming years (demand), there is a need for more wireless network capacity (supply). One of the major approaches to expand mobile wireless capacity is to add more spectrum to the market by enabling “spectrum sharing”. The FCC has issued many reports indicating that the US is dangerously close to running out of capacity for mobile data, which is why the FCC and the NTIA have been working continually to enable spectrum sharing.

The spectrum usage rights granted by the Federal government to spectrum users/licensees come with the expectation of protection from harmful interference. As a consequence of the growth of wireless demand and services of all types, technical progress enabling smart agile radio networks, and on-going spectrum management reform, there is both a need and opportunity to use and share spectrum more intensively.

This dissertation is written on the premise that spectrum sharing will be a major factor in increasing the capacity supply in the near future. The focus of this dissertation is to examine and quantify the benefits of spectrum sharing through different enforcement scenarios.

Enabling spectrum sharing regimes on a non-opportunistic basis means that sharing agreements must be implemented. To have meaning, those agreements must be enforceable. This

dissertation will examine the spectrum sharing between government and commercial users and try to generalize some finding, which can be implemented, in different spectrum sharing cases.

This analysis is valuable because it will help regulators/governments prepare for possible future scenarios in addressing the potential capacity crunch. In addition, it can give the incumbents more insight into expected future sharing as well as into how to optimize mitigation of possible harmful interference that may result. It is also of value to commercial users and operators in that they can use the results of this work to make more informed decisions about the economic benefits of different spectrum sharing market and opportunities.

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PREFACE

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I would also like to take this opportunity to express my deepest gratitude to my amazing parents for the constant encouragement that they have given me over the years, and I undoubtedly could not have done this without you.

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Above all, I thank God for everything.

1.0 INTRODUCTION

The increasing demand for spectrum makes the introduction of more spectrally efficient technologies and management regimes essential. Recent evidence demonstrates that the demand for spectrum access rights exceeds the available supply [1] [2]. One of the main factors leading to this imbalance is that the spectrum is not as well utilized as it could be. The future of wireless necessitates that we use the spectrum resources more efficiently, which requires a transition to a future in which spectrum is shared more intensively. The growing demand pressure expanded access to legacy networks for new uses and the need for significant spectrum reform to enable such sharing has been noted by the Federal Communications Commission (FCC) Spectrum Policy Task Force, reaffirmed by the National Broadband Plan (NBP) and the President's call for an additional 500MHz of spectrum for mobile broadband [2] [1], and most recently in the President’s Council of Advisors on Science and Technology (PCAST) report [3] address this issue intensively. In addition, the National Telecommunications and Information Administration (NTIA) has proposed several bands to facilitate spectrum sharing [4].

Realizing a future where spectrum sharing is the norm requires us to commercialize the next generation of wireless technologies, such as Cognitive Radios (CRs) and Dynamic Spectrum Access (DSA) systems that are needed to support higher spectrum utilization. These technologies will enable new business models and spectrum sharing regimes that pose a host of opportunities and challenges for spectrum managers and the entire wireless ecosystem. DSA technology promises to increase spectrum access and help overcome the lack of available spectrum for new wireless services. DSA does this by enabling spectrum sharing between different users such as Primary Users (PUs) and Secondary Users (SUs).

It is clear that mobile broadband is the great infrastructure challenge for wireless operators, particularly with the evidence of significant increase in mobile broadband traffic [3]. Data usage over mobile networks is rapidly increasing as more users surf the web, check email, and watch video on smart phones/tablets. Several research analysts share the view that mobile broadband traffic will continue a significant upward trend over the next 5 to 10 years [1] [5] [6].

The NBP recognizes the enormous potential of mobile broadband growth [2]. It recommends that the FCC make available 500 MHz of new spectrum for wireless broadband, including 300 MHz for mobile flexible use within five years. In addition, in 2010 the President released an Executive Memorandum calling for 500 MHz of new spectrum for mobile and fixed broadband use [5].

Due to the ever increasing demand for mobile broadband, wireless operators are forced to increase network capacity (the amount of data a network can carry). As the FCC stated in [1], it is unlikely that wireless operators will be able to accommodate this surging demand without additional spectrum. In addition, mobile broadband traffic has grown tremendously with the proliferation of smartphones, tablets, and other mobile devices with internet access. Finally, mobile broadband has the potential to transform many different areas of the economy by providing a platform for new innovation, and any limitation for that potential source will affect those platforms [7] [8] [9].

1.1 BACKGROUND

The radio “spectrum”[1] is a national resource, much like minerals and land; however, spectrum is reusable. One of the major purposes of spectrum management is to mitigate interference and increase spectrum efficiency. Legacy spectrum management is based on a static assignment policy, where government agencies assign spectrum to license holders on a long term basis for a large geographical regions. Recently, this policy has been faced with spectrum scarcity in particular spectrum bands, which increases the need for more efficient spectrum management.

1.1.1 Spectrum Management and Licensing

Spectrum management is the process of regulating the use of spectrum to promote efficient use and gain optimal social benefit from this scarce natural resource. The most common spectrum management approach is “command and control”, which is employed by most regulators around the globe [10]. Historically, spectrum has been highly regulated in order to prevent any harmful interference between the spectrum licensees. In the last decade, there have been significant innovations in the theory and practice of spectrum regulation. There is now a growing belief that current static “command and control” practices have delayed the introduction and growth of beneficial technologies and services [11].

1 Radio "spectrum" refers to the part of the electromagnetic spectrum corresponding to radio frequencies which is the full frequency range from 3 kHz to 300 GHz.

On the other hand, there is the “commons” or “unlicensed” approach where spectrum is available to all users who comply with certain pre-registration technical specifications and equipment certifications [12][13] [14]. For example, WiFi is the most common application of this kind of spectrum management approach and has proven its success worldwide. However, there are also limitations to this approach such as that the fact that the QoS is not guaranteed and it suitable for short-range network only [11] [15].

As a result, a new spectrum management approach has emerged in the regulatory field to increase spectrum efficiency and to facilitate the sharing. It lies somewhere between the “command and control” the “commons” approaches. It will enable additional users (i.e. SUs) to use/share the same spectrum band with the PU without causing harmful interference. This approach is considered in this dissertation as ground-base to facilitate spectrum sharing [16] [17].

1.1.2 Taxonomies of Spectrum Sharing

Spectrum sharing can take many forms of coordination between PUs and SUs and cooperation between the SUs themselves. Table 1-1 illustrates these different forms where each one has its own level of complexity on either the PUs or the SUs side.

In this Table, the horizontal dimension refers to the degree or type of coordination between the primary and secondary users. The coordinated approach explicitly defines the usage rights[2] of SUs by some kind of negotiation with the primary user. In the non-coordinated approach, the

2 For more insight about the concept of “usage right” in the spectrum sharing domain, please refer to [24], [77].

secondary user does not require explicit permission from the primary user and will not necessarily get any feedback.

The vertical axis addresses sharing among SUs, who may or may not cooperatively exploit the opportunity and use the idle primary spectrum bands. The focus in this dissertation will be on non-opportunistic sharing where an agreement takes place between the PUs and the SUs.

Sharing between the government incumbents (i.e. Federal or non-Federal agencies[3]) and commercial wireless broadband operators/users is one of the key forms of spectrum sharing that is recommended by the NTIA and the FCC. In addition, one of the broad visions of President Obama's Spectrum Initiative is that the Federal government must ensure sound government performance and effective use of its spectrum, pushing for effective repurposing, sharing, and innovative uses of spectrum wherever possible [3] [5].

Table 1-1 Illustration of different spectrum sharing cases

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Primary User Domain</td></tr>
<tr><td>No coordination</td><td>Coordination</td></tr>
<tr><td rowspan="2">Secondary Users Domain</td><td>Non-cooperative</td><td>Opportunistic Sharing
(e.g. Independent CRs)</td><td>Non-Opportunistic Sharing
(e.g. SU networks with small cell connect to regulations and policy database)</td></tr>
<tr><td>Cooperative</td><td>Opportunistic Sharing
(e.g. Exchange information between the CRs)</td><td>Non-Opportunistic Sharing
(e.g. SU networks with large cell such as LTE sharing the band with the PU)</td></tr>
</table>

[3] Throughout this dissertation, we refer to either Federal or non-Federal agencies as government users (i.e. PUs).

1.1.3 Spectrum Crunch or Capacity Crunch

The FCC has issued many reports indicating that the US is dangerously close to running out of spectrum for mobile data, which is why the FCC and NTIA have been working to free up more spectrums for wireless operators [1] [5]. Concerns about capacity and spectrum supply have pushed carriers to make deals and network changes. However, spectrum refarming has a roughly 10-15 year horizon, and the spectrum crunch appears imminent [18]. It will be very visible problem if we chart the spectrum in the pipeline (expected spectrum bands targeting the mobile broadband industry) against the growth mobile broadband traffic. The spectrum crunch is threatening to increase the number of dropped calls, slow down data speeds and raise customer prices.

Some researchers are considering the problem to be a “spectrum management” or “spectrum policy” crunch rather than a limitation on spectrum bands. A crunch occurs when demand outstrips supply. Others call it a “capacity crunch” problem. Either way, there is a supply shortage for high mobile broadband demand. The industry worries that it will not be possible to meet this increased demand cost-effectively and as a result, there will be congestion, higher prices, diminished user experience, or mix of these [19].

1.1.4 Mobile Broadband Traffic

Market research studies predict a significant mobile data traffic increase over the next 5 to 10 years. Mobile operators have to upgrade and optimize their networks to be able to meet future demand. The challenges of meeting escalating demand for mobile broadband applications is driving mobile operators to make heavy network investments and migrate to newer generation technologies. Consumer demand for mobile data services is increasing at a rapid rate. Based on an FCC report published in 2010 [1], recent indications show strong growth of mobile broadband usage due to the increasing penetration of new smart phones/tablets to the market. For example:

- AT&T has seen mobile network traffic increase 5,000% over the past 3 years, that is mainly caused by the exclusive introduction of new type of smart phones over AT&T network (the iPhone).
- Users of Clearwire's fourth generation (4G) WiMAX service consumed 7 GB per month, which is 280 times the amount of data used by a regular cell phone (in 2010).
- PC "air-card" users consume 1.4 GB per month, which is 56 times the amount of data used by a regular cell phone.

Looking forward, research generally share the view that mobile broadband traffic will continue a significant upward trend. This section will highlight the main drivers and forecast of this upward trend.

1.1.4.1 Traffic Drivers There are many factors driving the rapid increase in mobile broadband traffic. They can be grouped as follows:

- **Mobile Connections**: the growth rate of the number of mobile devices is higher than the number of mobile subscribers. For example, by 2015, researchers forecast that there will be more than 5.6 billion mobile devices and more than 1.5 billion machine-to-machine applications [20].
- **Enhanced Computing and Rich Applications**: mobile devices are becoming smarter and are consuming more network capacity. For example, over the 2010 – 2015 forecast period, global mobile data traffic is forecast to outgrow global fixed data traffic by 3

times [20]. Mobile video specifically, is predicted to make up two-thirds of mobile data traffic by 2015 [21].

- **High Speeds**: mobile connection speed is key enabler for mobile data traffic growth. In fact, mobility is becoming a requirement, not a preference. More speed means more consumption, and it is projected that mobile speeds will increase 10 fold from 2010 to 2015 [20] [22].

1.1.4.2 Traffic Forecast Recent studies have forecasted major growth in mobile data traffic. According to the last Cisco Visual Networking Index report [20], global mobile data traffic grew 70% in 2012; where data traffic increased from 520 petabytes/month at the end of 2011 to 885 petabytes/month at the end of 2012. In addition, the average mobile network downstream speed doubled, up from 248 kbps in 2011 to 526 kbps in 2012. Moreover, the average mobile network connection speed for smartphones in 2012 was 2,064 kbps, up from 1,211 kbps in 2011; and for tablets in 2012, it was 3,683 kbps, up from 2,030 kbps in 2011. In 2012, a fourth-generation (4G) connection generated 19 times more traffic on average than a non-4G connection. Although 4G connections represent only 0.9% of mobile connections, they already account for 14% of mobile data traffic. Global mobile data traffic will increase 13 fold between 2012 and 2017. It will grow at a Compound Annual Growth Rate (CAGR) of 66% from 2012 to 2017, reaching 11.2 exabytes per month by 2017 [20]; see Figure 1-1. To show other countries statistics, Table 1-2 gives a summary of mobile broadband traffic growth in different countries/regions [20] [21].

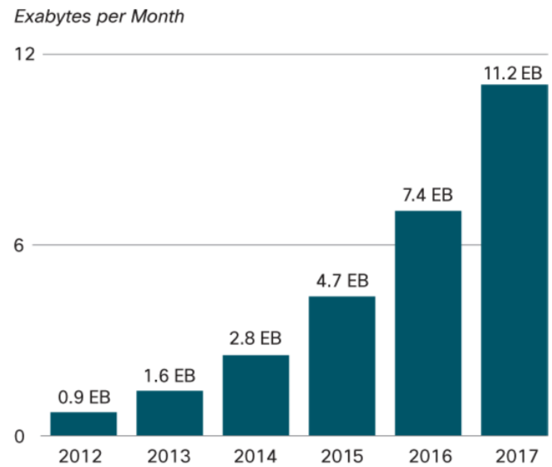

Figure 1-1 Forecast of global mobile data traffic

Table 1-2 Examples of mobile broadband traffic growth

Region	Mobile Traffic Growth Examples
Korea	As reported by Korean regulator KCC, mobile data traffic on 2G, 3G, and 4G networks increased approximately 80% between January and November of 2012.
China	China Mobile's mobile data traffic grew 77% from mid-2011 to mid-2012. China Unicom's mobile data traffic grew 112% from mid-2011 to mid-2012.
Japan	As measured by Japanese regulator MIC, mobile data traffic grew 113% from September 2011 to September 2012.
Australia	As reported by Australian regulator ACMA, mobile data traffic grew 40% from mid-2011 to mid-2012.
Italy	As reported by Italian regulator AGCOM, mobile traffic in Italy in 3Q12 was up 32% compare to 3Q11.
Middle East and Africa	The Middle East and Africa will have the strongest mobile data traffic growth of any region at 77% CAGR.

As reported in the recent "Ericsson Mobility Report", 40% of mobile phone sales were smartphones in the third quarter of 2012, which was an indication that smartphones will soon dominate mobile data traffic. Meanwhile, mobile data traffic doubled between Q4-2011 and Q4-2012. The study also showed that smartphones were expected to grow 12 times between 2012 and 2018 [21]; see Figure 1-2. Nokia Siemens Networks warned that the mobile industry will need to prepare for 1000 times as much traffic by 2020[4]. Based on the UMTS Forum report, in 2020, total worldwide mobile traffic will reach a 33 fold increase compared with the 2010 figure [22].

Based on the 2010 FCC report [1], the amount of data used by a single mobile user increased over 450% between Q1-2009 and Q2-2010. AT&T, the exclusive US carrier of the iPhone (at time of report publication), has seen mobile network traffic increase 5,000% over the period of 2007 to 2010. Therefore, the FCC expects the "mobile data demand" to grow between 25 and 50 times over 2010 levels over the coming 5 years.

---

[4] Tomas Novosad, Senior RF Consultant, Nokia Siemens Networks [available at: http://www.ieee-globecom.org/downloads/GLO2013_AP.pdf]

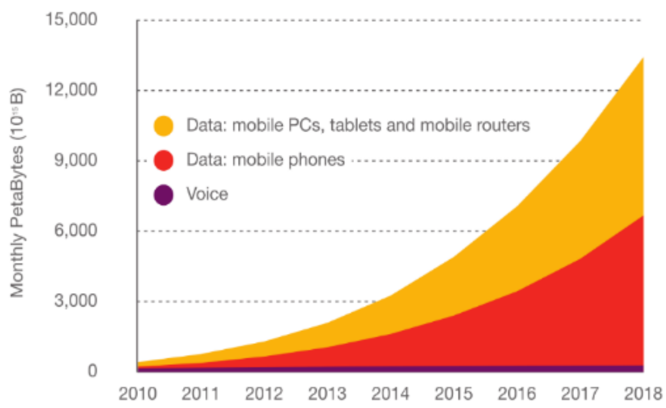

Figure 1-2 Forecast of global mobile traffic for voice and data 2010-2018

The Office of Communication (Ofcom) in UK issued a strategy report [18] which concluded, in an average scenario, the demand for mobile data will experience an 80 fold increase between 2012 and 2030, and that number could reach a 300 fold increase in the high increase scenario. In the UK, mobile data volumes were approximately four times greater at the end of 2010 than they were at the end of 2007.

All these traffic forecasts indicate that there is dramatic growth in the capacity demand. Figure 1-3 shows a summary of forecasts addressed in this section over the coming 5 years based on different furcated projections. The average growth between 2013 and 2017 is over 20 times over the 2012 baseline (we did not include Nokia Siemens Networks expectations, because it is very high compared to others).

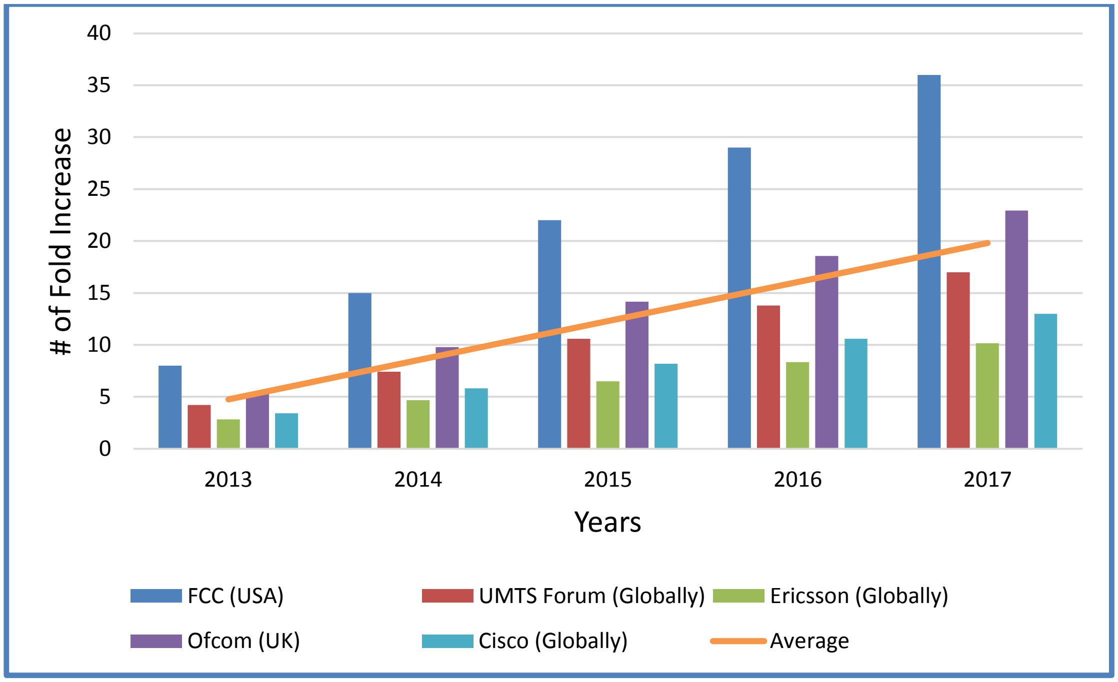

Figure 1-3 Mobile broadband traffic; 5 Years from 2012 baseline

1.1.5 Dynamic Spectrum Access

Spectrum sharing requires the commercialization of the next generation of wireless technologies, such as CRs and SDRs to enable DSA systems needed to support a higher utilization of spectrum. CRs and SDRs are often referred to together and sometimes the terms may be used interchangeably. CRs distribute decision-making functionality into the radio access network, and ultimately to the handsets, allowing them to make operational decisions, including such functions as sensing the spectrum environment for spectrum holes, controlling frequency selection, power, or other operating parameters/modes. In contrast, SDRs are an implementation technology, implementing in software what previously would have been implemented in radio hardware. As such, SDRs are a key enabling technology for CRs. For further discussion of the distinctions between SDRs and CRs, please refer to [23].

DSA, like SDRs and CRs, is another term that may be interpreted narrowly or broadly. In its narrow definition, DSA refers to the use of CR/SDR and related radio technologies to enable more dynamic spectrum management methodology. Used more broadly, DSA refers to the whole class of technologies, business models, and policies that enable spectrum resources to be shared more intensively across users, uses, and locations (where "locations" refers to the full dimensionality of the spectrum, time, space, waveform, etc.). In this dissertation, we will use DSA in both senses. It is the need to share spectrum more broadly that provides the principal economic driver for adopting novel radio technologies like CR/SDR, but it is the special regulatory enforcement challenges and opportunities associated with these new radio technologies that are the principal focus of this dissertation.

1.2 MOTIVATION

Due to the expected high growth rate of mobile broadband traffic over the coming years (demand), there is a need for more network capacity (supply) by finding the optimal and visible sharing solutions among available options to increase network capacity. There is an urgent need for on-going spectrum policy reform to make spectrum sharing a reality. Generally speaking, spectrum can be shared in frequency, time and geographical dimensions or any combination thereof. Beyond the technical aspects of spectrum sharing that must be resolved, lie questions about how much benefits we can get out of each shared spectrum scenario and which one of the possible sharing scenarios has the most incentive to share.

While DSA embeds functionality that poses additional enforcement challenges, it also offers new tools for technical enforcement. Distributed intelligence to radio means that radio is increasingly capable of participating in intelligent and dynamic automated spectrum sharing. Through protocols, policy-based language frameworks, and other tools, radio systems' ability to technically manage compliance with sharing protocols has been enhanced [24].

Spectrum sharing imposes risk for both PUs (e.g. harmful interference) and SUs (abuse by PUs to prevent sharing). Thus, enforcement is essential to minimize that risk and achieve multiple goals, such as: ensuring "fair" access to spectrum, and enforcing sharing contracts.

1.3 PROBLEM STATEMENT

The focus of this dissertation is to determine the benefits of spectrum sharing through sharing between government and commercial users. We quantify enforcement benefits in real case studies and test the proposed hypotheses. This includes finding a relationship between different sharing aspects and characteristics, such as geographical size of spectrum shearing area, frequency, and spectrum opportunity cost. There are many scenarios where spectrum sharing can take place, so the emphasis of the dissertation is on government and commercial spectrum sharing. The government incumbent will be the PUs, and the commercial users will be the SUs.

This dissertation evaluates the benefits of enforcement. In other word, it sets the upper bound of the reasonable cost of enforcement to share the spectrum in specific scenarios. We evaluate the shared area by moving from pure ex ante enforcement toward ex post enforcement settings in our model.

1.4 RELATED WORK

There are few papers that consider spectrum sharing in connection with enforcement and DSA systems. Most notably, a series of papers by Sahai and his co-authors consider mechanisms to enforce sharing [25][26][16][17][18]. Sahai's papers focus on opportunistic sharing enabled by cognitive radios that actively sense and respond to their local environments, and the focus of enforcement in those papers is on mechanisms that are embedded in CR technology. Also, [30] proposed a system to secure dynamic spectrum transmissions, where authorized users embed secure spectrum permits into data transmissions. However, all the above papers focus on opportunistic sharing, whereas the focus in this dissertation will be on non-opportunistic sharing.

In the area of spectrum sharing, there are active initiatives and plans to make the sharing between government and commercial word reality. The NTIA react to the President's call to seek opportunities to make spectrum available for wireless broadband [5]. It is the task to assess the "Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, 4200-4220 MHz, and 4380-4400 MHz Bands"[5]. Thus, the

5 Commerce Spectrum Management Advisory Committee (CSMAC) formed five working group to repurpose candidate bands for wireless broadband.

NTIA[6] issued a "technical analysis" in October 2010 showing their views of enabling the spectrum sharing in these bands [4]. It is considered as one of the fundamental reports examining candidate bands for sharing in focused action plan. The final recommendations, which are related to this dissertation, is to have exclusion zones to protect the PUs. They build those zones based on the worst case scenarios, zones are large and the spectrum opportunity cost is very high [31]; for more information about "spectrum opportunity cost" concept, please refer to Appendix (A).

A recent report by the President's Council of Advisors on Science and Technology (PCAST) recommended using small cell in 3.5GHz band [3]. In the PCAST Report, two technological advances were identified that promise for increasing spectral efficiency. First, increase the use of small cell network deployments will multiply wireless capacity within existing spectrum resources. Second, increase spectrum sharing between government and commercial applications. The proposed 3.5GHz band would foster the widespread utilization of both of these technological advances and promote the efficient use. The PCAST report is a high level guidelines report, it does not specify the detailed sharing scenarios or how the enforcement will take place.

The FCC, also, issued number of recent studies and reports showing the importance of this type of sharing and the critical role of enforcement. They highlight clearly the existence of "spectrum crunch" and they believe spectrum sharing is a major driver to overcome this problem [1]. In addition, the FCC issued a "Notice of Proposed Rulemaking and Order" in December 2012 [32], and further notice in April 2014 [33], in which they propose to create a new Citizens

[6] The NTIA work in this project with other partners as the Department of Commerce, Department of Defense, Department of the Interior, and the National Aeronautics and Space Administration.

Broadband Service in the 3.5 GHz band. The FCC proposed this band to be shared between the current government agencies and small cell SUs. They also mentioned briefly that the shared band would be managed by a Spectrum Access System (SAS) incorporating a dynamic database and, potentially, other interference mitigation techniques.

A recent paper by Leon and Sicker model the interference between PU and expected SUs and shows the need for an appropriate spectrum sharing policy in 3.5GHz band [34]. It is one of first papers to examine the effect of different propagation models over the spectrum sharing value.

Globally, there is increasing interests in this type of sharing, as well, and the way it should be regulated. For example, the Ofcom in the UK issued a public consultation titled "Securing long term benefits from scarce spectrum resources" which demonstrate the increasing concern of capacity crunch and the optimal way to regulate/enforce more spectrum sharing [18]. In addition, the Australian Communications and Media Authority (ACMA) issued recently a report (titled: "Towards 2020 - future spectrum requirements for mobile broadband") stating the same concerns and the advantages of government and commercial sharing [35].

"*Spectrum pooling*" is another way to enhance spectral efficiency. The goal of "*Spectrum pooling*" is to enhance spectral efficiency by overlaying a new mobile radio system on an existing one [36]. There are main two differences between the idea of "*Spectrum pooling*" and my proposed work. First, in "*Spectrum pooling*", there should be perfect channel knowledge at the primary receiver and transmitter [37] [38]. Second, there should be full interaction between the PUs and SUs, such as time synchronization between the two [36] [37]. As a result, the technology options, to be used by the SUs is limited by the PU specifications.

These reports and public consultations set a high-level framework about capacity crunch problem and the need to find an optimal solutions; without going deeply and demonstrate the tradeoff between different spectrum sharing scenarios. This work has started from this understanding and take the research farther, and so far we published five papers in this regards [39] [24] [40] [41] [42].

2.0 FACTORS TO INCREASE NETWORK CAPACITY

Due to the ever increasing demand for mobile broadband, wireless operators are forced to keep up and increase network capacity. Generally, three factors increase mobile network capacity: (1) adding more cell sites, (2) technology, and (3) adding more spectrum. In this chapter, the roles and the expectation for each factor will be studied and illustrated. Then, the importance of spectrum sharing (as part of third factor) will be highlighted.

According to historical data, Cooper's Law [43] stated that global wireless network capacity[7] increased about 1 million times from 1950 to 2000. Approximately, this increased 20 times from adding more spectrum, 25 times from more efficient technologies and 2,000 times from adding more cells [19] [44].

There is broad agreement throughout the literature that this historical increase has been dominated by the "cell sites" factor [6] [45] [19]. The expectation is that "cell sites" factor will continue to dominate the spectrum and technology; see Table 2-1. The challenge now is how those three factors will affect the capacity in the future? If network capacity/efficiency doubled every 2.5 years (based on Cooper's Law), is this enough to carry the forecasted traffic demand? Which one of those factor can play more of a role compared to historic data to overcome the capacity shortage? These are some of the point we are addressing in this chapter.

---

[7] Based on Marty Cooper statement: (…. compare the number of "conversations" (voice or data) that can theoretically be conducted over a given area in all of the useful radio spectrum. It turns out that this number has doubled every two-and-a-half years for the past 104 years) [43].

Table 2-1 Main factors to increase the capacity over the past 50 years

Factor	Coefficient of Increase
Adding more cell sites	2000
Technology	25
Adding more spectrum	20

2.1 MORE CELL SITES

A cell site is a cellular site where electronic communications equipment (e.g. antennas) are placed, such as on a tower, pole or even the rooftop of a high building. Adding more cell sites is one of the three factors that can expand the network capacity. This option is unlimited and unbounded. It is unlike the "spectrum", where the spectrum is a finite resource. It is also unlike "technology", which is limited by Shannon's Law of transmission capacity. The only constraining factor for cell site is cost. This is why over the last few decades, most of the gains in capacity have come from more cell sites [19].

Adding more cells can be done to cover more areas (coverage), and/or to increase the capacity in a specific areas (dense the network). In fact, frequency may be reused by subdividing cells (replacing large cell with small ones), thus increasing the amount of traffic that an "Hz" of spectrum can carry within an overall geographic area. This is measured by bps/km^2 and is known as "spectral efficiency". Although it is a very effective mechanism to deepen network capacity, it is expensive and requires the construction of extra towers, deploying more antennas and base station equipment, etc. In addition, it needs additional backhaul to link new towers back into the core network.

2.1.1 Number of cell sites

According to data published by the Wireless Association (CTIA) [46], the number of cell sites in the US has been growing at about a 6% Compound Annual Growth Rate (CAGR) over the past five years; see Table 2-2. It is evident that the growth rate has been decreasing over the time. One of the main reasons for that growth reduction is the fact that the incremental benefits of adding a cell site are lower than before.

Mobile operators usually handle mobile broadband traffic growth by adding new cell sites to existing towers. However, that is an expensive process, and many metropolitan areas are now so packed with cell sites which implies that adding new ones would be riddled with interference concerns [1].

Table 2-2 Number of cell sites in the US

Date	Number of Cell Sites	Yearly Growth	Average Growth over 5 Year
1997	38,650	-	**-**
1998	57,674	49.2%	**-**
1999	74,157	28.6%	**-**
2000	95,733	29.1%	**-**
2001	114,059	19.1%	**-**
2002	131,350	15.2%	**28.2%**
2003	147,719	12.5%	**20.9%**
2004	174,368	18.0%	**18.8%**
2005	178,025	2.1%	**13.4%**
2006	197,576	11.0%	**11.7%**
2007	210,360	6.5%	**10.0%**
2008	220,472	4.8%	**8.5%**
2009	245,912	11.5%	**7.2%**
2010	251,618	2.3%	**7.2%**
2011	256,920	2.1%	**5.4%**
2012	285,561	11.1%	**6.4%**

William Webb in his book “Understanding Weightless” [6] demonstrated the effect of adding cells with a lower radius; see Figure 2-1 [8]. Based on this graph, reducing cell range from 5km to 2km will require increasing number of cells from 1 to 6 cells. However, there is around a 25 fold increase in the total capacity which gets the advantage of more modulation efficiency by lowering the cell size. Thus, adding more cells is expected to continue as a main factor in the future to solve the capacity crunch, where wireless operators would logically deploy the lowest cost option to increase network capacity.

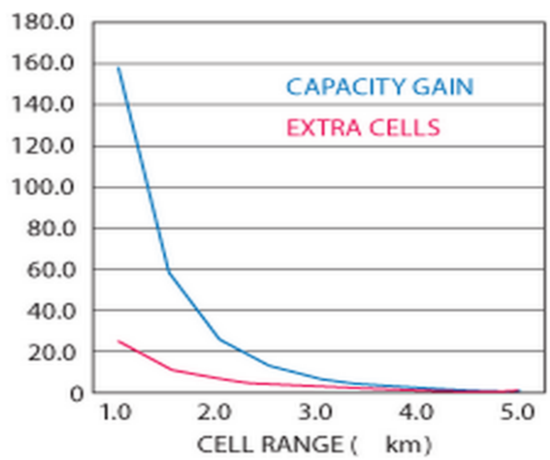

Figure 2-1 Effect of adding cell sites with small radius

[8] Source: W. Webb, "Understanding Weightless" book [6].

2.1.2 Offloading to Wi-Fi and Femtocells

Offloading technique can be defined as the process of transferring the broadband/data traffic that is ordinarily generated on the cellular network to a fixed network such as WiFi or Femtocell access points. The offloaded traffic frees up capacity on the cellular network, which gives a cost effective solution for a cellular operator.

The European Union published a book recently discussing the idea of how is traffic offloading evolving over time, and how does this evolution influence the need for spectrum? [47]. The argument in this book is based on other research analyses (i.e. Cisco). The related findings of this book can be summarized as follow

- The volume of traffic that is already being offloaded (through Wi-Fi mainly) already exceeds that of the cellular network.
- The current offloading traffic is under estimated, and can be expected to grow even faster than the forecasted figures.
- Seek to make more spectrum for WiFi applications (unlicensed bands).

The Ofcom has expected that offloading mobile data traffic onto fixed networks using Wi-Fi and Femtocells could serve over half of the predicted increased demand for mobile data traffic [18]. Cisco has estimated that mobile offload increases from 33% (429 petabytes/month) in 2012 to 46% (9.6 exabytes/month) in 2017, as a percentage of total mobile broadband traffic from all mobile-connected devices; see Figure 2-2.

Based on Cisco report, without offload taken into account, global mobile data traffic would grow at a CAGR of 74% instead of 66% [20]. This gives an indication of that even the offloaded traffic is underestimated (as the European Union suggested), the expected increase in the demand is really high and need more preparation to bridge the gap between forecasted demand and expected supply. In addition, there is increase desire for mobility which gives the cellular connectivity more advantage over fixed/nomadic offloading connectivity.

Although there is growing offloaded traffic over WiFi or Femtocell access point, it is still not clear what percentage of traffic is counted as offloaded, and what traffic is originally fixed. The FCC and the UMTS Forum, in their latest related reports, did not take account of the offloading factor. The UMTS Forum said that WiFi and Femtocells imply some usage restrictions/limitations on the quality, mobility and security of the service. They are a ”second choice” option to a primary mobile broadband access and should be considered as complementary, not competing [48]. Traffic growth is high regardless whither offloading is considered as part of “more cell sites” factor or as a complementary option for wireless operators, so we will ignore it.

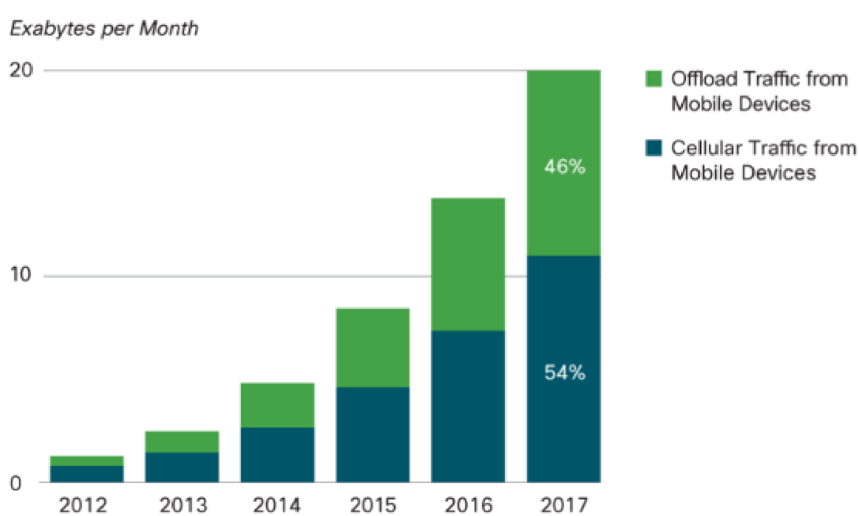

Figure 2-2 Offloading to Wi-Fi or Femtocells

2.2 TECHNOLOGY

From the previous section, it is clear that the "more cell sites" option will not be a cost effective solution to supply all needed forecasted capacity [1] [3] [19] [27] [28]. So, will technology be a sufficient complement? If the efficiency (due to technology) could be doubled, could twice the capacity be obtained?

It appears that multiple antenna (MIMO) systems hold the most promise, with apparently large gains possible. Transmission from multiple cells, which is called coordinated multi-point transmission (CoMP[9]) in 4G [6], is another approach as well. Carrier aggregation is also part of new cellular technology (i.e. LTE-Advanced), whereby a device can simultaneously use multiple bands of frequencies to deliver higher data rates [50] [51].

The first generations of wireless communication (1G) technologies had a spectral efficiency of less than 0.1 bps/Hz on a sector basis. The 2G technologies had an efficiency of 0.25 bps/Hz. The 3G technologies had an efficiency of 0.5 bps/Hz which has been rising to 1.0 bps/Hz for advanced implementations. Now, the 4G technologies have an approximate efficiency of 1.4 bps/Hz [52]. The highest spectral efficiency of LTE-Advanced with 4x4 MIMO is 3.7 bps/Hz at the center of the cell site coverage [53].

This factor is strictly bounded by the Shannon capacity formula, and that limitation is not easy to go around [54]. Evolution in wireless technologies includes a steady series of

[9] This idea could be challenging, where it will be hard to make a user-equipment that can work across large numbers of bands. There are now some 40 bands identified for 4G; it seems unlikely that any user-equipment device could support them all.

improvements in spectral efficiency, however, technologies are approaching the theoretical limits of spectral efficiency [55]. Based on these statistics; technology alone will be insufficient to bridge the capacity gap between the forecasted demand and the expected supply.

2.3 MORE SPECTRUM

There is a wide belief that the current spectrum allocations for mobile broadband services is not enough to line with the forecasted demand; even they called this as “spectrum crunch”. Adding more spectrum to the market can involve three main techniques:

- Allocate exclusive spectrum to mobile broadband operators.
- Allowing spectrum sharing between different types of uses/users.
- Assign more spectrum for unlicensed usages, such as WiFi bands.

This section will highlight these three different techniques and shows the most expected one to overcome the capacity problem in the near future.

2.3.1 Exclusive Spectrum

For mobile operators, the most common technique to obtain spectrum is to obtain exclusive spectrum band. This allocated spectrum gained either (1) from available spectrum, which means that it is not been allocated to anybody, or (2) from allocation due to the spectrum refarming process, where the government moves spectrum assignment/allocation from one user type to another due to the change in demands and needs. In either case, this is an exclusive allocation where a licensee has the full usage right (unshared) across the usage right area.

The fact is that there is not much "unused" spectrum now to allocate and "spectrum refarming" process takes years to be effective (and varies from a country to another). Spectrum refarming takes from 10 to 15 years to be achieved [1]. It is not a good strategy to see previous spectrum allocations in the US, for example, and scale it up for the future; Table 2-3[10] illustrates the significant assignments of spectrum by the FCC. Spectrum is a finite resource. Thus, it is more accurate and informative to compare growth in mobile traffic versus spectrum resources; please see Figure 2-3 [44]. It shows details of spectrum allocation efficiency (the amounts of spectrum licensed vs spectrum utilization).

Table 2-3 The US mobile spectrum allocations

Year	Allocation	Band	Name
1983	40 MHz	850 MHz	Cellular
1989	10 MHz	850 MHz	Cellular
1993	14 MHz	800 MHz	SMR
1995	130 MHz	1900 MHz	PCS
2005	194 MHz	2500 MHz	EBS/BRS
2006	90 MHz	1700/2100 MHz	AWS-1
2008	70 MHz	700 MHz	700 MHz
Totals	548 MHz (assuming all EBS/BRS spectrum to be usable) 409.5 MHz (assuming only 55.5 MHz of EBS/BRS spectrum)		

[10] These data in Table 2-3 had been assembled from multiple sources including the FCC by [44].

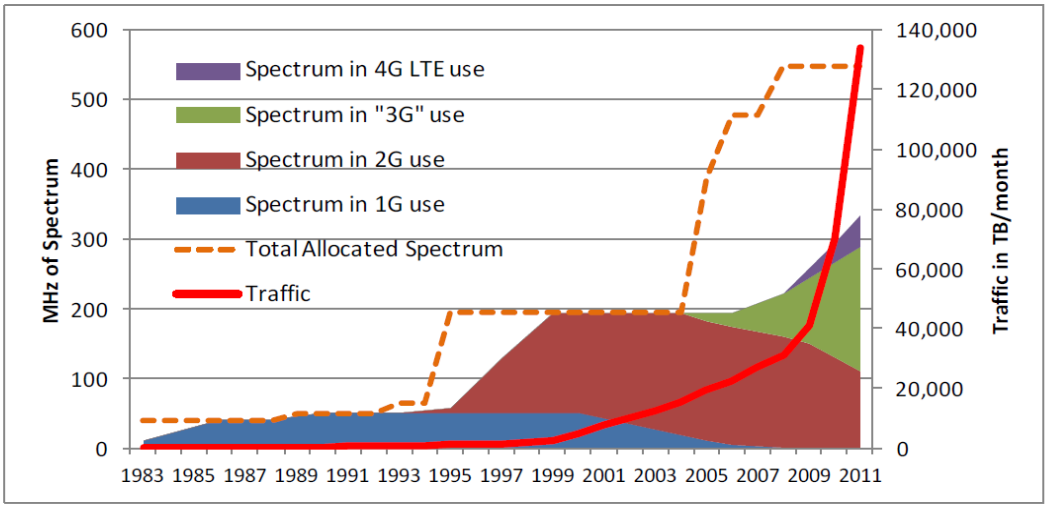

Figure 2-3 Spectrum growth vs traffic growth

Webb in his article about "the European Spectrum Capacity Crunch" said 6.3 GHz of spectrum would be needed by 2016[11] [19] [56]. He adds "since operators require spectrum below 3 GHz to achieve viable propagation, this is clearly impossible, so there is no way whatsoever that the capacity crunch can be wholly addressed by using more spectrum".

2.3.2 Shared Spectrum

There are limitations (e.g. time, cost, and availability) to supply the mobile broadband market with "exclusive spectrum" to solve the near future problem of rising demand. Therefore, the reasonable solution must rely on the "shared spectrum" approach. That is why the FCC [1], the NTIA [4] [5],

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[11] If we just consider the "spectrum" as the only available factor to increase the network capacity.

and the PCAST group [3] confirms this direction as the most significant approach for overcoming the problem.

The first wave of spectrum sharing between PUs and SUs is the TV White Space (TVWS) scenario. It is non-opportunistic sharing, where the major element to facilitate this process is the TVWS database. This dissertation focusses on the second wave of spectrum sharing, which is sharing between government agencies (as PUs) and commercial operators (as SUs).

2.3.3 Unlicensed Spectrum

In specific type of usage right, there is what is called “unlicensed usage right” where the spectrum is available for use by all under certain specifications and rules, for example, the 2.4GHz band for WiFi [57] [58]. It is part of the "commons” model of open-spectrum where spectrum is shared equally between users. It implies more supply of spectrum to the market. There is overlap between (a) unlicensed spectrum and (b) small cell site. If mobile operator offload the traffic to a small cell (e.g. WiFi) though unlicensed band, we can say both (a) and (b) are exploited to help in capacity crunch problem.

Unlicensed spectrum could be seen as special case of spectrum sharing where all the sharing party have the same usage right. This means there is no PUs or SUs, they are equal. Using unlicensed band by mobile operators to help overcome the high traffic growth is beneficial progression. However, there are many limitations, as mentioned in section 2.1.2 (Offloading to Wi-Fi and Femtocells).

2.4 SUMMARY

Based on Copper's Law (and based on historical data), the capacity of the network will increase 2 times every 2.5 years. On the other hand, based on our analysis summarized in Figure 1-3, the average forecasted mobile broadband traffic increased 10 times every 2.5 years. Clearly there is a gap between the two numbers.

The first two factors, mentioned in this chapter (i.e. "cell site" and "technology"), are expected to have the similar effect rate over the capacity in the future; whereas the "more spectrum" could be the key solution in this case by adding the "sharing" inspiration. Although, as it was mentioned above, the "cell site" factor is still expected to be the superior factor in the increase since the capacity scales exponentially with number of cell sites. However, the capacity scales approximately linearly with spectrum and technology, so doubling the spectrum provides double the capacity. Similarly, doubling the technical efficiency doubles capacity [6].

To sum up the discussion, the "cell site" factor is bounded by the cost, the "technology" factor is limited by efficiency evolving path, and the "more spectrum" factor through spectrum sharing approach is the most applicable way to expand the capacity faster in a shorter time to meet the forecasted demand. It is one of the main motivations for us in this work to explore more in spectrum sharing field.

3.0 RESEARCH QUESTIONS AND DESIGN

The objective of this dissertation is to examine and quantify the benefits of spectrum sharing through different enforcement scenarios. It includes finding a relationship between different sharing aspects and characteristics. As mentioned earlier, the review of literature shows the critical need to add more wireless network capacity. There are three factors to overcome this capacity crunch: (1) adding more cell sites, (2) technology, and (3) adding more spectrum. The focus will be on spectrum sharing as part of the third factor, which can be considered as adding more spectrum liquidity to the wireless market.

Implementing spectrum sharing regimes on a non-opportunistic basis means that sharing agreements must be implemented. To have meaning, those agreements must be enforceable. This dissertation will discuss the enforcement of spectrum sharing and will demonstrate and examine diverse scenarios, which can be implemented, at different spectrum sharing environments.

This analysis is valuable because it will help regulators/governments prepare for possible future scenarios in addressing the capacity crunch. In addition, it can give government users more insight into expected future sharing as well as into how to optimize the mitigation of possible harmful interference due to sharing.

It is also of value to commercial users and operators in that they can use the results of this work to make more informed decisions as to the economic benefits of different spectrum sharing market and opportunities. Spectrum sharing can take different forms, so, precise operating principles must be established and a clear understanding of the desired scenario is necessary as well.

3.1 RESEARCH QUESTIONS

The research for this dissertation is guided by the following questions:

Q.1) What is the role of enforcement in spectrum sharing to solve the capacity crunch in mobile broadband networks?

Q.1.1) How can spectrum sharing be an important factor to overcome the capacity crunch?

Q.1.2) How can enforcement be an incentive for the PUs and the SUs to share the spectrum?

Q.1.3) What are the differences between centralized and decentralized enforcement?

Q.2) What are the possible spectrum sharing scenarios? How will those scenarios vary based on different spectrum sharing environments?

Q.3) How can "ex ante" and "ex post" enforcement approaches affect spectrum sharing utilization?

Q.3.1) What is the "ex ante" enforcement approach?

Q.3.2) What are the pros and cons of the "ex ante" enforcement approach?

Q.3.3) What is the "ex post" enforcement approach?

Q.3.4) What are the pros and cons of the "ex post" enforcement approach?

Q.3.5) What possible enforcement scenarios exist between the extremes of those two approaches?

Q.4) What is the relationship between sharing approach and spectrum opportunity cost[12]?

Q.4.1) What is the opportunity cost of exclusive spectrum?

Q.4.2) How the opportunity cost of shared spectrum will vary with "ex ante" and "ex post" enforcement approaches?

Q.5) What are the benefits of spectrum sharing?

Q.5.1) How can we quantify the benefits of different spectrum sharing scenarios?

Q.5.2) What is the upper bound of the reasonable cost of enforcement to share the spectrum in a specific scenario?

Q.6) How can the proposed levels of sharing and enforcement be generalized to take place in different sharing scenarios?

Q.6.1) How that can be applied to real case scenarios, such as: 1695-1710MHz band and 3.5GHz band?

Q.6.2) What are the commonalities between these mechanisms in light of changing sharing environments?

[12] For more information about "spectrum opportunity cost" concept, please refer to Appendix (A).

3.2 RESEARCH DESIGN

This section shows the overview research settings followed by the research hypotheses.

3.2.1 Research settings

The high-level preamble of this research is summarized in Figure 3-1. It shows the overall structure that we followed to narrow down the research scope from large capacity problem to spectrum sharing and enforcement domain. There are list of settings that are considered before we test the hypotheses:

S1) Define the enforcement concept in the spectrum sharing domain.

- Identify the importance of spectrum sharing as a leading enabler compared to other factors (e.g. more cell site and technology) to address the capacity crunch.
- Identify the differences between centralized and decentralized enforcement.
- Identify the types of harmful interference that are considered in this work, and who should be protected.

S2) Classify enforcement approaches in spectrum sharing and highlight the most reasonable approaches in the domain of spectrum sharing.

S3) Define the “ex ante” enforcement approach.

- Highlight the main features of the “ex ante” approach.
- “Ex ante” tools that will be analyzed in this dissertation includes:
  - Exclusion zones (main tool in the research model)

- Policy language
- Device standardizations

S4) Define the “ex post” enforcement approach.

- Highlight the main features of the “ex post” approach.
- “Ex post” tools that will be analyzed in this dissertation includes:
  - Sensing network
  - Litigation and fines
  - Interference threshold at PU location

S5) Identify possible enforcement scenarios that exist between the extremes of “ex ante” and “ex post” enforcement approaches.

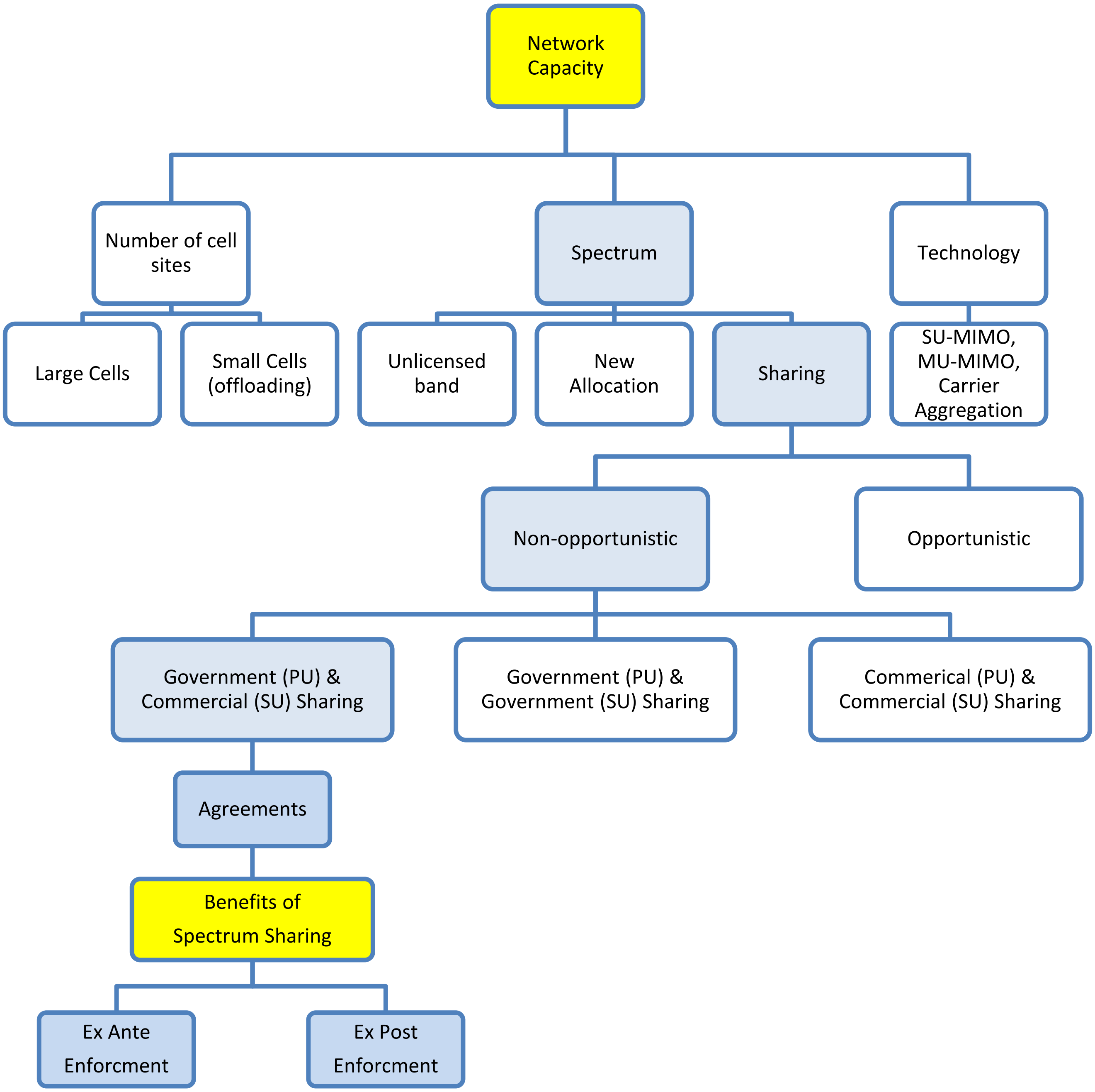

Figure 3-1 The overall structure that was followed to narrow down the research

3.2.2 Hypotheses

This is a list of hypotheses that we are testing in this dissertation. The following section will show how these hypotheses are connected to the research questions and outline.

The current and most common spectrum management approach is to allocate exclusive spectrum licenses (i.e. exclusive usage right) for wireless operators. Some licensees (i.e. PUs) do not operate and build wireless networks over the whole usage right area, such as particular government agencies. Their usage exists in specific locations and the rest of the usage right area is left unutilized. This means that there is high opportunity cost of these exclusive spectrum licenses. Spectrum sharing will increase spectrum utilization, either by allowing sharing at unutilized "PU's usage right area" or within "PU area of operations".

H1) The opportunity cost of exclusive spectrum is high and it is inversely proportional to spectrum sharing utilization.

Historically, spectrum has been highly regulated in order to prevent any harmful interference between the spectrum licensees. By introducing spectrum sharing as critical enabler to overcome the capacity crunch problem, preventing harmful interference through an appropriate enforcement level is a central point of effective spectrum sharing. There are two loci at which spectrum sharing may be enforced: "ex ante" enforcement (prevent any potentially harmful interference event before it has occurred), and "ex post" enforcement (after a potentially harmful interference event has occurred).

H2) Complexity and cost of the "ex post" enforcement approach is higher than the "ex ante" enforcement approach.

There are possible spectrum sharing scenarios that exist between the extremes of “ex ante” and “ex post” approaches. The choice of ex ante approach affects ex post strategies. There will be a point where the marginal benefit is equivalent to the marginal complexity/cost of enforcement. The best hybrid of those two enforcement approaches for a sharing environment is varies based on different characteristics, include but not limited to:

- PUs features:
    - PUs’ Receiver characteristics
    - Location of PU operation and network
        - Fixed location
        - Mobile applications bounded in a zone
        - Mobile applications all over the “spectrum usage right” area
- SU features:
    - Small cell networks (indoor and outdoor)
    - Large cell networks
- Frequency of shared band
- Power of SUs transmitters

H3) There is more than one relationship-curve by moving from the “ex ante” towards the “ex post” enforcement approaches, which varies by changing the sharing environment characteristics.

We believe that the additive benefits will vary by changing the sharing mechanisms. By moving towards the “ex post” enforcement approach, spectrum utilization increase, and the exclusion zone to protect the PUs will be smaller.

H4) Spectrum utilization will increase by raising the dependency on the “ex post” enforcement approach.

3.3 RESEARCH OUTLINE

Table 3-1 summarizes the correspondence of research settings and hypotheses with the comprehensive research questions in previous sections. One of the main outcomes of this research is to quantify the benefits of enforcement in shared spectrum bands. We try to facilitate spectrum sharing while protecting the PUs from adverse impact.

These benefits will draw the upper line limit for reasonable enforcement cost. We are not trying to build separate cost model to figure out precisely how much an enforcement scenario will cost; since DSA is still a relatively new research field and there is a lot of uncertainty associated with this cost estimate (e.g. cost and density of sensor networks). It will be part of the proposed future works beyond this research to try to model the enforcement-cost and compare it with the outcome of this research.

Table 3-1 Correspondence research settings and hypothesis with research questions

Research Settings and Hypothesis	Research Questions
S1 and S2	Q1, Q2
S3 and S4	Q3.1- Q3.4
S5	Q3.5
H1 and H2	Q4, Q5.2
H3	Q3.5
H4	Q5.1, Q6

As an approach to address the setting (***S1-S5***) of this research, ***chapter (4)*** covers that and links the foundations that are covered in ***chapter (2)*** to the rest of this work. It lays the basis of spectrum sharing notion and explain why the enforcement is a key enabler for sharing and then capacity. Figure 3-2 illustrates the idea of interaction between enforcement and spectrum sharing benefits. In addition, enforcement concept at spectrum sharing environment is described in details to show significant aspect that need to be considered. Finally, it shows the pros and cons of "ex ante" and "ex post" enforcement approaches, and possible enforcement scenarios exist between the extremes of those two.

In ***chapter (5)***, we demonstrated the model of spectrum sharing in which all factors that affect the sharing can be examined and studied. This chapter will demonstrate the simulation model design which can be applied to a variety of spectrum sharing environments. In addition, it is flexible to be customized to capture the characteristics for both PUs and SUs.

In ***chapter (6)*** and ***chapter (7)***, we modeled two real case studies. The first case examines the 1695-1710 MHz band. The second case focusses on the 3550-3650 MHz band. These two chapter also test the propose hypotheses. They are demonstrating advantages of spectrum sharing and the idea that there is not a single approach that applies for all type of sharing environment, nevertheless, at each case there are custom design sharing approach.

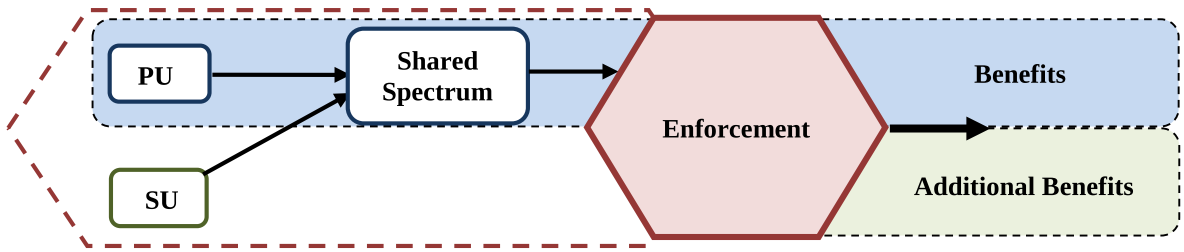

Figure 3-2 Illustration of the research setting idea

4.0 ENFORCEMENT IN SPECTRUM SHARING

The spectrum access rights granted by the Federal government to spectrum users come with the expectation of protection from harmful interference. As a consequence of the growth of wireless demand and services of all types, technical progress enabling smart agile wireless networks, and on-going spectrum management reform, there is both a need and opportunity to use and share spectrum more intensively and dynamically. A key element of any framework for managing harmful interference is the enforcement of those rights[13]. Since the rights to use spectrum and to protection from harmful interference vary by band (licensed/unlicensed, legacy/newly reformed) and type of use/users (primary/secondary, overlay/underlay), it is reasonable to expect that the enforcement approaches may need to vary as well.

4.1 ENFORCEMENT CONCEPTUALIZATION

The ultimate goal of enforcement is to induce "socially optimal" behavior, which may deviate from "individually optimal" behavior because of externalities, mistakes, or other sources of market failures. Socially optimal behavior includes investments in protection (harm avoidance)

[13] The enforcement approach is linked directly to the usage rights regime (two sides of the same coin). Spectrum sharing regimes are allocations of usage rights over the electrospace. Because the usage of an electrospace may result in incidental or deliberate interference, enforcement seeks to ensure compliance with the usage rights regime.

technology and in operating behavior that results in socially desirable outcomes. The full consideration of what an appropriate definition of harmful interference is beyond the scope of this work. For further discussion about harmful interference, please refer to [59], [60]. The enforcement approach may mandate certain behaviors or impose rewards/sanctions that may induce incentives toward desirable behaviors or penalize undesirable behaviors or outcomes (harmful interference).

Traditionally, in the spectrum field, the enforcement process is to prevent an interference event before it happens, such as geographical or spectral (i.e. guard band) separation between licensees, and transmitters/receivers specifications [24]. Transmitter specifications include "emission masks" which indicate how signal energy may be transmitted in frequency and antenna parameters, including type and height. Together, these transmitter specifications can be used to predict, with high likelihood, the electrospace the signal/service will occupy. Receiver specifications are useful in predicting the performance of a wireless communications system.

4.1.1 Spectrum Holes

Spectrum may be considered underutilized when the signal to noise ratio of the primary transmission is above the minimum needed for successful communications. Thus, secondary transmission opportunities can exist by adding small levels of transmit power or by identifying periods and spaces of no (or very low) primary user signal power and utilizing those at higher power levels.

One of the attempts to define the spectrum holes is Tandra et al. [61] where the authors tried to find strategies for sensing spectrum holes based on probabilistic models. In addition, the density of spectrum holes is based on the sensitivity of sensing methodology and the amount of interference the primary user can tolerate to allow sharing. For more about spectrum holes, please refer to one of my papers in this regards [39] [24] [41].

4.1.2 Centralized vs Decentralized Enforcement

The enforcement can be centralized or decentralized, or more generally, a mix of both. The classic form of centralized enforcement relies on a regulator such as the FCC or NTIA, but could be undertaken by a spectrum sharing broker or band manager. Decentralized enforcement might include other radios in the environment that might, for example, refuse to forward packets or connect to radios that are behaving badly. Centralized or decentralized enforcement might rely on reputation effects.

For example, a database with information about the availability of spectrum holes or other operating instructions may be employed as centralized technical enforcement components, such as the database used in TV White Space applications. On the other hand, radio "black boxes"[62] or collaborative sensing might be employed as elements in decentralized enforcement.

Spectrum sharing pushes the enforcement towards decentralized case. While CRs embeds functionality that poses additional enforcement challenges, it also offers new tools for technical enforcement. Distributed intelligence to radio means that radio is increasingly capable of participating in intelligent and dynamic automated enforcement.

4.1.3 In-Band and Out-Of-Band Interference

Traditionally, interference is classified as in-band or out-of-band interference. The former mainly due to devices using the same spectrum band, and the latter due to devices' emissions using out-of-band spectrum and partially due to receiver sensitivity as well.

From an enforcement perspective, the "usage right" regime determines whether there is harmful interference or not. For example, under some interpretations of exclusively/licensed spectrum, the PU has a right to exclude other users/uses from the spectrum.

This dissertation considers in-band interference only, where the SUs use the share the same band with the PU.

4.1.4 Ex Ante and Ex Post Enforcement

There are two loci at which usage rights may be enforced:

- Ex ante enforcement:
  - The actions that been taken to prevent and avoid any potentially harmful interference event before it has occurred.
- Ex post enforcement:
  - The actions that been taken after a potentially harmful interference event has occurred.

Figure 4-1 The tandem of ex ante and ex post enforcement

Ex ante and ex post approaches work in tandem, not in isolation. Thus, the choice of ex ante approach affects ex post strategies [24]. The choice of how to design the enforcement approach directly and indirectly impacts the enforcement-cost. In particular, the costs of inducing good behavior (avoiding bad one) must be balanced against the social costs and benefits under different scenarios. Therefore, the cost of strong ex ante rules is that they need to be enforceable and may pose the risk of overly restricting behaviors that may be reduce the welfare enhancing (e.g. innovation) as well as decreasing the value of the sharing opportunity for the entrant (i.e. SUs).

4.1.5 Analogy

Police perform the action of ex ante and ex post enforcement. They act to detect bad acts (before harm happens) by giving citations for cars with illegal brake lights or for driving too fast, even if not unsafely, for example. Their presence provides assurance of enforcement thus deterring bad behavior just through their presence. They enforce after harm has already happened (ex post) by, for example, assessing liability in accidents, penalizing unsafe driving with stronger tickets, and by testifying in court. The police behave differently in a world with cameras; that is, they know where traffic is most likely to require their oversight, what evidence they need to establish at the scene vs. what is recorded remotely [24].

To extend the analogy a little bit further, one may think that the “traffic laws” could be changed with technology as CRs/SDR changes the DSA mechanisms. For example, a "speed pass" that allows different vehicles to travel at different speeds based on some criteria (e.g. ex ante driver skill certification), variable fines for use of HOV lanes during congestion periods, or modifications to car operation in response to car/road real-time diagnostics (e.g. detection of low tire pressure and bad road conditions).

4.2 EX ANTE

As described above, ex ante enforcement measures are designed to prevent in-band interference from occurring. In this section, major ex ante enforcement tools are highlighted and their effects on “sharing benefits” are examined.

4.2.1 Exclusion Zones

The development of exclusion zones – spatial regions where the SU may not operate – is a principal ex ante tool. The exclusion zone is basically constructed by a database that summarizes all PU spectrum usages. PU spectrum usages can be static or dynamic (temporally or spatially), in either cases they can be stored with a feedback kink between the PU and the database. The database can subsequently be accessed easily by SUs to determine exclusion zone boundary. In this case, there is no need for the SU to sense the PU signal. This is consistent with the PCAST report recommendation of using the database approach in static sharing environment [3]. In other cases where the PU spectrum usage is not predictable, the SUs should sense the PU existence to be able to share the spectrum with them.

Generally speaking, spectrum can be shared in frequency, time and spatial dimensions or any combination thereof. If two users do not share the spectrum on at least one of these three dimensions, each of them is said to have exclusive right to that part of the spectrum that they do use. In this regards and at this dissertation, the sharing between the PUs and SUs exist at two dimensions: (1) spectrum and (2) time; with different level of spatial dimension. Exclusion zones are a special tool to facilitate an ex ante enforcement mechanism which prevents harmful interference. Exclusion zones are not the only ex ante enforcement mechanism; however, it is the most important and the one we are focusing on at this research.

In this dissertation, we propose different “protection/exclusion zone” concept to increase spectrum sharing efficiency (i.e. increase benefits). Protection/exclusion zone will encompass a smaller area with increasing dependence on ex post enforcement approach; see Figure 4-2.

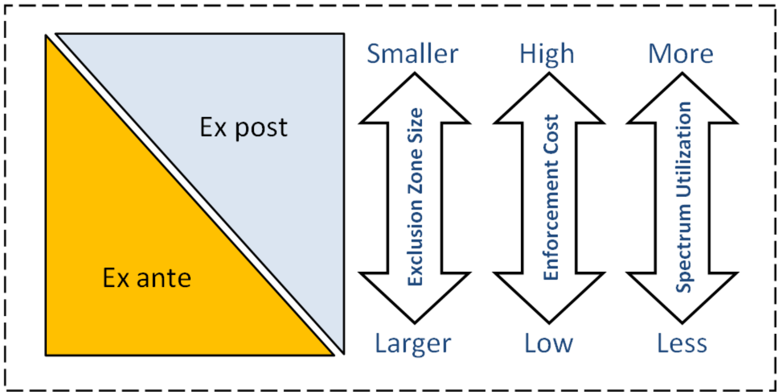

Figure 4-2 Tradeoff between ex ante and ex post enforcement

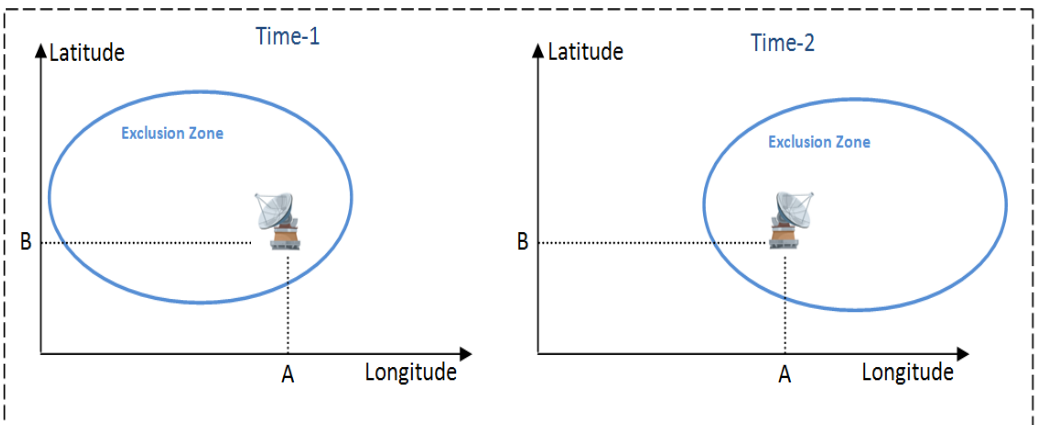

Figure 4-3 The concept of dynamic exclusion zones [14]

[14] The exclusion zone will shift and vary based on the "PU antenna" shifts (the PU antenna is fixed station). If a static exclusion zone is used, it must be the union of all possible antenna positions.

In some cases, the exclusion zone could be dynamic which increases the spectrum utilization compared with static exclusion zones. For example, in the case where the PU antenna orientation is not fixed, the use of static exclusion zones represents a worst-case situation. In any particular reception episode, the exclusion zone is ovate, as shown in Figure 4-3. If a static exclusion zone is used, it must be the union of all possible antenna positions. It would thus be large compared with the exclusion zone associated with a particular receiving episode.

4.2.2 Policy Language

Spectrum sharing "policy language" research is another way to achieve ex ante enforcement. It is considered as a decentralized enforcement approach as well. For example, SUs should be required to have this policy language installed on their devices to be able to share the spectrum. These policies will dictate the SUs' usages to be within the agreed sharing limitations.

A policy is a selection of facts specifying spectrum usage [63]. These facts are interpreted through a reasoning instance, which is called "policy reasoner". The "policy reasoner" is able to consider a flexible number of policies realizing a policy adaptive cognitive radio [63] [64]. One advantage of this type of ex ante enforcement is to reduce the certification effort of SUs' devices, where the policy is not static and can be changed dynamically. If policies, policy reasoners, and devices can be accredited separately, accreditation becomes a simpler task for each component. In addition, devices and enforcement-policies can evolve independently over time, which is superior to separating policies from devices.

There is a dramatic increase in standards work due to the progress of CR technologies. The IEEE Standards Coordinating Committee 41 (SCC41) represents standards projects in the areas of

DSA, CRs, interference management, coordination of wireless systems, advanced spectrum management, and policy languages for next generation radio systems [65]. While policy language-based approaches hold great promise, they should be harmonized with an enforcement ecosystem that ensures compliance with agreed-upon rules and supplements the detection and enforcement adjudication process with complementary mechanisms.

4.2.3 Device Standardizations

In a wireless world, device standardization is the process of developing and implementing technical standards. There are many useful advantages to this process, including but not limited to: assuring compatibility between devices working by the same standard, managing in-band/out-band interference, making type approval or certificate of conformity possible (which is granted to a device that meets a minimum set of regulatory, technical and safety requirements). The most important benefit of standardization - and most relevant to this dissertation - is to avoid harmful interference between wireless networks/devices as a process of “ex ante” enforcement mechanisms.

For example, WiFi devices are standardized and approved (i.e. type approval) to operate only at limited frequency bands, such as 2.4GHz or 5GHz, which prevent the device from interfering with the PU of other bands. Another part of the standardization process is the power characteristics and limitations that manage interference. Those standards are part of “ex ante” enforcement to avoid interference before it happens.

4.2.4 Summary

The tools discussed in this section are the three common “ex ante” enforcement tools. For the scope of this dissertation, we are focusing and examining the “exclusion zone” specifically. In spectrum regulations, the static exclusion zone is already applied in many applications. For example, we can assume the spectrum-exclusion-license in a given country as a large nationwide exclusion zone for that licensee. In spectrum sharing, we propose the idea of small exclusion zones which will play a critical role in increasing sharing efficiency. In addition, we propose that SUs can work within the exclusion zones under different types of enforcement regulations.

4.3 EX POST

Weak ex ante enforcement mechanisms must often be paired with stronger ex post enforcement mechanisms to deal with inevitable interference events. Since ex post mechanisms involve the adjudication of actual interference events, they typically involve collecting information that can be used in agreed-upon adjudication procedures. In the absence of particular procedures (which would normally be negotiated between primary and secondary users), we can assume this information would include the detection of interference events attributable to the SU(s). It is likely that this information would include a time stamp and other information, such as the location at which the signal is detected, as well.

In addition, exclusion zones do not provide a guarantee of in-band interference avoidance. Since propagation is unpredictable, signals could occasionally travel farther than expected.

Likewise, the exclusion zones do not explicitly account for tall features, like tall buildings and mountains, which can cause longer than expected propagation distances. Moreover, a SU can intentionally or accidently cross the boundary of an exclusion zone and cause interference. As a result, ex post mechanisms are needed to provide data to PUs and SUs to better adjudication procedure and to further tune the system for future interference avoidance.

This section will cover the three major tools to facilitate “ex post” enforcement related to spectrum sharing.

4.3.1 Sensing Network

As a main element of ex post enforcement tools in spectrum sharing, there should be a sensor network able to detect and determine any interference source. Attributing an interference event is necessary for enforcement settlement because it is not reasonable to hold SUs accountable for all interference events. In some exclusion zones, there should be more than one sensor station for greater accuracy in detecting interference events. Therefore, there is a need for a sensing network that can detect interference events across the zone. It is a critical element of the enforcement process in shared environments[15]. There is a tradeoff between the cost of a sensing network and its accuracy in detection interference events.

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[15] In some static sharing environment or under specific circumstances, there may not be a need for sensing network, such as TVWS case. At TVWS, the enforcement based only on very large exclusion zones (ex ante) and a database gathering the static TV stations characteristics.

Attributing an interference event to an SU is necessary for appropriate adjudication. For example, inter-modulation products from a nearby but unrelated user could cause significant electromagnetic energy to occur in the PU's band, causing interference. To associate an interference event with the SU(s) means that the PU has either some knowledge about the SU's signal characteristics and/or an identification code that can easily be obtained by demodulating part or all of the SU's signal. In some cases, the ex post process can be relaxed. For example, if the SU is a single cellular operator (e.g. LTE), demodulation of the cellular signal to uniquely identify the SU (i.e. causing the harmful interference) may not be necessary since all the users belong to a single operator (and that operator is responsible for them); that will lead to a reduction in ex post enforcement costs. If multiple SUs exist, the cellular signal would have to be demodulated to identify the source of the interference.

Spectrum sharing is a complex dynamic and multi-stakeholder system that could benefit from the feedback provided by practice so that the system can be optimized to perform "better" by an agreed-upon set of attributes. A collaborative and adaptive ex post enforcement approach could (and probably would) result in benefits to both PUs and SUs. The PUs could look forward to a decreasing rate of significant interference events and the SUs could look forward to reduce ex ante rules (e.g. exclusion zones) that would allow them to use the shared spectrum as effectively as possible.

Generally speaking, the sensor density is dependent on a variety of factors, including spectrum band, characteristics of the primary signal and sensing bandwidth. In addition, there is a tradeoff between the number of sensor stations and the ability to minimize the exclusion zone size that should be considered during implementation (to the extent that the definition of the "ex ante" exclusion zone is dependent on the greater precision of the "ex post" sensors).

4.3.2 Litigation

In ex post enforcement, the PU must present evidence to an adjudicator in support of a claim of interference[16]. In some cases, they may need to provide evidence that the interference event was disruptive. Gathering evidence to support an interference claim would almost certainly require the existence of a sensor network that is capable of gathering adjudication evidence. This sensor must be able to (1) detect signal energy at or above an agreed-upon interference threshold and (2) determine if the signal energy could reasonably be attributed to a SU.

It is likely that the sensing would be performed (at least) by the PU, since they would be making claims for adjudication. The SU may wish to have an independent sensor to (1) validate the claim of the PU and (2) provide additional information that the PU may not have provided. Such additional information might include the direction of the interfering signal and the ID of the SU-unit that transmitted the offending signal.

A mutually trusted third party could also provide sensing information to both the primary and secondary users if the costs of sensing are too high. It is most likely to be the case in many real government and commercial sharing scenarios. The FCC and the PCAST report predict this likelihood and there is suggestion of what is called “band manager” [3].

[16] It is not always clear who is the adjudicator. In the USA, the NTIA retains responsibility for civilian federal spectrum management, whereas the FCC does for commercial spectrum management. Furthermore, courts have jurisdiction for resolving property disputes. Thus, the adjudication venues, which is beyond the scope of this dissertation, must be defined in advance.

4.3.3 Interference Threshold at PU Location

A traditional exclusion zone, usually, is a setting to make the PUs does not notice the existence of the SUs. This means, the PUs' receivers will not be exposed with any additional interference due to the sharing. In certain case, where there is a bit high trust between the PU and SUs, it is possible to relax the ex ante enforcement process to be only agreed interference threshold (above the regular PU's noise floor) that the SUs promise to not exceed. That does not mean we do not have to have sensing networks to locate the interferer, but it gives the SUs the choice to internally decide the way prevent exceeding the threshold at the PU area.

4.3.4 Summary

In this section, three ex post tools was highlighted. Although the major role of ex post enforcement is to detect and identify who caused harmful interference, it is very important to set the appropriate penalty/sentence against him. Following the law and economics literature, the purpose of enforcement is to make rights definition meaningful. If we assume rational economic actors, we can establish some parameters around penalties as well as enforcement costs.

Penalties serve to promote coordination between primary and secondary users and also to compensate for violations. To ensure cooperation, the SU should find it cheaper to coordinate than to pay a penalty. Thus, the product of the penalty and the probability of detection should be greater than the benefit the SU obtains from transmitting in a way that causes interference.

$$\boldsymbol{d} \times \boldsymbol{P} \geq \boldsymbol{B}$$

Where:

$$\begin{cases} \boldsymbol{d}:\ the\ probability\ of\ detection\ and\ successful\ adjudication \\ \boldsymbol{P}:\ the\ penalty\ paid \\ \boldsymbol{B}:\ benefit\ the\ SU\ obtains\ from\ transmitting\ in\ a\ way\ that\ causes\ interference \end{cases}$$

The uncertainties of frequency propagation mean that interference events may be accidental. If the average payment is based on willful interference, the SU will (1) have an incentive to optimize their system to eliminate interference events and (2) be indifferent to intent (i.e. willful or accidental).

4.4 BENEFITS AND COST OF ENFORCEMENT

One of the main outcomes of this research is to quantify the benefits of enforcement in shared spectrum scenarios. These benefits will draw the upper line limit for reasonable enforcement cost. Therefore, the model has been built in this dissertation is not a cost model to figure out precisely how much an enforcement scenario will cost, rather quantify the sharing benefit over different level of enforcement methodologies.

4.4.1 Precision of Enforcement

In general, we consider an enforcement approach to be more precise if it more specifically differentiates legitimate users and uses from illegitimate ones. The enforcement-cost (including the complexity) of precision depends on some attributes of the system itself. The maximum practical cost of enforcement is closely linked to the value of the resource: the more valuable resource becomes, the more worthwhile it may be to invest in more precise enforcement technology.

For SUs, the most precise enforcement approach would be ability to control/identify (on a moment-by-moment basis) a particular event based on factors such as the device's location and the PU's instantaneous usage. Ex ante enforcement would involve permission to transmit on the shared band, and ex post enforcement would entail identifying the precise time and location of SU devices whose signals exceeded the agreed-upon in-band interference threshold. By contrast, the least precise enforcement mechanism would involve the creation of large exclusion zones as an ex ante tool, and a simple in-band interference threshold detection system, perhaps with signal classifiers (to exclude non-secondaries interference) but without any attempt to locate the interfering mobile.

4.4.2 Enforcement Cost

Funding of the enforcement infrastructure is yet another important issue. Several methods for funding have been applied in different industries. For example, in many contexts, the enforcement action is funded from general government tax receipts (e.g. Homeland Security), while in others, industry-specific taxes or fees (e.g. license fees for hunting and fishing) may be used to fund the enforcement effort. Also, funds collected in the form of sanctions may be used to help defray enforcement costs [24].

An optimal enforcement approach is inextricably linked to the usage rights regime and economic environment in which it is expected to function. Thus, costs of inducing good behavior (avoiding bad behavior) must be balanced against the social costs and benefits under different scenarios. Also, enforcement-cost is associated with the collection of evidence and establishing its provenance at various stages in the process. The process needs to anticipate the challenges of detecting "bad" behaviors (i.e. behaviors that have a high probability of resulting in actual harm) or actual harm itself, establishing liability, adjudicating whatever sanctions are appropriate, and then imposing those sanctions.

Evidence collection can be done by the market participants or by a third party (such as government). The costs of such information processing/decision-making may be significant, and these costs need to be weighed with due consideration of the costs/benefits associated with the rights that the enforcement approach is intended to enable [24]. Thus, when it is difficult (expensive) to detect harmful behavior, it may be preferable to rely on stronger ex ante rules.

The ex ante and ex post enforcement effects are intimately linked as well. For example, if the ex ante rules and processes are sufficiently strong, then ex post harm may be prevented altogether. Also, certain types of ex ante rules may be easier to monitor, hence lowering the cost of enforcement. Even strong ex ante rules may require ex post enforcement; for example, licensing approval for equipment is usually based on a prototype or pre-production unit, but compliance of production units may require some kind of policing to ensure compliance.

5.0 SPECTRUM SHARING MODEL

The centerpiece of this dissertation is a model of spectrum sharing in which all factors that affect the sharing can be examined and studied. In addition, it is being used to test the hypotheses of this dissertation. Although, our goal to test these hypotheses, we try to draw the possible lessons that can be taken from simulating real case scenarios of spectrum sharing.

This chapter will demonstrate the simulation model design which can be applied to a variety of spectrum sharing environments. In addition, it is flexible to be customized to capture the characteristics for both PUs and SUs. The following chapters will illustrate the simulation results of this model in two case scenarios.

5.1 GENERAL MODELING

The current approach to spectrum sharing using exclusion zones (as suggested by NTIA) is based primarily on ex ante enforcement by setting a very large exclusion zones, see Figure 5-1. This dissertation, however, increase the role of ex post enforcement. The proposed modeling of geographical exclusion zones moves from a purely ex ante approach (large exclusion zone only) towards ex post enforcement, see Figure 5-2. The model includes these additions:

- Benefits evaluation of spectrum sharing within the exclusion zone.
    - Model of a “Gray space” area.
    - Model of a “Black space” area.

- Benefits evaluation of spectrum sharing outside the exclusion zone.
    - Model of a “White space” area.

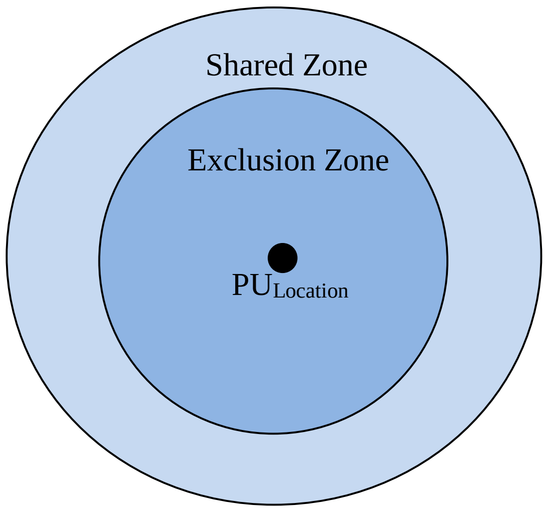
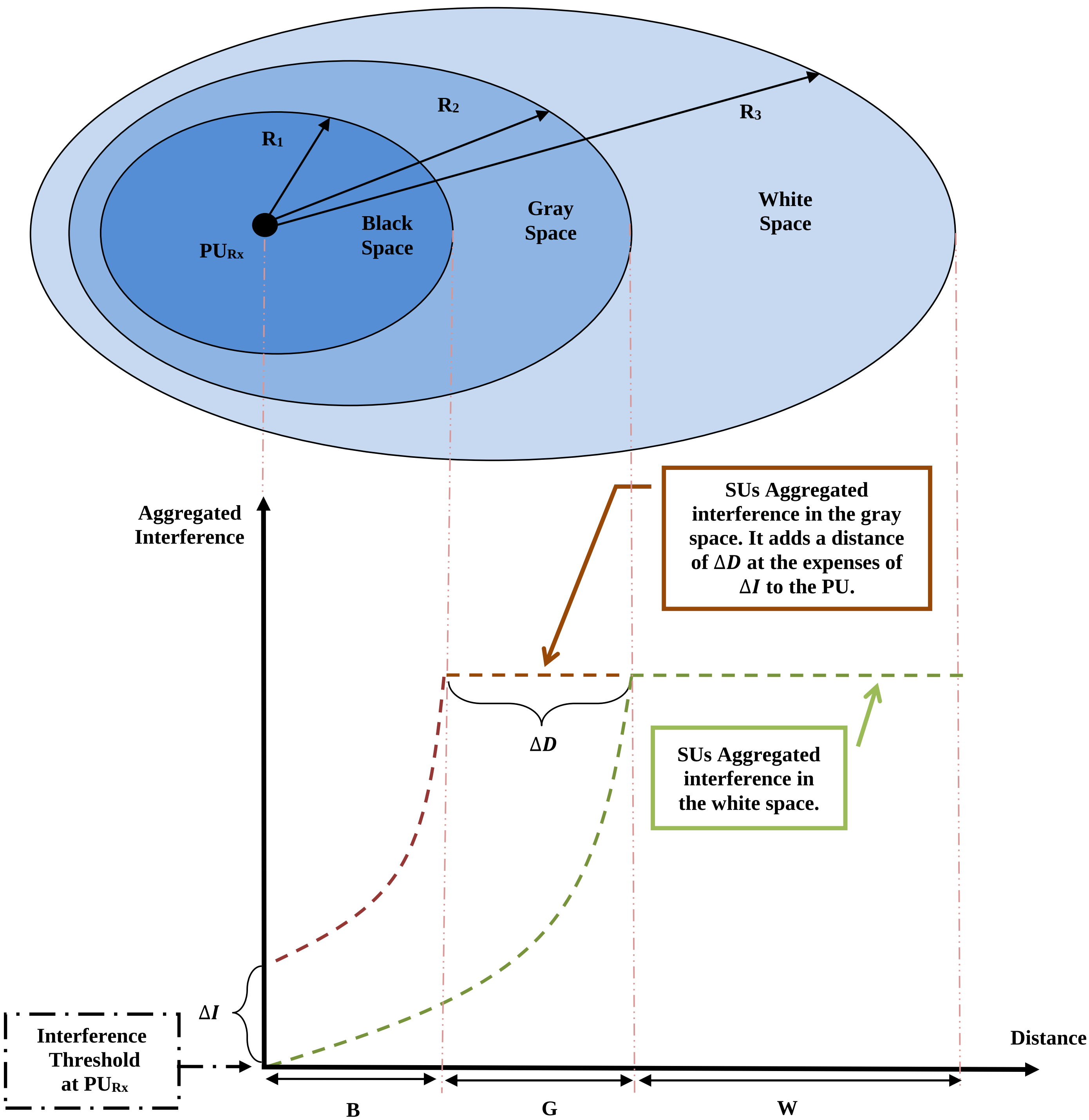


Figure 5-1 Current proposed idea

In Figure 5-2, the PU antenna is represented in the center of simulated area/circle. The x-axis represents the distance from the PU antenna to the perimeter of the “PU usage right area”.

- R1: proposed radius of Back space.
- R2: proposed radius of Gray space. R1 and R2 are the key variables affecting the function of sharing utilization.
- R3: the radius of PU usage right area. It is the total area where the PU is originally licensed to use the spectrum. We assume this radius to be 100km during the simulation.

Figure 5-2 Research Model



5.1.1 White Space (W)

- $Area = \pi\ (R_3^2\ -\ R_2^2)$
- This is the area where the SUs can operate at the maximum standardized power-limit without causing harmful interference to the PU.
- The expected enforcement effort to facilitate sharing in this area is relatively less compared to the other proposed areas.
    - In special cases where the cost of ex post enforcement is higher than the benefits of sharing Gray and Black spaces, we probably need ex ante enforcement only to share the W space, through simple database holding the boundary of the exclusion zone at R_2.
    - The relatively low enforcement effort in W space area is one of the major advantages of sharing, where utilization increases at lower enforcement cost.
- R_3 represents either the border of “spectrum usage right” of the PU or it could be bounded by another exclusion zone domain.
- It is very important to differentiate between “operations area” and “usage right area”.
    - The usage right area is the geographical area where the PU is licensed to use its spectrum/frequency.
    - The operations area is the geographical location where the PU uses the spectrum (i.e. builds its network).
    - In special domain, W space sharing benefits will increase if the difference between “operations area” and “usage right area” increases (the “operations area” is always less than or equal the “usage right area”.

5.1.2 Gray Space (G)

- $Area = \pi\ (R_2^2\ -\ R_1^2)$
- This is the area where the aggregated interference from SUs will be greater than the interference threshold of the PU receivers and below the maximum interference threshold set by the PU which is part of sharing enforcement procedure.
- R_1 depends on the sensitivity of PU receivers to additive noise caused by spectrum sharing.

5.1.3 Black Space (B)

- $Area = \pi\ (R_1^2)$
- This area is close to the PU receiver, where the penalties for interference would be set to give the SU an incentive to create profit maximizing zones out from sharing.
- Sharing in this area is expected to be heavily based on ex post enforcement.
- B space is expected to be shared by a centralized SU, represented, for example, by a single operator or interface that would manage all the related secondaries. This is the most likely case when we have large cells of SUs (i.e. LTE network). Thus, enforcing SU behavior will be achieved through this single interface. For more information about the differences between centralized and decentralized SUs, please refer to [24] [41].
- In special cases, B space could be very small or almost zero, in which case the PU can coexist with the maximum possible interference threshold caused by SUs (where the whole exclusion zone becomes G space).

- One of the purposes of this model is to evaluate the benefits of W, G, and B spaces, even if it is not possible to share the G and/or B spaces. In the end, we need the value of the exclusion zone for each level of enforcement scenario, so that, for example, we could recommend re-locating the PU antenna if possible based on a cost-benefit analysis.

Table 5-1 Summary of proposed classifications

Sharing Domains[17]				
Spectrum	**Temporal**	**Spatial**	**Space Type**	**Enforcement Nature**
yes	yes	no	$W_{Spatial}$	Heavily based on Ex Ante enforcement
yes	no	yes	$W_{Temporal}$	Not considered in this dissertation
yes	yes	yes	G	Based on both Ex Ante and Ex Post enforcement
			B	Heavily based on Ex Post enforcement

[17] For more information, please refer to section 1.1.2 (Taxonomies of Spectrum Sharing).

5.2 MAIN FUNCTION OF SIMULATION

The key component of this simulation is the methodology that has been used to determine the aggregated interference level at a PU location with many SUs sharing the band. The aggregate interference level at PU receivers depends on several factors, such as channel parameters, spatial distribution of SUs, and transmit power level. In this work, we have created a reasonable representation of the aggregate interference in the spectrum sharing environment where multiple SUs cause interference to a single PU. Moreover, we will explore the impact of aggregate interference over sharing benefits.

In this model, each simulated SU can cause interference to the PU which can be defined in equation (1). Then, aggregated interference is calculated by converting the individual interference in “dBm” to “Watt” in order to add them together. Then the sum is converted to “dBm” again in equation (2).

$$\boldsymbol{I} = \mathbf{I_{SU}} + \mathbf{G_{PU}} + \mathbf{G_{SU}} - \mathbf{PL} - \mathbf{FDR} - \mathbf{L_{PU}} - \mathbf{L_{Additional}} \tag{1}$$

$$\boldsymbol{I_{AGG}} = \mathbf{10}\boldsymbol{Log_{10}}\left[\sum_{j=1}^{N} \boldsymbol{I}\right] + \mathbf{30} \tag{2}$$

Table 5-2 Model equations descriptions

	Description	Unit
I	SU interference (at the PU receiver)	dBm
I_{SU}	SU transmitted power	dBm
G_{PU}	Antenna gain of the PU	dBi
G_{SU}	Antenna gain of the SU	dBi
PL	Propagation Loss	dB
FDR	Frequency Dependent Rejection	dB
L_{PU}	Losses at PU antenna	dB
$L_{Additional}$	Additional Losses (e.g. penetration loss factor)	dB
I_{AGG}	Aggregated interference power at PU receiver	dBm
N	Number of SU	N

5.2.1 SU Transmitted Power

Since the number of simulated SUs is very large (i.e. tens of thousands) around the PU location, the transmit power should be modeled in a more accurate way[18]. To do this, we follow a probability distribution function for the transmit power of SUs. More details follow in the two case studies in the following chapters.

[18] Some researchers in this field suggest using average transmit power which will be reasonable for small number of SUs in a small area of simulation.

5.2.2 Antenna Gain

The gain of SU antennas is set at zero in this model, which means that we are not considering any gain on the SU side due to the characteristics of the technology representing the SUs, such as LTE-UE, Femtocells, and WiFi.

For the PU, we follow the ITU-R F.1245-1 recommendation [66]. This is a mathematical model of the average radiation pattern that should be adopted for frequencies in the range 1-40 GHz. This ITU recommendation is the best prediction model for antenna pattern which has been used widely in this type of research. We believe that if there is a percentage of error due to relying on this recommendation, it will be very miner and will not affect the results significantly. There are two cases:

<u>Case-1</u>: When the ratio between the antenna diameter and the wavelength is greater than 100 (D / λ > 100), the following equation should be used:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\varphi\right)^2 \qquad for \qquad 0^o < \varphi < \varphi_m$$

$$G(\varphi) = G_1 \qquad for \qquad \varphi_m \le \varphi < \max(\varphi_m, \varphi_{r)}$$

$$G(\varphi) = 29 - 29 \log\varphi \qquad for \qquad \max(\varphi_m, \varphi_{r)} \le \varphi < 48^o$$

$$G(\varphi) = -13 \qquad for \qquad 48^o \le \varphi \le 180^o$$

Where:

G_{max} : $maximum\ antenna\ gain\ (dBi)$

$G(\varphi)$: $gain\ relative\ to\ an\ isotropic\ antenna\ \ (dBi)$

φ: $off-axis\ angle\ (degree)$

D: $antenna\ diameter\ (meter)$

λ: $wavelength\ (meter)$

$$G_1 = 2 + 15\log\left(\frac{D}{\lambda}\right) \qquad ; \quad (gain\ of\ the\ first\ side\ lobe)$$

$$\varphi_m = \frac{20\lambda}{D}\sqrt{(G_{max} - G_1)} \qquad ; \quad (degree)$$

$$\varphi_r = 12.02\left(\frac{D}{\lambda}\right)^{-0.6} \qquad ; \quad (degree)$$

Case-2: When the ratio between the antenna diameter and the wavelength is less than or equal to 100 ($D/\lambda \leq 100$), the following equation should be used:

$$G(\varphi) = G_{max} - 2.5 \times 10^{-3}\left(\frac{D}{\lambda}\varphi\right)^2 \qquad for \qquad 0^o < \varphi < \varphi_m$$

$$G(\varphi) = 39 - 5\log\left(\frac{D}{\lambda}\right) - 25\ \log\varphi \qquad for \qquad \varphi_m \leq \varphi < 48^o$$

$$G(\varphi) = -3 - 5\log\left(\frac{D}{\lambda}\right) \qquad for \qquad 48^o \leq \varphi \leq 180^o$$

Figure 5-3 shows the azimuth and elevation antenna pattern from the simulation model where the maximum antenna gain equals 43 dBi and the minimum elevation angle for PU antenna is 27 degrees.

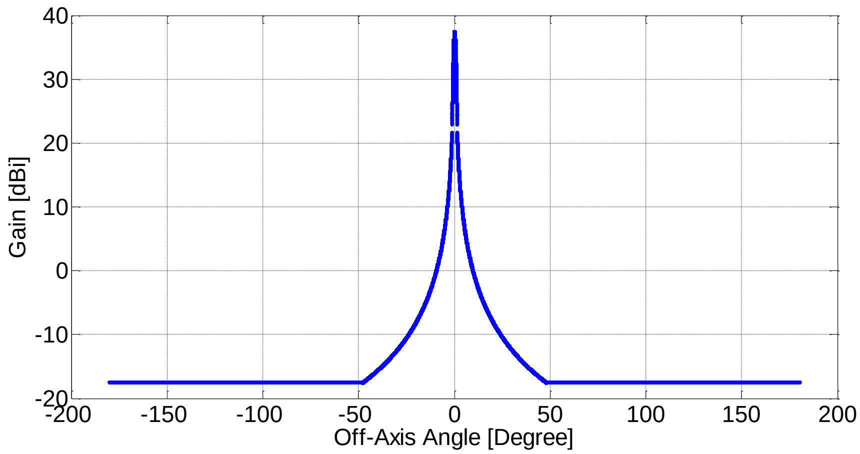


Figure 5-3 PU antenna gain pattern

5.2.3 Path Loss

Path loss is the reduction or attenuation in power density of a signal wave as it propagates through space. This model uses the Hata path loss models to relate the size of a shared area (W, G, and B space areas) with SU signals. Its effects on transmit power were represented in Figure 5-2 as a dashed line. It shows two cases: (1) the representation of maximum allowable signal power of the SU while working in the W space area; (2) the representation of maximum allowable signal power of the SU at the G space area. In the second case, a sharing distance gain of ΔD at the expenses of ΔI at the PU side. Due to the characteristics of path loss, the marginal distance increase is typically larger than the increase in marginal interference, $\Delta D > \Delta I$.

To reflect the terrain of the simulated area, four Hata models were implemented: open, suburban, small city, and large city. These models are the most commonly used in wireless communication field, particularly because they can capture the long distances as well as four distinct terrain models. The following equation represents the value of path loss:

$$PL = 69.55 + 26.16Log_{10}(f) - 13.82\ Log_{10}(h_b) - a(h_m) + [44.9 - 6.55Log_{10}(h_b)]Log_{10}(d) - K \qquad \mathbf{(3)}$$

<u>*Where:*</u>

h_m: $Hight\ of\ mobile\ station$

h_b: $Hight\ of\ base\ station$

$$a(h_m) = \begin{cases} [1.1Log_{10}(f) - 0.7]h_m - [1.56Log_{10}(f) - 0.8] & \rightarrow Open, Subueban, SamllCity \\ 3.2\ [Log_{10}(11.75h_m)]^2 - 4.97 & \rightarrow Large\ City \end{cases}$$

$$K = \begin{cases} 4.78[Log_{10}(f) - 18.33Log_{10}(f) + 40.94] & \rightarrow Open \\ 2[Log_{10}\left(\frac{f}{28}\right)]^2 + 5.4 & \rightarrow Subueban \\ 0 & \rightarrow\ SamllCity, Large\ City \end{cases}$$

5.2.4 Frequency Dependent Rejection

Per the ITU[19] and NTIA documents [67], “Frequency Dependent Rejection (FDR) accounts for the fact that not all of the undesired transmitter energy at the receiver input will be available at the detector. FDR is a calculation of the amount of undesired transmitter energy that is rejected by a

[19] See, Recommendation ITU-R SM.337 (2008).

victim receiver. This FDR attenuation is composed of two parts: on-tune rejection (OTR) and off-frequency rejection (OFR). The OTR is the rejection provided by a receiver selectivity characteristic to a co-frequency transmitter as a result of an emission spectrum exceeding the receiver bandwidth, in dB. The OFR is the additional rejection, caused by specified detuning of the receiver with respect to the transmitter, in dB".

Based on ITU recommendations (ITU-R SM.337), there are many ways to measure FDR value. In this spectrum sharing model, we tend to go for the most conservative option when there is a list of possibilities, meaning that we choose the option with the most protection for PU receivers. Therefore, the value of FDR is set at zero since its value (if any) is very small and not significant in many cases in this analysis. Although FDR has been built into the simulator for future analysis, in this dissertation, we ignore its effects in both 1.7 GHz and 3.5 GHz cases to simplify the exposition.

5.2.5 Assumed Losses

5.2.5.1 Losses at PU antenna These are losses associated with PU receivers, such as insertion loss, cable loss, or polarization mismatch loss. This depends heavily on the characteristics of the antenna. It will be assumed to be 2dB in our analysis.

5.2.5.2 Additional Losses This captures the additional power loss coefficients for any losses over the transmission space, such as indoor transmission loss calculation or floor penetration loss factor. For this factor, we rely on some of the assumptions from ITU recommendation ITU-R P.1238-6.

5.2.6 Aggregate Interference

To model the accumulated interference, equation (2) aggregates interference power from all SU transmitters surrounding a primary receiver. This is the most complex step of the model because the model simulates each SU individually (i.e. based on its location, path loss, terrain effects, gain, transmit power, etc.), then aggregates them to measure the interference level at each specific exclusion zone radius calculations.

5.3 MODEL DESIGN

One of the goals in the building of this model has been to be expandable to any future spectrum sharing scenario. In this dissertation, the PU is assumed to be a single PU receiver and there are a large number of SUs. In the case of spectrum sharing, the SUs will be seen by the PU as additive noise/interference on top of any pre-existing noise (i.e. noise before sharing). This additive interference will affect PU receivers only, not the transmitters. Therefore, the location of the PU receivers is what we are considering to force a protection distance between SUs' location and PU receivers.

5.3.1 Settings

- A single PU receiver that is bounded by three types of zones: B, G and W spaces.
- The external radius of W space (i.e. R_3) is 100km.
- A large group of SUs.
- We set the interference threshold level of the PU to be $G_{boundary}$ which determines the closest distance between the SUs and the PU.
- It is assumed that the PU will agree to tolerate some extra interference (i.e. ΔI) to increase the sharing utilization (i.e. ΔD). This extra interference level is bounded by $B_{boundary}$.
  - G_{boundary} and B_{boundary} are negative values [dBm]
  - $G_{\text{boundary}} < B_{\text{boundary}}$ or $|G_{\text{boundary}}| > |B_{\text{boundary}}|$
- From these distances, we can find out the additive area that can be added to the sharing scenario.

5.3.2 Research Assumptions

In this dissertation, certain assumptions are taken into consideration:

- We assume that PUs are not utilizing the spectrum efficiently over the whole usage right area. Certain parts of usage right areas are unutilized, which allows for spatial spectrum sharing.
- The harmful interference caused by SUs affect PU receivers, not the transmitters. Therefore, the location of those PU receivers are specifically considered during the construction of the exclusion zone in order to protect PU operation.
- Generally speaking, there are two types of spectrum sharing: opportunistic or non-opportunistic sharing.
  - We consider non-opportunistic sharing, where there is an agreement (i.e. coordination) between PUs and SUs to make the sharing possible.
- SUs are expected to be either centralized or decentralized users. By that we mean:
  - Centralized: a single operator or interface (e.g. LTE operator) manages all the related secondaries. It is the most likely case when we have large cells of SUs. Thus, enforcing SUs will be accomplished through this single interface.
  - Decentralized: each SU shares the spectrum under a pre-registration type of process (albeit still non-opportunistic sharing). These are most likely small cells (e.g. WiFi).
- We expect that the PU is a government incumbent (i.e. Federal or non-Federal agency) and that the SU is a commercial wireless broadband operator/user.
- There are two types of in-band interference that may exist due to the sharing scenario illustrated in this dissertation:
  - Interference from a SU to a PU:

        - This is the interference under consideration in this work, where the PU should be protected.
        - This interference will be mitigated by ex ante and ex post enforcement scenarios.
    - Interference from a PU to a SU:
        - This type of interference is caused by the PU signal reaching the operation area of SUs.
        - The exclusion zone will be modeled to protect the PU only.
        - This type of interference is beyond the scope of this work, where the SUs should, typically, expect this type of interference as part of the sharing environment.

5.3.3 Area of simulation

The simulated area is a circle of 100km radius where the PU receiver is centered in the middle. Since 100km is a long distance, the model is capable of dividing it into different segments, each with its own terrain and population characteristics. For simplicity's sake, we divide it into two segments:

- **Inner area**: the area is relatively small in order to capture the terrain characteristics of the most interferer area to the PU. For example, Figure 5-4 shows that the inner area has a radius of 40km.
- **Outer area**: the area between the inner area radius and 100km. SUs in this area have less effect on the PU receiver compared to SUs in the inner area.

The SUs are randomly distributed over the simulated area. The key input to the model is the population density (people per km^2) to represent the existence of SUs. Not all the population of that area transmit at the same time, so, we multiply the population density by what we call the "Active Factor", which can vary based on the of simulated SU technology type.

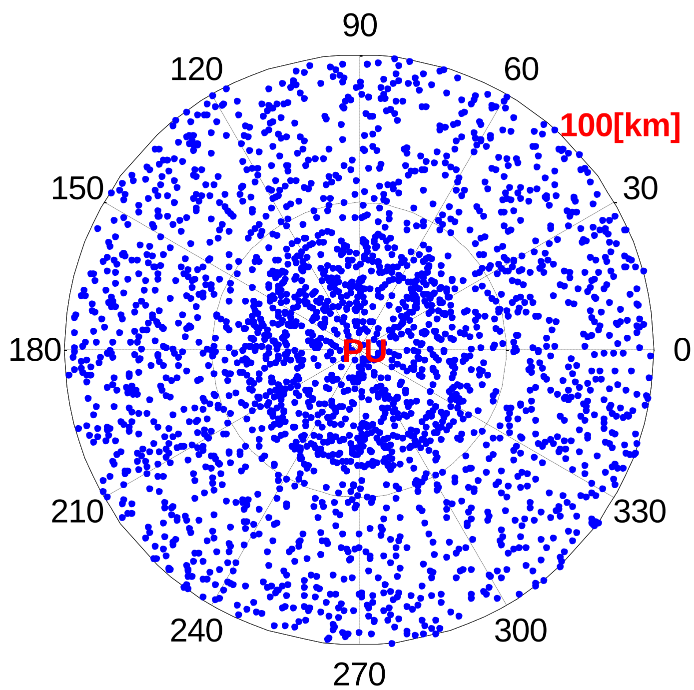


Figure 5-4 Area of simulation, the PU receiver is located in the center

5.4 FINDINGS AND OBSERVATIONS

There are many inputs and variables in this model. In this section, we will examine the main ones; the rest will be covered through the real case scenarios that follow in the next chapters. The major inputs to this model analysis are listed in Table 5-3.

As we mentioned in the main model design (i.e. Figure 5-2), we are trying to quantify the benefits of spectrum sharing under different enforcement and sharing scenarios. The following are some of the main variables that we highlighted here:

- The radius of B space and G space.
- Frequency of shared band.
- The PU Gain (Azimuth & Elevation angles).
- SU density per km^2.
- Interference protection threshold of PU receiver.
- G boundary limit in dBm which define the radius of G space [e.g. $I_{AGG} \leq (-110)$].
- B boundary limit in dBm which define the radius of B space [e.g. $I_{AGG} \leq (-90)$].

Table 5-3 Major model inputs and variables

Frequency		2 GHz
“PU Antenna” azimuth angle		360 Degrees
Minimum “PU Antenna” elevation angle		20 Degrees [20]
SU transmit power (I_{SU})		Standard LTE-UE (see 6.2.2)
Maximum “PU Antenna” gain		40 dBi
SU gain (G_{SU})		0 dBi
Additional Losses ($L_{Additional}$)		0 dB
FDR		0 dB
L_{PU}		2 dB
Inner area	Radius	From 0 to 40km
	Density	6 Active SUs per km^2
Outer area	Radius	From 40km to 100km
	Density	2 Active SUs per km^2
$G_{boundary}$		-110 dBm
$B_{boundary}$		-90 dBm
Terrain Type		Suburban
PU Antenna Height		20 m

Note:
If one/number of these inputs mentioned in the x-axis or in the legend of the following figures, that means they take the values mentioned in such figures. The rest stay as they are listed in this table.

[20] The minimum elevation angle is consider as fixed input to the model and added to the “gain function” in the simulation model; that because we try to represent the worst case scenario which is the case where the interference increase as we decrease the elevation angle.

5.4.1 PU Antenna Gain

Figure 5-5 shows the gain from the perspective of the PU antenna. It demonstrates the setting of our model. Please note, this figure is a 3-D visualization of an area that was originally circular (Note: In this figure, to aid visualization, the inner and outer area densities are reduced to 2.5 SU/km^2 and 0.3 SU/km^2, respectively).

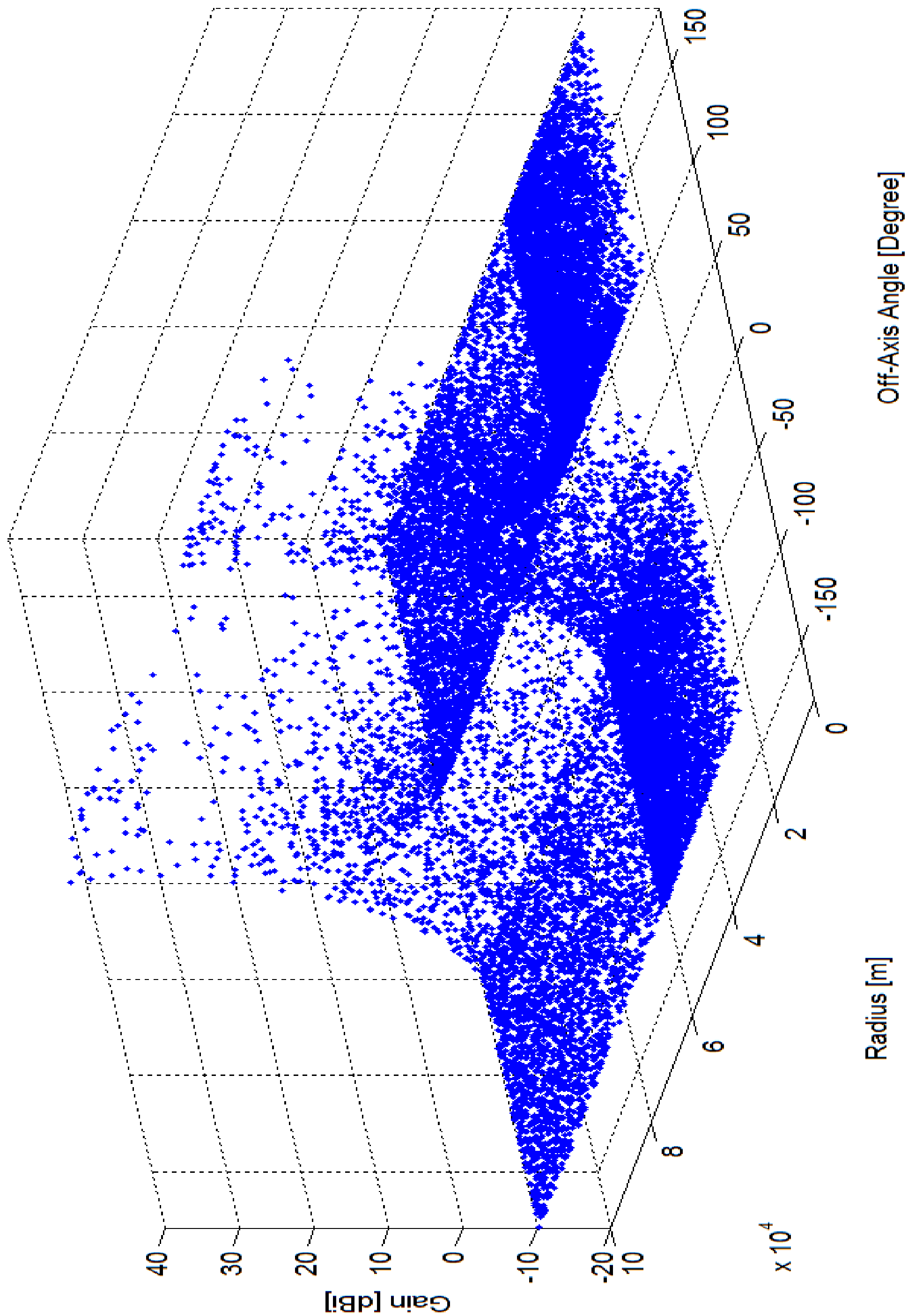


Figure 5-5 PU antenna gain visualization

5.4.2 SUs Density

This section examines the relationship between the level of SUs density and the radius of different types of exclusion zones. W space radius is fixed at 100km and is constant thought out the simulation. G and B space radiuses vary based on SUs density. Figure 5-6 summarize these relationships.

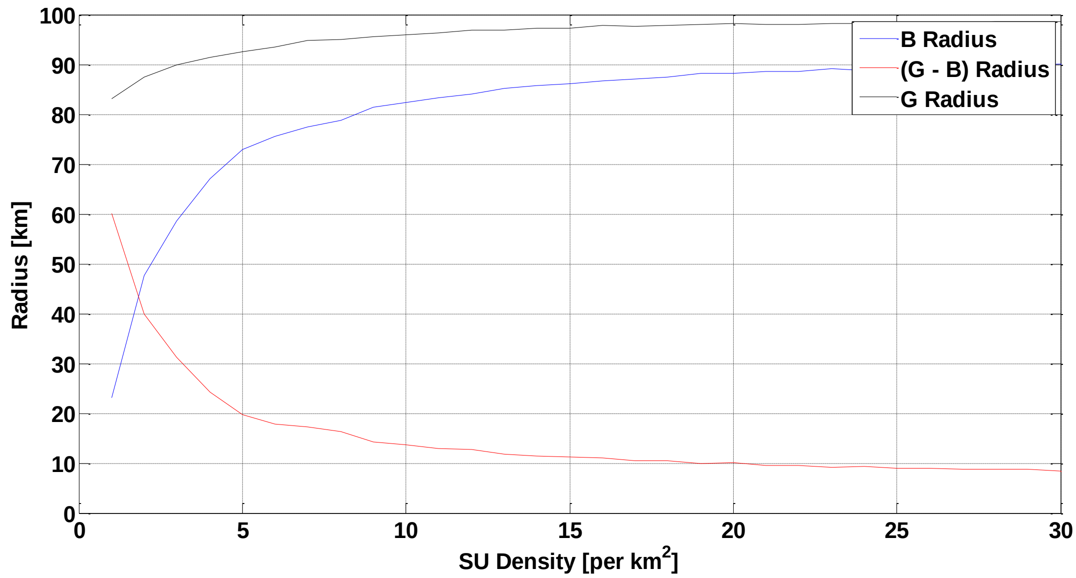


Figure 5-6 Relationship between SU density and space radius

By examining the above figures, we can conclude the following about this model setting:

- Interestingly, the G radius is relatively constant for SUs density greater than 10 users per km^2. Thus, we conclude that the W space area is not sensitive to SUs density above 10 users per km^2.
- In this figure, (G-B) distance is the difference between R_2 and R_1.

- (G-B) is very sensitive to any change in SUs density up to 13 users per km^2, after which point the radius remains relatively constant.

- G space area increases as the SUs density decrease. This is very interesting where there is more incentive to have larger G space in the case with less SUs density.
  - At $SU_{density} = 1/km^2$; the (G-B) radius, which defines the G area, is 60km.
  - At $SU_{density} = 5/km^2$; the (G-B) radius is 20km only.

5.4.3 Frequency

In this section, we will show how the simulated model reacts to different frequency bands. The frequency will vary from 0.5 GHz to 5 GHz and we will examine how the G and B radii reacts. The major variables are still the same as in Table 5-3, where the frequency is the variable. From Figure 5-7, Figure 5-8, Figure 5-9, and Figure 5-10, we can conclude the following:

- The effect of SUs density decreases as we lower the frequency in a sharing environment. We can see that G radius has less variance at 0.5 GHz compared to 5 GHz, by moving along the x-axis. This is also the case in B radius.
  - The reason for that is longer propagation for lower frequencies which increase the aggregated interference.
- At higher SUs density, the differences between the radiuses at different frequencies is minimized.
  - In Figure 5-9, the frequency band effect on G radius is very minimal for $SU_{density} > 5/km^2$.

    - In Figure 5-10, the frequency band effect on B radius is also minimal for $SU_{density} > 10/km^2$.
- In Figure 5-8, it is notable that at low density, the B radius is zero. This means the exclusion zone will be G space only.

To highlight the important of this findings, we will demonstrate this example. Let assume spectrum sharing at W space only, see Figure 5-9, where W area is bounded by G radius. Suppose there is a regulator who wants to assign two different SUs services with two different expected densities of SUs, all else being equal:

- Two different SUs services:
    - Service A: has $SU_{density}$ = D per km^2
    - Service B: has $SU_{density}$ = 3D per km^2
- Assume there are two spectrum bands that are recommended for sharing with these two services.
    - Band-X: 1GHz
    - Band-Y: 3GHz
- How the regulator will react?
    - The intuitive answer could be that: service B (higher density) should share band-Y (to exploit the frequency propagation of higher frequency) and service A should share band-X.
    - That is true if D = 0.1, relatively low densities for both services.
    - However, if D = 10, the answer is it does not matter and the frequency is not a sensitive factor any more.

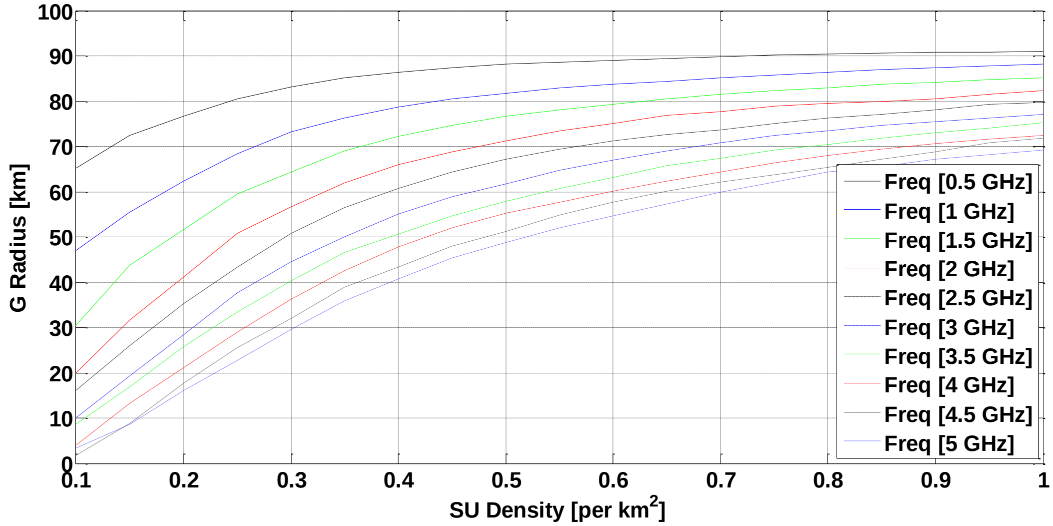


Figure 5-7 Frequency band effect on G radius, SU/km^2 is between 0.1 and 1

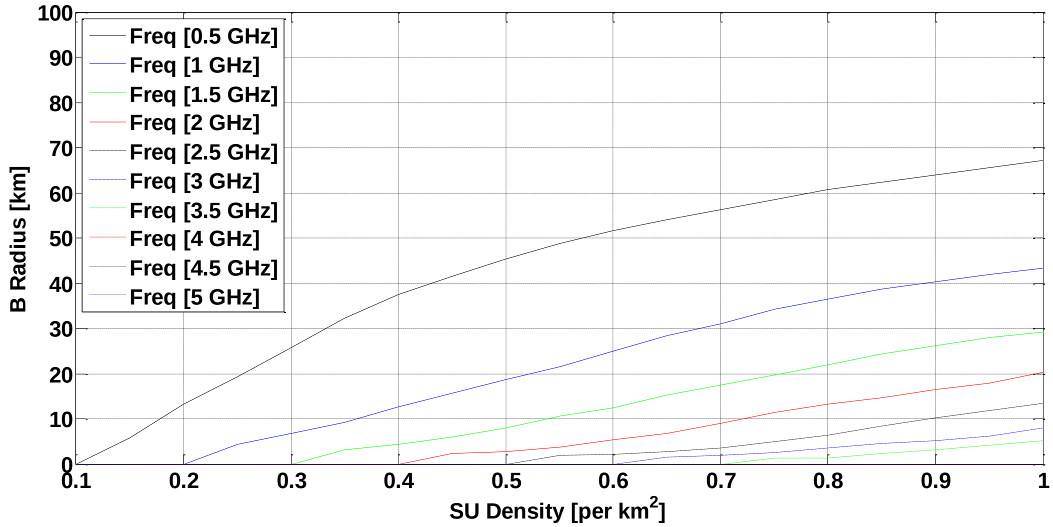


Figure 5-8 Frequency band effect on B radius, SU/km^2 is between 0.1 and 1

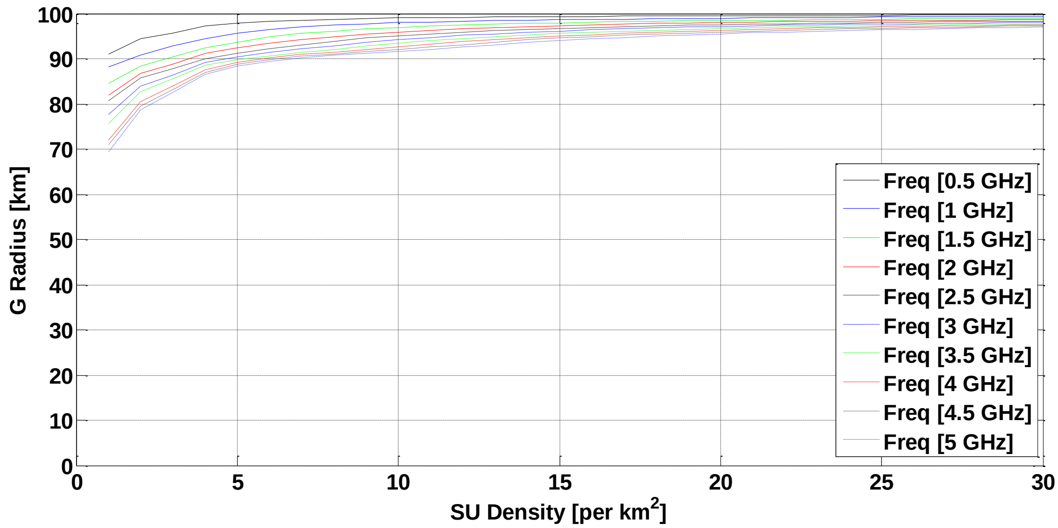


Figure 5-9 Frequency band effect on G radius, SU/km^2 is between 1 and 30

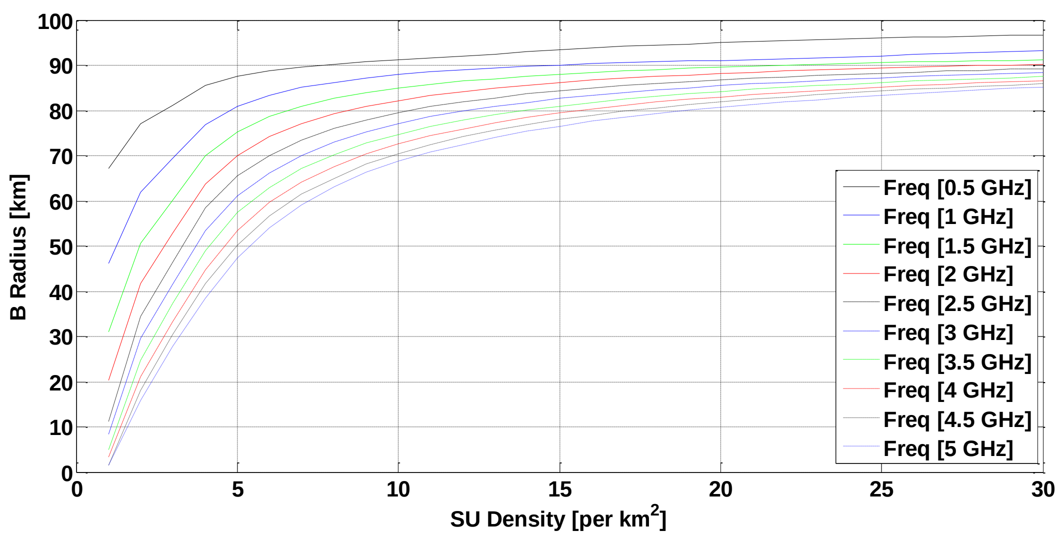


Figure 5-10 Frequency band effect on B radius, SU/km^2 is between 1 and 30

5.4.4 Interference Threshold

Here, we examine the effect of changing the interference threshold boundary (in dBm) on the exclusion zone radius. To do that, we will consider one interference threshold in this simulation. We pick the G boundary to examine this relationship over two different entries: (1) changing the SUs density, and (2) changing the frequency band.

In Figure 5-11, the G radius remains at approximately 100km till reaching (-130dBm) for all different SUs densities. Also, the G radius reaches zero around (-75dBm). That leads to these findings:

- If the PU antenna interference threshold is less than (-130dBm), it is very sensitive to interference, and the exclusion zones will be very large.
- If the interference threshold is higher than (-80dBm), this means we will not need any exclusion zones at this model setting at SUs density less than or equal to 1. This means, there is no G space in the case.
- By increasing the SUs density, the interference threshold limit changes accordingly.

As mentioned in Table 5-3, the difference between G and B boundaries is assumed to be (+20dBm). This is the amount we assumed that the PU will accept as additional aggregated interference on top of its "interference threshold" level to practice the sharing at G space. Based on research model (Figure 5-2), to push the exclusion zone radius from "R_2" to "R_1", we will increase the aggregated interference level from (-110dBm) to (-90dBm). The benefit is an area of sharing that is vary in size based on SUs density sharing the band. From Figure 5-11; we notice the following:

- In this part, we ignored W and B spaces and focus on G space only.
- We got different size of G space by changing the SUs densities.
    - In ($SU_{density}$ = 1/km^2) case, the gain of adding (+20dBm) is 55 km. It is reduction on exclusion zone radius that is proportional to G area (R2 – R1 = 55 km).
    - In ($SU_{density}$ = 5/km^2) case, the gain of adding (+20dBm) is 20km.
- This prove one of the findings at previous section (5.4.2), where the incentive to gain more G area is increased as we decrease the SUs density.

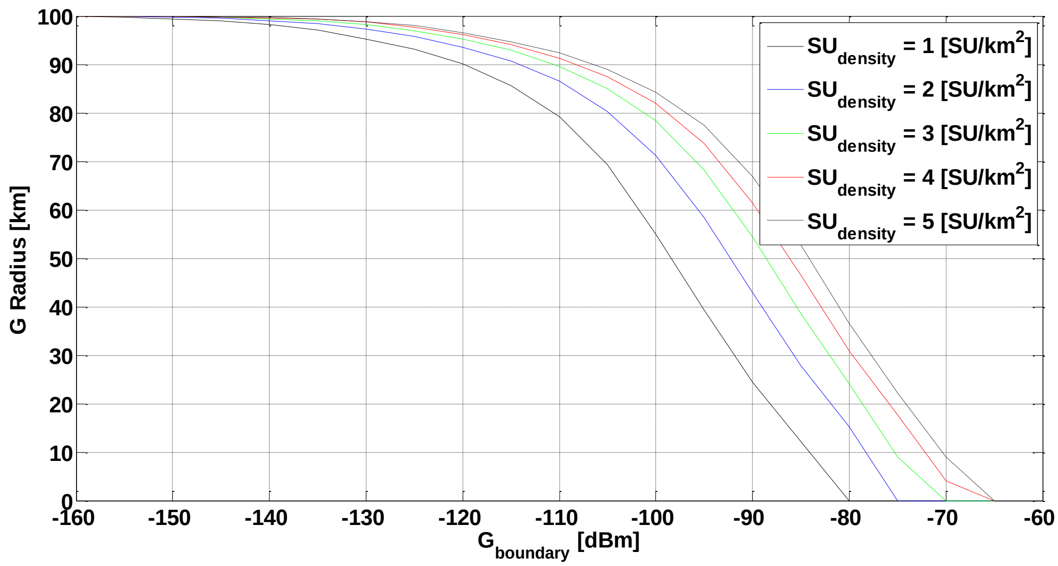


Figure 5-11 Effects of interference threshold on G radius with different SUs densities

In Figure 5-12, the inner area density is 10 SU/km^2 and the outer area density is 1 SU/km^2. We can conclude the following:

- At a specific point on the G boundary (x-axis), as the frequency decreases, the G radius increases.
- The curve pending at radius=40 km is due to the difference in SUs density between inner and outer areas.
- The sensitivity of the interference threshold is lower at higher SUs densities. That is clear from this figure, where the slope of the curves above radius=40km is higher (in magnitude) than below it.

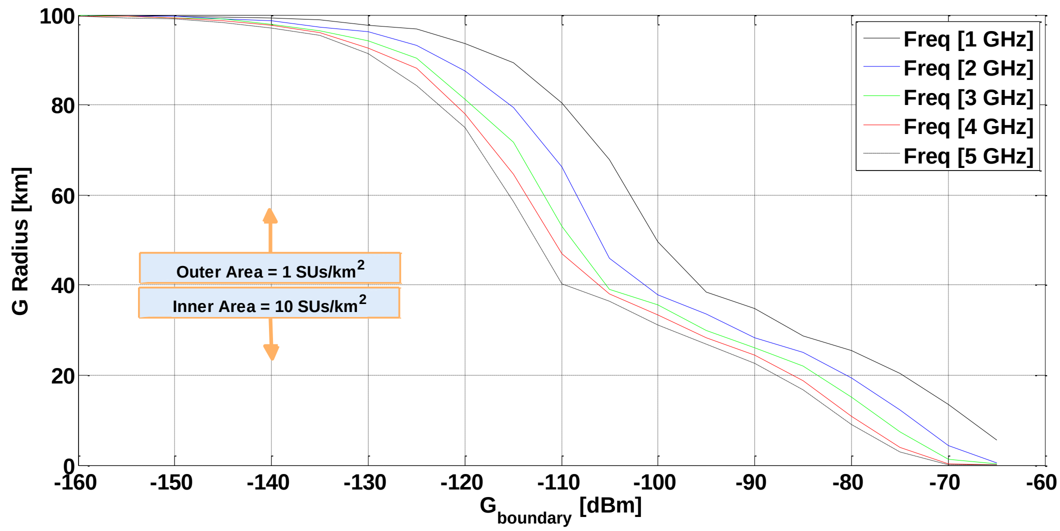


Figure 5-12 Effects of interference threshold on G radius with different frequency bands

5.4.5 MIMO Effects on Aggregated Interference Level

In wireless field, Multiple Input and Multiple Output (MIMO) is the use of multiple antennas to improve wireless-channel performance. Recently, there are a growing number of technologies that adopt the use of MIMO. In this dissertation model, we assume all the SUs to be SISO (Single Input and Single Output). Therefore, we will try to highlight in brief this case: if a SU uses MIMO systems instead of SISO, how that will influence the aggregated interference level at PU receiver?

MIMO systems have been studied intensively in recent years. Majority of the work done in this area focusses on the relationship between the performance of the network and number of antennas that been used and the optimal combination figure [68] [69]. Many suggest that under the same throughput requirements, MIMO systems require less transmission energy compared to SISO systems [70] [71]. A study done over LTE networks showed that (for given reference data rates) there is power efficiency gain [72]. MIMO system will minimize the transmission energy more at long-range compare to small-range networks. Hence it is tempting to believe that MIMO systems are more energy efficient than SISO systems.

The distance between the transmitter and the receiver (within the SUs network) will play also a role that affects the power efficiency of MIMO system. For the PU, we are only concerned about the aggregated interference at its location, so, we assume the PU receiver to be single antenna.

In this dissertation, we assume that the SUs using SISO systems, and this is considered a conservative approach, since the SISO will cause more aggregated interference at the PUs. If we add MIMOs in the SUs network, the aggregate interference at the PU receiver is expected to be either less or the same (at maximum) as SISO. For more detailed information, please refer to Appendix (B).

5.5 SPECTRUM PRICING

Generally, a wireless operator will base its decision to acquire a spectrum band on costs as well as on a projection of future revenues [73]. Doing that in addition to evaluating other alternatives is part of the process to measure its opportunity cost. To calculate the cost of obtaining access to spectrum resources, it is very common for wireless operators to use the concept of net present value (NPV). They evaluate the cost of any spectrum as an expression of the price per megahertz [73], where they value spectrum opportunities by MHz POP (the price per megahertz - population).

$$\frac{Price}{MHz\ POP} = \left[\frac{Spectrum\ Price(\$)}{Bandwidth\ (MHz) \times Population}\right]$$

Based on a recent ITU broadband report [73], we summarize the following:

- Per German spectrum auction results in May 2010, the average $[USD]/MHz POP for four different bands, based on World Bank 2009 population count, is $0.28 per MHZ POP.
- In Hong Kong, the 4G auction (90 megahertz of paired spectrum in the 2.6 GHz band) was completed in early 2009, finishing with an average of $0.31 per MHz POP.
- The global average for 700 MHz and 800 MHz auctions is $0.9 per MHz POP.
- Since 2002, the global average for 2.1 GHz spectrum has been $1.33 per MHz POP.

- The global average for 2.6 GHz has been $0.07 per MHz POP since 2005.

In the US market, the FCC held an auction in 2008 for broadcast TV spectrum in the 700 MHz band; the average spectrum valuation for mobile broadband use was $1.28 per MHz POP, and the value of unpaired spectrum was $0.78 per MHz POP [2]. For 1.9 GHz band (in 2004) and AWS band (in 2006), the average was $1.7 per MHz POP and $0.54 per MHz POP, respectively [74].

For spectrum bandwidth, population, and spectrum price in a specific scenario, we can arrive at its real value based on the market price of spectrum[21]. Since we will examine two cases in the following chapters (1.7GHz band and 3.5GHz band) within the US, we will base our evaluation of cost per MHz POP on the FCC database. More detailed procedures will be provided in the following chapters.

5.6 CASE STUDIES OF GOVERNMENT-COMMERCIAL SHARING

Sharing between the government incumbents (i.e. Federal or non-Federal agencies) and commercial wireless broadband operators/users is one of the key forms of spectrum sharing that is recommended by the NTIA and the FCC. In addition, one of the broad visions of President Obama's Spectrum Initiative [3] is that the Federal government must ensure sound government

[21] We will use this "spectrum opportunity cost" to evaluate the benefits of spectrum sharing in the proposed model instead of exclusive usage right. For more information about opportunity cost definition, please refer to Appendix (A).

performance and effective use of its spectrum, pushing for effective repurposing, sharing, and innovative uses of spectrum wherever possible. The NTIA has issued reports [4] [5] to evaluate different Federal and non-Federal spectrum bands for the near-term viability of accommodating wireless broadband systems. Those bands include the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz Bands. In this dissertation, the PUs are the Federal and non-Federal agencies whereas the proposed wireless broadband systems are the SUs.

Two bands have been selected to be case studies in this work: 1675-1710 MHz and 3500-3650 MHz bands. In the 1675-1710 MHz band, the PU is fixed and the expected SU is centralized (LTE mobile operator). For 3.5 GHz band, the PU is mobile service and the expected SUs are technologies with limited power transmission (small cells). The following two chapters will cover these two bands.

6.0 SPECTRUM SHARING IN THE 1.7 GHZ BAND

The 1675-1710 MHz frequency range (35MHz) is allocated to Meteorological-Satellite (MetSat; space-to-earth) and meteorological aids (MetAids; radiosondes) services. It is one of the bands proposed by the NTIA to accommodate new spectrum sharing between government and commercial usages. However, due to the large number unlicensed or unregistered (fixed, transportable, and mobile) non-Federal meteorological receivers, the NTIA has limited the expected sharing band to be the 1695-1710 MHz band (15MHz).

The Commerce Spectrum Management Advisory Committee (CSMAC) has formed five working groups to repurpose candidate bands for wireless broadband; one of them specifically focuses on 1695–1710 MHz Weather Satellite Receive Earth Stations (WG-1). According to the last full report released from WG1 [67], sharing in the 1695-1710 MHz band should be limited to commercial systems operations (LTE mobile uplink use only) because, in part, the 1695-1710 MHz is immediately adjacent to the AWS-1 uplink band (which will maximize its usefulness for commercial services) and also because mobile uplinks transmit at much lower power than downlinks.

6.1 PRIMARY AND SECONDARY USERS

This section will provide brief technical specifications/information on MetSat-earth-stations (PU) and the expected LTE-User-Equipment (LTE-UE) that could share the spectrum band.

6.1.1 Primary User

The PU is the National Oceanic and Atmospheric Administration NOAA, which provides the weather satellite receive earth-stations (MetSat) [4] [5]. The NOAA operates both geostationary and polar-orbiting satellite transmitting systems in the 1675-1710 MHz band. The NOAA, the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), the Department of Interior (DoI) and other Federal and non-Federal entities operate earth-stations to receive environmental research and weather data transmitted from the Geostationary Operational Environmental Satellite (GOES) and Polar- Orbiting Environmental Satellites (POES). The GOES is used for rapid real time observations of hurricanes, severe weather, short-range warning, and weather forecast models. The POES makes high resolution real time hazard observations and weather forecast models.

MetSat is a fixed service working in 1675-1710MHZ band (Space-to-Earth). The NTIA report [4] concluded that sharing is possible in the 1695-1710 MHz band (15 MHz) between MetSat receive stations and wireless broadband systems. Originally, 18 MetSat earth-stations will continue to operate where they will be protected by exclusion zones. Based on a recent WG1 report [67], there are an additional 9 stations that need protection as well, resulting in a total of 27 earth stations.

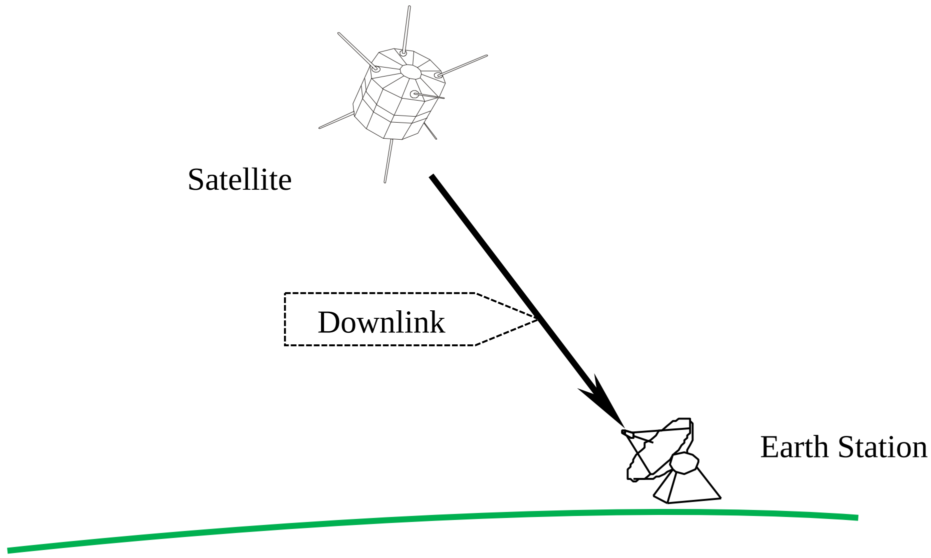


Figure 6-1 The proposed sharing is "15 MHz" of the downlink band

6.1.2 Secondary User

The SU is expected to be a commercial mobile LTE operator where the shared band would be used for uplinks from the handsets to the base stations. It is expected to be paired with the 2180-2200 MHz band for the downlink [67]. From the SU viewpoint, there are many possible scenarios that may take place in this sharing environment. A single SU (i.e. mobile LTE operator) sharing the band with MetSat at the same location is a likely scenario.

The SU has two possibilities: either it has exclusive LTE spectrum bands in addition to MetSat/LTE shared band (1695-1710MHz), or it will have only the shared spectrum band, see Figure 6-2. In case A, the LTE-UE will still have connectivity by handing off from the shared band to an exclusive band. In case B, the LTE-UE will have no choice but to stop the service within the boundary of exclusion zones. It is most likely that this band will be shared by an LTE operator who has other exclusive LTE bands (case A).

There are two types of in-band interference that may exist due to the sharing scenario illustrated in this band. First, the interference from LTE-UE (i.e. user's handset) to MetSat-earth-stations, where the PU should be protected. Second, the interference caused by MetSat satellite to the SU base station. The space-to-earth signal will interfere with the LTE-base-stations, which may need special filters to avoid this interference. This second type is not considered in this dissertation.

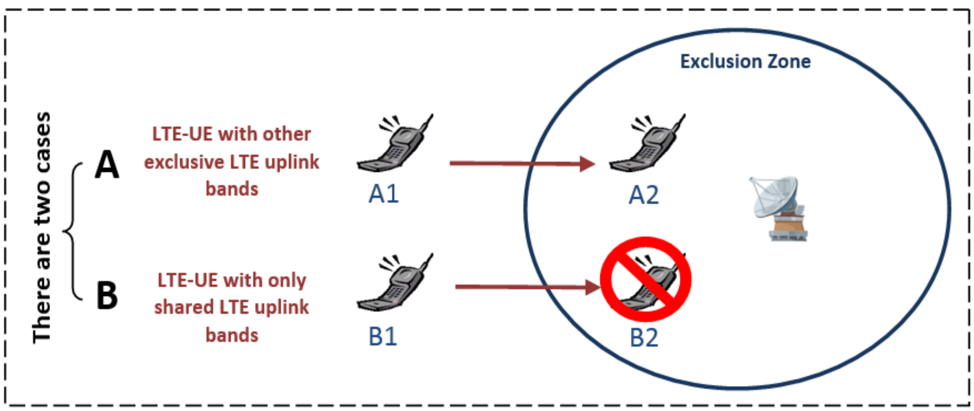


Figure 6-2 Illustration of two different cases of LTE operators

6.2 SIMULATION SETTINGS

The published information about MetSat earth-stations (by NTIA) is only for the original 18 earth stations; information on the additional 9 earth-stations is not available. Therefore, we will illustrate our simulation methodologies using these 18 MetSat stations and that could be generalized to any additional future station, although some of these 9 additional earth-stations are in the same location as the original 18 (i.e. adjacent to each other).

The specifications of the 18 earth-stations are summarized in Table 6-1. To give more realistic insight into the location of these earth-stations, we drew them using “google-earth” in Figure 6-3. Some of them are located in very populated areas. Therefore, part of our analysis is to find out which of these earth-stations should be re-located to increase the benefits of spectrum sharing.

Table 6-1 Specifications of the MetSat 18 earth-stations

	Earth Station Name	Latitude	Longitude	Zip Code	Station Type
1	Wallops Island, VA	375645N	0752745W	23337	POES/GOES
2	Fairbanks, AK	644814N	1475234W	99709	POES/GOES
3	Suitland, MD	385107N	0765613W	20395	POES/GOES
4	Miami, FL	254700N	0801900W	33126	POES/GOES
5	Ford Island, Pearl Harbor HI	212212N	1575744W	96818	POES/GOES
6	Sioux Falls, SD	434409N	0963733W	57022	POES/GOES
7	Elmendorf Air Force Base, AK	610859N	1492812W	99518	POES/GOES
8	Anderson Air Force Base, GU	133452N	1445528E	96929	POES/GOES
9	Monterey, CA	363600N	1215400W	93940	POES/GOES
10	Stennis Space Center, MS	302359N	0893559W	39529	POES/GOES
11	Twenty-Nine-Palms, CA	341746N	1160944W	92285	POES/GOES
12	Yuma, AZ	323924N	1143622W	85365	POES/GOES
13	Cincinnati, OH	390608N	0843036W	45202	GOES
14	Rock Island, IL	413104N	0903346W	61201	GOES
15	St. Louis, MO	383526N	0901225W	63118	GOES
16	Vicksburg, MS	322123N	0905129W	39183	GOES
17	Omaha, NE	412056N	0957534W	68064	GOES
18	Sacramento, CA	383550N	1213234W	95605	GOES

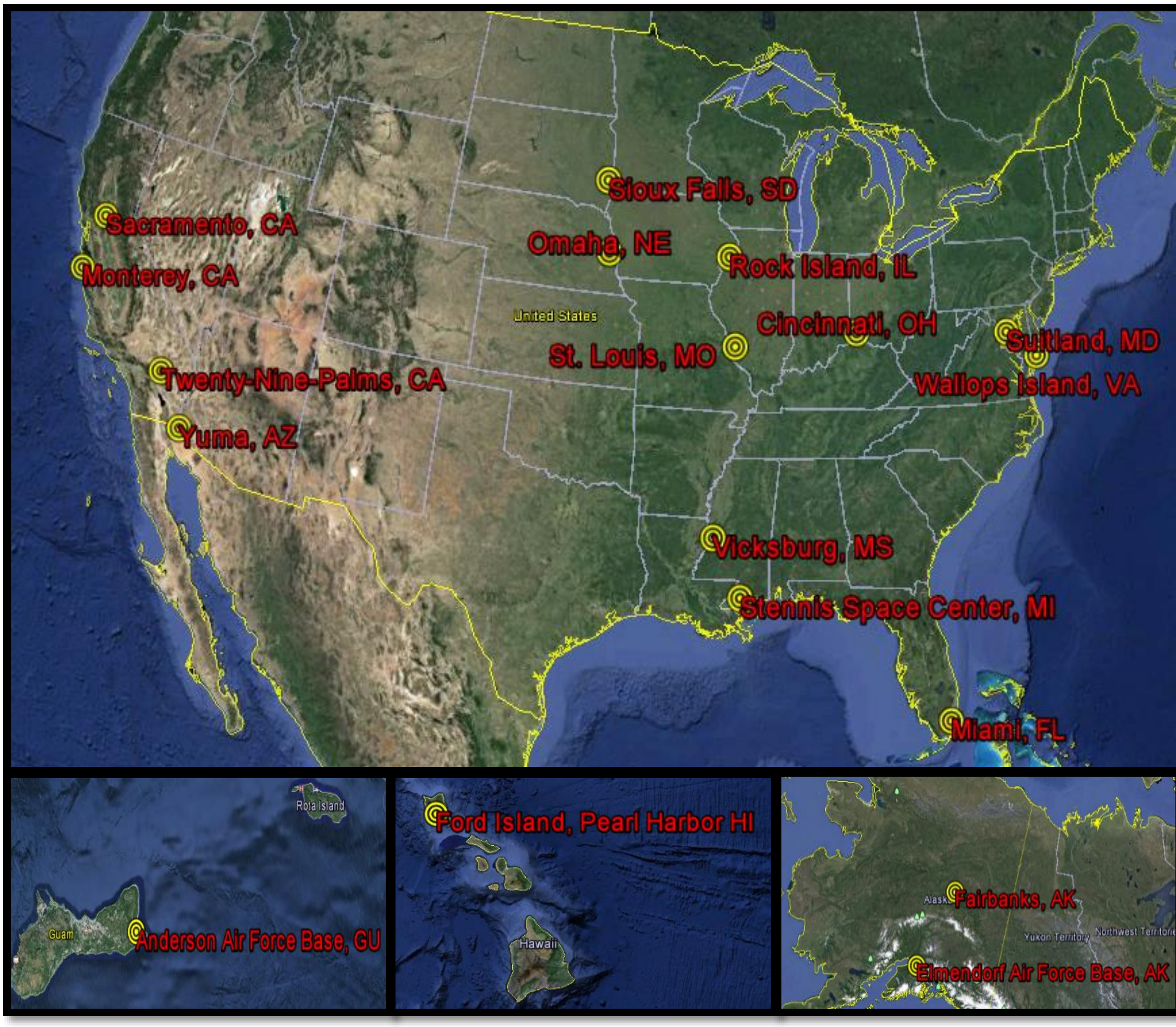


Figure 6-3 Locations of the 18 earth-stations (*using google-earth*)

6.2.1 PU Characteristics

Most of the technical specifications of the MetSat earth-stations are gathered from NTIA report [4] and CSMAC WG-1 report [67], including minimum elevation angle, maximum antenna gain, antenna height, and interference protection threshold. One of the major additional factor that has been added to this analysis is the real population affected by the exclusion zone of each MetSat earth-station. To do that, a full analysis was performed at each earth-station to determine the population surrounding the earth-station. Table 6-2 summarizes these details. Some of the stations exist beside the coast line or on an island. Thus, we used the level of "zip-code area" to determine the population density to increase the accuracy of our analysis.

There are many advantages of doing population density analysis. First, we try to avoid assumption of the population density around each station. That allows us to determine a more exact cost/value of exclusion zones. Second, it gives us the ability to more accurately predict the number of "active SUs" in each sharing scenario. Also, we use this information to determine the type of path loss to use around each station based on the population density (e.g. open, suburban, small city, or large city).

The 100km radius is divided into five sections:

1. Area from 0km to 20km from the earth-station
2. Area from 20km to 40km
3. Area from 40km to 60km
4. Area from 60km to 80km
5. Area from 80km to 100km

All collected information is summarized in Table 6-3 and Table 6-4.

Table 6-2 Detailed specifications for each MetSat 18 earth-station

Earth Station Number	POP within Radius=100 km (Population)	Minimum Elevation Angle (Degrees)	Antenna Gain (dBi)	Antenna Height (m)	Interference Protection Threshold (dBm)
1	553,281	14	43.1	17	-120.6
2	98,102	14	43.1	17	-120.6
3	8,537,701	5	29.5	86.8	-120.9
4	5,075,122	5	29	33	-124.1
5	955,959	5	29	33	-120.9
6	408,398	27.7	31	14.5	-121.6
7	401,952	5	29	33	-120.9
8 [22]	0	5	29	33	-120.9
9	2,574,415	5	29	33	-120.9
10	1,780,419	5	29	33	-120.9
11	2,710,745	5	29	33	-120.9
12	334,248	5	29	33	-120.9
13	3,376,536	43.9	39	200	-122.5
14	974,045	24.4	39.6	25	-122.5
15	2,999,809	42.6	36.7	20	-122.5
16	746,133	48.6	36.7	20	-122.5
17	1,327,903	28	36.7	20	-122.5
18	4,669,749	43.2	36.7	20	-122.5

[22] "Anderson Air Force Base, GU" earth-station (station#8) is not included in the simulation analysis, because it is on an unpopulated island. Thus, it will be ignored at the rest of this chapter.

Table 6-3 Population density analysis (1/2)

station #	Station Name	0 - 20 km			20 - 40 km		
		POP	Land Area	POP/km^2	POP	Land Area	POP/km^2
1	Wallops Island, VA	21457	735.8	29.2	43395	1629.5	26.6
2	Fairbanks, AK	56162	336.8	166.8	34801	5445.6	6.4
3	Suitland, MD	2084464	1108.8	1879.9	2278840	3740.9	609.2
4	Miami, FL	1887459	909.3	2075.7	1413334	1163.2	1215.0
5	Ford Island, Pearl Harbor HI	740057	787.6	939.7	213150	761.7	279.9
6	Sioux Falls, SD	9432	854.9	11.0	62945	4082.9	15.4
7	Elmendorf Air Force Base, AK	254274	707.3	359.5	39408	2554.4	15.4
9	Monterey, CA	128900	427.5	301.5	273575	2191.7	124.8
10	Stennis Space Center, MS	71275	935.2	76.2	149562	2678.8	55.8
11	Twenty-Nine-Palms, CA	12458	1150.3	10.8	85081	4997.4	17.0
12	Yuma, AZ	146618	673.6	217.7	49072	909.3	54.0
13	Cincinnati, OH	946640	1137.3	832.4	825550	3976.7	207.6
14	Rock Island, IL	294980	1160.6	254.2	87174	3463.7	25.2
15	St. Louis, MO	985290	1095.9	899.1	1139953	3795.3	300.4
16	Vicksburg, MS	45862	968.9	47.3	27552	4095.9	6.7
17	Omaha, NE	157068	976.7	160.8	598972	3660.6	163.6
18	Sacramento, CA	934006	1020.7	915.0	936335	3906.7	239.7

Table 6-4 Population density analysis (2/2)

station #	40 - 60 km			60 - 80 km			80 - 100 km		
	POP	Land Area	POP/km^2	POP	Land Area	POP/km^2	POP	Land Area	POP/km^2
1	137519	1709.8	80.4	114334	2655.4	43.1	236576	3663.2	64.6
2	3866	518.1	7.5	942	0.0	0.0	2331	29269.4	0.1
3	1972273	4753.9	414.9	1504070	7365.3	204.2	698054	9619.2	72.6
4	849692	3025.9	280.8	419607	5559.6	75.5	505030	5401.6	93.5
5	0	0.0	0.0	0	0.0	0.0	2752	323.8	8.5
6	205383	5277.2	38.9	47603	9953.4	4.8	83035	10981.9	7.6
7	52270	4930.1	10.6	34828	8160.6	4.3	21172	619.2	34.2
9	331163	2474.1	133.9	687062	4215.0	163.0	1153715	7860.1	146.8
10	360108	4186.5	86.0	900947	5686.5	158.4	298527	6862.7	43.5
11	181948	2940.4	61.9	977583	6054.4	161.5	1453675	8230.6	176.6
12	2315	1274.6	1.8	15313	15665.8	1.0	120930	1272.0	95.1
13	363904	6111.4	59.5	622054	9233.2	67.4	618388	10603.6	58.3
14	110831	6673.6	16.6	189199	8401.6	22.5	291861	11453.4	25.5
15	375529	5528.5	67.9	282903	9787.6	28.9	216134	10399.0	20.8
16	166967	6046.6	27.6	360933	9331.6	38.7	144819	10427.5	13.9
17	164614	6650.3	24.8	309786	9393.8	33.0	97463	9546.6	10.2
18	549464	5958.5	92.2	1173529	8935.2	131.3	1076415	9093.3	118.4

These population analyses provide a powerful tool to evaluate the “opportunity cost” of B, G and W space. This allows us to list the earth-stations based on: area impacted, population, value of spectrum, and so on. Figure 6-4 summarizes the population density for all 18 earth-stations based on the five different areas. One of the highest impacted area is the Miami earth-station, where there are 1.8 million people living within a 20km radius of the earth-station.

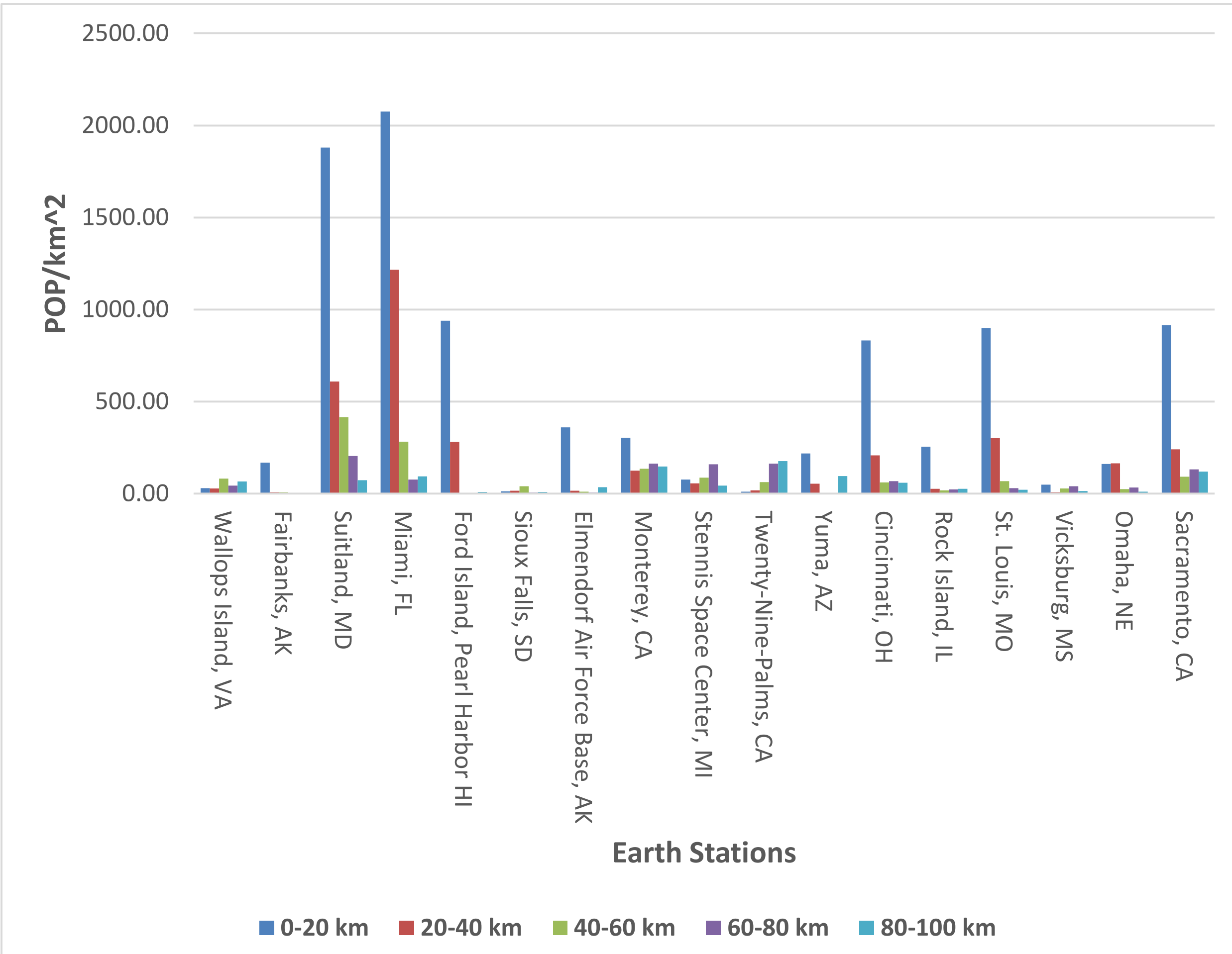


Figure 6-4 Population density, based on the five different areas

For each earth-station, we produce a population density chart that relates the POP/km^2 with the radius of the circled area around the PU location. Figure 6-5 illustrates the population characteristics chart of the Miami, FL earth-station. The following observation can be made:

- This chart gives the sharing benefits function versus distance from the PU antenna.
  - If the exclusion zone shrinks from 100km to 60km, the marginal additive benefits are comparatively lower compared to the rest of the area.
  - This means that shrinking the exclusion zone from 100km to 60km is less valuable compared to shrinking it from 60 to 20km, for example.
- This gives an indication of the benefits function by moving from ex ante towards ex post approach.
- It also gives an indication that the marginal benefits of spectrum sharing along the x-axis (distance from the PU) varies with the environment.

Appendix (C) shows the population density chart for other earth-stations.

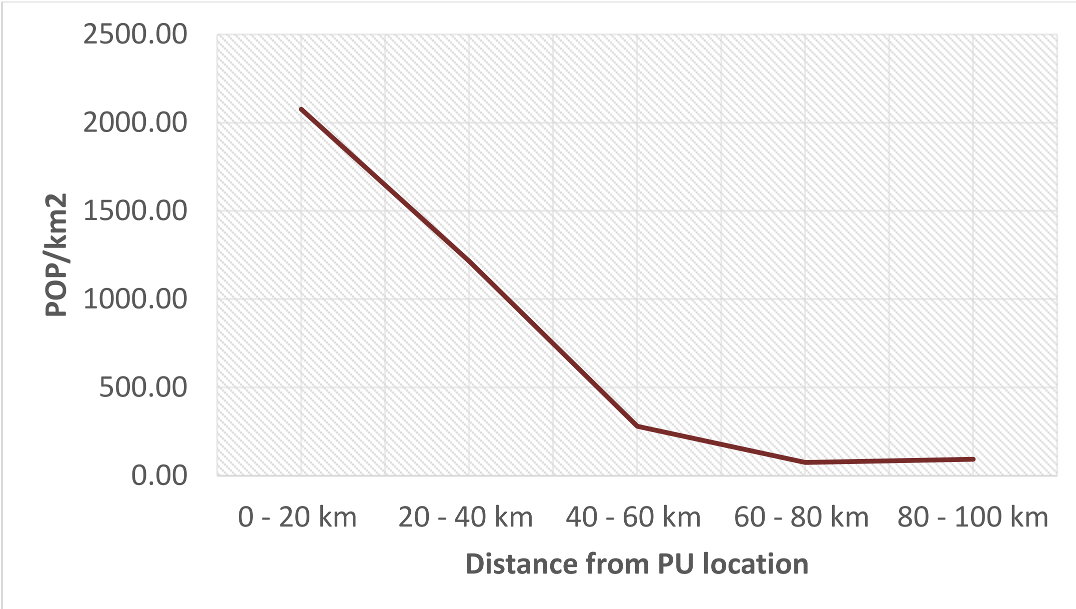


Figure 6-5 Population characteristics chart for “Miami, FL” earth-station

6.2.2 SUs Characteristics

The SUs is LTE-UE (uplink). Since the simulation involves a huge number of SUs, we prefer to use the Probability Distribution Function (PDF) to represent the power of each SU[23]. Figure 6-6 and Figure 6-7 represent the PDF of the path loss models. We can see that there is a greater probability of transmitting by high power in open/suburban areas than in small/large city areas due to the relative distance of the LTE-UE from the base stations (i.e. eNodes).

[23] It is very common in the literature to use single average transmit power (e.g. all SUs transmit at 1dBm); however, we prefer to be more realistic and use this setting. These values are from NTIA tables when they analyses LTE-UE characteristics [67].

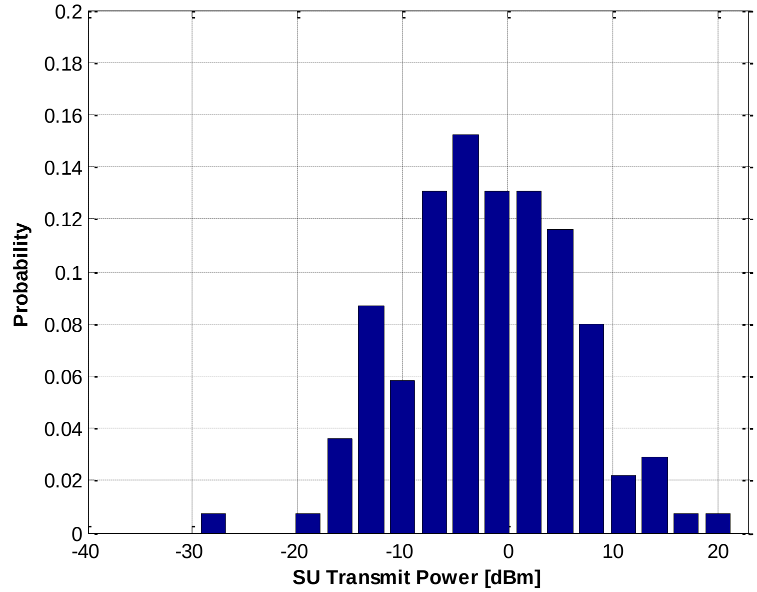


Figure 6-6 Probability distribution function of LTE-UE in small and large city areas

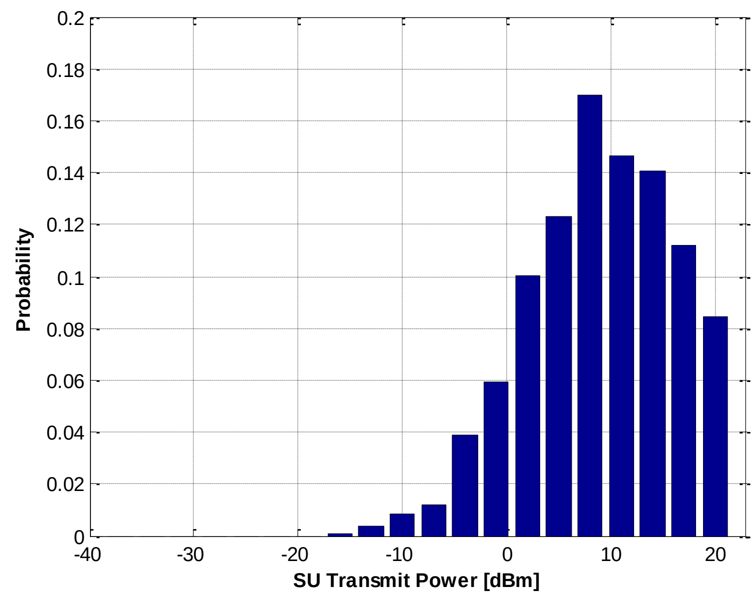


Figure 6-7 Probability distribution function in suburban and open areas

6.3 ANALYSIS AND RESULTS

6.3.1 Inputs to Simulation Model

One of the most critical settings in simulation models is the G and B space boundaries (in dBm), which defines each specific boundary. They are defined in MetSat as follows:

- **$G_{boundary}$**
    - This is the "interference protection threshold[24]" at the PU antenna specification.
    - In the MetSat case, it is in the range of -120 dBm. Table 6-2 lists the interference protection threshold at each earth-station.
- **$B_{boundary}$**
    - This is a new approach to be used to define B space area.
    - Its value (in the classical scenario) is (+20dBm) over G space boundary.
    - For example, if $G_{boundary}$ = -122dBm, then $B_{boundary}$ = -102dBm.
    - As mentioned earlier, the PU is assumed to accept additional aggregated interference to its interference threshold as part of sharing enforcement methodology.

[24] In this dissertation, the "interference protection threshold" and the "threshold" for an antenna are used interchangeably.

The model starts with no sharing area, so the exclusion zone equals the simulated area (i.e. radius = 100km). Then, the simulation model shrinks the exclusion zone, which increases the aggregated interference at the PU antenna, until it reaches the boundary of the G space. From this we arrive at the G space radius. It then continues to shrink the exclusion zone until it reaches the boundary of B space, from which we arrive at the B space radius. Any aggregated interference below the G space boundary is considered to be caused by SUs sharing in the W space area, and the PU will not be affected by this level of interference.

As mentioned earlier, the Hata model is used to represent the path loss model and reflect terrain characteristics. Since we have the real data for population density at each earth-station location, this information will be exploited to form a relative terrain type. It is classified based on the population density (pop/km^2) as follows[25]:

- POP/km$^2 < 50$
  - "open" terrain
- $50 \leq$ POP/km$^2 < 100$
  - It is "suburban" type of terrain
- $100 \leq$ POP/km$^2 < 200$
  - "small city" terrain
- POP/km$^2 \geq 200$
  - "large city" terrain

[25] This is novel methodology developed here instead of assumed density or terrain type. The terrain is classified based on the density of inner circle with a radius of 40km.

Table 6-5 summarizes the relevant inputs to the simulation model based on MetSat case specifications. The population data are based on the latest official U.S. Census Bureau (2010) [75], see Table 6-6.

Table 6-5 Relevant inputs to the simulation model based on MetSat case

<table>
<tr><th>Input</th><th>Value</th><th>Note</th></tr>
<tr><td>Frequency</td><td>1702.5
[MHz]</td><td>• It is the center frequency of 1695-1710 MHz band</td></tr>
<tr><td>PU Azimuth Angle</td><td>-180 to 180
[Degrees]</td><td>-</td></tr>
<tr><td>PU Elevation Angle</td><td>From Table 6-2
[Degrees]</td><td>• This value represent the PU minimum elevation angle
• To reflect the worst case scenario to insure protection for the PU</td></tr>
<tr><td>Additional Losses</td><td>0
[dBm]</td><td>• This is the classical scenario where we did not consider any additional losses (most conservative scenario)</td></tr>
<tr><td>Density1
(0 to 40km)</td><td>From Table 6-3
[SU/km^2]</td><td rowspan="2">• This is real population density within circle of radius of 40km or within area between radius 40km and 100km
• Then, it will be multiplied by 0.1% to reflect the expected active SUs transmit at the same time.
• "Active Factor = 0.1%" is the classical value, and it will examine at the sensitivity analysis part at the end of this chapter</td></tr>
<tr><td>Density2
(40 to 100km)</td><td>From Table 6-4
[SU/km^2]</td></tr>
<tr><td>PU losses</td><td>2
[dBm]</td><td>-</td></tr>
</table>

Table 6-6 Population data based on the latest U.S. Census Bureau (2010)

Station #	0 - 40 km			40 - 100 km			Terrain Type
	POP	Land Area(26)	POP/km^2	POP	Land Area	POP/km^2	
1	64852	2365.28	27.42	488429	8028.50	60.84	Open
2	90963	5782.38	15.73	7139	29787.56	0.24	Open
3	4363304	4849.74	899.70	4174397	21738.34	192.03	Large City
4	3300793	2072.54	1592.63	1774329	13987.05	126.86	Large City
5	953207	1549.22	615.28	2752	323.83	8.50	Large City
6	72377	4937.82	14.66	336021	26212.44	12.82	Open
7	293682	3261.66	90.04	108270	13709.84	7.90	Suburban
9	402475	2619.17	153.67	2171940	14549.22	149.28	Small City
10	220837	3613.99	61.11	1559582	16735.75	93.19	Suburban
11	97539	6147.67	15.87	2613206	17225.39	151.71	Open
12	195690	1582.90	123.63	138558	18212.44	7.61	Small City
13	1772190	5113.99	346.54	1604346	25948.19	61.83	Large City
14	382154	4624.35	82.64	591891	26528.50	22.31	Suburban
15	2125243	4891.19	434.50	874566	25715.03	34.01	Large City
16	73414	5064.77	14.50	672719	25805.70	26.07	Open
17	756040	4637.31	163.03	571863	25590.67	22.35	Small City
18	1870341	4927.46	379.57	2799408	23987.05	116.71	Large City

[26] Land Area: is the size of all areas designated as land in the Census Bureau's national geographic database (i.e. exclude water such as lake or seas).

6.3.2 Benefits Evaluation of Spectrum Sharing

To show the benefits of sharing scenarios that are represented in this dissertation, we get the real cost/price of spectrum from the FCC auction-database of comparable spectrum bands. The most relevant and reasonable band to 1.7GHz is the AWS-1 band. This band was auctioned in 2006. For a more detailed analysis of the prices of the AWS-1 band and the FCC geographic licensing schemes, please see Appendix (D).

We analyze AWS-1 band based on FCC auction-database [76] for each earth-station area to find the real cost of spectrum ($/MHz-POP) and use that to evaluate the benefits that are gained from allowing sharing. For each station, we did the following:

- Collect "spectrum auction" data to find the spectrum cost at each relevant area of an earth-station at three different spectrum bands:
    - Block A: 1710-1720 / 2110-2120 (20 MHz) - Cellular Market Area (CMA) licenses
    - Block B: 1720-1730 / 2120-2130 (20 MHz) - Economic Area (EA) licenses
    - Block C: 1730-1735 / 2130-2135 (10 MHz) - Economic Area (EA) licenses
    - We consider these three blocks since they are licensed in a small area and they are adjacent to 1695-1710MHz band. The other three (Block D, E, and F) are licensed at Regional Economic Area Grouping (REAG) licenses which is very large area that does not help in predicting the spectrum value for a circle area with a radius of 100km.
- Calculate the average spectrum price for each station area (based on A, B, and C blocks) to be used in this analysis.

- Collect population density for circle area centered by the earth-station with different radiuses to determine real density for pop/km^2 for each earth-station throughout each surrounding circle area around. Then, these data is used to find the \$/MHz-POP value for each earth-station separately.

- Find the value based on the following function:

$$Zone\ "Value" = \left[\frac{Price}{MHz\ POP}\right] \times POP_{Impacted} \times BW$$

<u>Where:</u>

$$\frac{Price}{MHz\ POP} = \left[\frac{spectrum\ price(\$)}{bandwidth\ (MHz) \times Population}\right]$$

$$POP_{Impacted} = Number\ of\ population\ impacted\ by\ excultion\ zone$$

$$BW = Bandwidth\ of\ Shared\ band$$

The following tables summarize our analysis for each earth-station[27]. Table 6-10 shows the average \$/MHz-POP for each one of the stations, which is being used as input to evaluate the spectrum sharing benefits in our model.

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[27] Earth-station #8 (Anderson Air Force Base, GU earth-station) is not included in the following tables, because it is on an unpopulated island.

Table 6-7 Analysis summary of AWS-1, block A (20 MHz)

Station #	Net Price	Population	$/MHz-POP
1	$695,000.00	188,579.00	0.18
2	$549,750.00	128,275.00	0.21
3	$133,150,000.00	4,182,658.00	1.59
4	$35,633,000.00	3,876,380.00	0.46
5	$3,583,000.00	876,156.00	0.20
6	$426,000.00	148,281.00	0.14
7	$539,000.00	260,283.00	0.10
9	$974,000.00	401,762.00	0.12
10	$2,920,000.00	246,190.00	0.59
11	$179,161,000.00	15,620,448.00	0.57
12	$119,000.00	179,741.00	0.03
13	$19,451,000.00	1,553,843.00	0.63
14	$405,000.00	359,062.00	0.06
15	$25,089,000.00	2,518,470.00	0.50
16	$75,750.00	160,830.00	0.02
17	$1,543,500.00	673,884.00	0.11
18	$7,722,000.00	1,640,558.00	0.24

Table 6-8 Analysis summary of AWS-1, block B (20 MHz)

Station #	Net Price	Population	$/MHz-POP
1	$246,000.00	363,970.00	0.03
2	$1,809,000.00	626,932.00	0.14
3	$148,708,000.00	8,403,130.00	0.88
4	$61,055,000.00	5,602,222.00	0.54
5	$4,254,000.00	1,211,537.00	0.18
6	$940,000.00	519,143.00	0.09
7	$1,809,000.00	626,932.00	0.14
9	$80,834,000.00	9,111,806.00	0.44
10	$3,264,000.00	396,754.00	0.41
11	$215,620,000.00	18,003,420.00	0.60
12	$215,620,000.00	18,003,420.00	0.60
13	$21,894,000.00	2,184,860.00	0.50
14	$1,394,000.00	558,913.00	0.12
15	$23,498,250.00	3,558,651.00	0.33
16	$4,212,000.00	1,432,518.00	0.15
17	$6,735,000.00	1,044,156.00	0.32
18	$8,878,000.00	2,311,567.00	0.19

Table 6-9 Analysis summary of AWS-1, block C (10 MHz)

Station #	Net Price	Population	$/MHz-POP
1	$109,000.00	363,970.00	0.03
2	$1,111,000.00	626,932.00	0.18
3	$76,066,000.00	8,403,130.00	0.91
4	$21,314,000.00	5,602,222.00	0.38
5	$2,440,000.00	1,211,537.00	0.20
6	$404,000.00	519,143.00	0.08
7	$1,111,000.00	626,932.00	0.18
9	$23,028,000.00	9,111,806.00	0.25
10	$443,000.00	396,754.00	0.11
11	$114,816,000.00	18,003,420.00	0.64
12	$114,816,000.00	18,003,420.00	0.64
13	$5,124,750.00	2,184,860.00	0.23
14	$1,193,000.00	558,913.00	0.21
15	$8,421,750.00	3,558,651.00	0.24
16	$3,258,000.00	1,432,518.00	0.23
17	$1,737,000.00	1,044,156.00	0.17
18	$4,960,500.00	2,311,567.00	0.21

Table 6-10 Analysis summary, based on average spectrum auction prices

Station #	Earth Station Name	$/MHz-POP
1	Wallops Island, VA	**0.07**
2	Fairbanks, AK	**0.16**
3	Suitland, MD	**1.07**
4	Miami, FL	**0.48**
5	Ford Island, Pearl Harbor HI	**0.19**
6	Sioux Falls, SD	**0.10**
7	Elmendorf Air Force Base, AK	**0.14**
9	Monterey, CA	**0.37**
10	Stennis Space Center, MS	**0.39**
11	Twenty-Nine-Palms, CA	**0.60**
12	Yuma, AZ	**0.61**
13	Cincinnati, OH	**0.48**
14	Rock Island, IL	**0.12**
15	St. Louis, MO	**0.36**
16	Vicksburg, MS	**0.16**
17	Omaha, NE	**0.22**
18	Sacramento, CA	**0.21**

6.3.3 Sharing Benefits

In this section, we quantify the spectrum sharing benefits in MetSat case. First, the model will deliver the B and G radiuses as exclusion zones around each earth-station. Then, by using population and spectrum price analyses, we can evaluate the additive gain of the additional proposed areas shared as B, G, or W spaces.

6.3.3.1 Black Space The summary of B space analysis based on the classical scenario (as mentioned in Table 6-5) is listed in Table 6-11. The total spectrum value for the B space area is $193 million. Some black spaces are very small in area and impact relatively large populations; the value, then, depends more on the population density than on the size of the geographic area.

According to our definition, which is based on the classical scenario inputs, the B space boundary occurs when the PU receiver will accept more than 20dBm as additional aggregated interference above the interference threshold of that receiver. So, in some earth-stations, the black space is very valuable and may be worth sharing.

"*Anderson Air Force Base, GU*" earth-station is not included in the table, because it is on an unpopulated island. Thus, effect of the exclusion zone is insignificant at this location.

6.3.3.2 Gray Space The summary of G space analysis based on the classical scenario is shown in Table 6-12. The total G space area is worth $52 million. Appendix (E) summarizes the analysis of both B and G spaces together. The total spectrum value of the G+B space is $244 million.

Table 6-11 Benefits evaluation summary of B Space

station #	Black Space Analysis				
	Radius (km)	Land Area (km2)	Population Affected	Population Impacted (%)	Value ($)
1	56.73	3,930	175,304	0.06%	187,945
2	3.55	26	7,894	0.00%	19,223
3	78.55	16,298	7,707,479	2.50%	123,248,661
4	40.12	2,078	3,310,138	1.07%	23,856,598
5	29.52	1,119	913,032	0.30%	2,612,780
6	5.41	73	1,579	0.00%	2,261
7	25.54	1,145	268,289	0.09%	579,678
9	63.53	5,694	775,494	0.25%	4,333,835
10	83.00	14,896	1,015,651	0.33%	6,000,135
11	98.49	21,207	2,610,050	0.85%	23,402,738
12	13.81	451	114,054	0.04%	1,040,131
13	21.65	1,311	1,036,004	0.34%	7,473,844
14	2.20	8	14,867	0.00%	27,861
15	0.99	8	26,937	0.01%	146,598
16	4.28	60	7,128	0.00%	17,466
17	1.27	8	2,819	0.00%	9,453
18	0.82	8	19,001	0.01%	60,152
	Total Area Impacted (%)			0.70%	
	Total Population Impacted (%)			5.83%	
	Total Value ($)			193,019,360	

Table 6-12 Benefits evaluation summary of G Space

station #	Gray Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value
1	92.20	4,723	259,949	0.08%	278,693
2	12.75	461	49,258	0.02%	119,948
3	97.62	9,117	733,388	0.24%	11,727,452
4	90.51	11,456	1,451,888	0.47%	10,463,947
5	39.48	430	40,175	0.01%	114,967
6	62.44	12,295	276,428	0.09%	395,858
7	60.37	7,047	77,663	0.03%	167,802
9	91.21	8,995	1,607,321	0.52%	8,982,486
10	95.10	3,518	597,666	0.19%	3,530,816
11	99.70	75	63,413	0.02%	568,586
12	36.44	1,119	80,125	0.03%	730,711
13	46.20	5,588	876,570	0.28%	6,323,670
14	32.30	3,192	322,087	0.10%	603,595
15	13.44	490	542,969	0.18%	2,954,973
16	70.57	15,210	472,218	0.15%	1,157,093
17	10.19	282	121,799	0.04%	408,420
18	21.39	1,378	1,065,758	0.35%	3,373,926
	Total Area Impacted (%)			0.87%	
	Total Population Impacted (%)			2.80%	
	Total Value ($)			51,902,943	

6.3.3.3 White Space The information listed in Table 6-13 is very critical and clearly shows the benefits of sharing the band with the PU. When the SUs share the band, and aggregated interference falls below the interference threshold of the PU (W space sharing) yields a spectrum value of $2.3 billion. This will incur a lower enforcement-cost compared to G or B space sharing.

Table 6-13 Benefits evaluation summary of B, G, and W Space

	Black	**Gray**	**Black + Gray**	**White**
Total Area Impacted (%)	0.70%	0.87%	1.56%	98%
Total Population Impacted (%)	5.83%	2.80%	8.63%	91%
Total Value ($)	193,019,360	51,902,943	244,922,303	2,327,334,430

6.4 SENSITIVITY ANALYSIS

Adjusting the input assumptions to the model allows us to understand the sensitivity of the results to potential variance of critical input data. In this section, we test the sensitivity of our results against any variance in the critical inputs to the simulation model.

6.4.1 Additional Losses

This section shows the effect of conceding additional power loss coefficients for any losses over the transmission space, such as indoor transmission loss calculation or floor penetration loss factor. In the last section (classical scenario), the additional losses are set at zero to represent a conservative scenario in order to protect the PU antenna. Here, we will consider two additional values to examine the sensitivity of this factor to the sharing benefits analysis. Appendix (E) summarizes all the analysis performed in this section.

$L_{Additional}$ = 0 dB

This is the analysis shown at last section. In this case, the total G+B space is worth $244 million and the W space is worth 2.3 billion. This case is the "classical scenario" where the additional losses are set at zero.

$L_{Additional}$ = 10 dB

Table 6-14 summarizes this analysis; see Appendix (E) for full analysis.

Table 6-14 Sensitivity analysis in B, G, and W space: additional losses = 10 dB

	Black	**Gray**	**Black + Gray**	**White**
Total Area Impacted (%)	0.43%	0.66%	1.08%	99%
Total Population Impacted (%)	3.23%	3.40%	6.63%	93%
Total Value ($)	111,757,643	95,668,974	207,426,617	2,378,335,113

$L_{Additional}$ = 20 dB

Table 6-15 summarizes this analysis; see Appendix (E) for full analysis.

Table 6-15 Sensitivity analysis in B, G, and W space: additional losses = 20 dB

	Black	**Gray**	**Black + Gray**	**White**
Total Area Impacted (%)	0.28%	0.45%	0.73%	99%
Total Population Impacted (%)	2.02%	3.20%	5.22%	95%
Total Value ($)	76,142,942	99,111,533	175,254,475	2,414,081,926

It is clear that the "*Additional Losses*" factor is not very sensitive in the overall perspective, and did not cause high variance at the B, G, and W space values. However, for each earth-station, as shown in Appendix (E), some station shows sensitivity to this factor. For example, the value of G+B space in "Sioux Falls, SD" earth-station drops significantly after adding losses to the model. For "*Additional Losses*" equals 0, 10, and 20 dBm, the values are $398k, $29k, and $2k, respectively

6.4.2 SUs Active Factor and Density

In the classical scenario and from the real population density values, we multiply the population density by the "Active Factor", to reflect the expected active SUs transmitted at the same time, which is 0.1%. This means that we expect 1 of each 1000 of total population to be active at the same time to share the band with the PU. The active factor is intended to be a realistic estimate, and we will evaluate it in this sensitivity analysis.

We compute it at G radius, where we repeat the analysis with two values:

- Active Factor = 0.5% (5 times the classical scenario value)
- Active Factor = 0.05% (half the classical scenario value)

From the analysis summarized at Table 6-16, it is clear that this factor is very critical and its sensitivity is different from one station to another. The variance due to each "active factor" (i.e. 0.5%, 0.1%, and 0.05%) increases at earth-stations that have a small radius, such as station #2 and station # 17. The reason is that the $G_{boundary}$ is very sensitive to SUs density when SUs are located a relatively small distance from the PU location.

Although, there is not solid base that we can validate this assumption, we believe that (0.1%) percentage of active SU is reasonable assumption in such spectrum sharing environment, and we set that value as an input to our classical scenario.

Table 6-16 Active factor of SUs for G space

station #	Gray Space Radius [km]		
	Active Factor = 0.5%	Active Factor = 0.1% (Classical Scenario)	Active Factor = 0.05%
1	96.7	92.20	85.3
2	33.6	12.75	6.4
3	99.6	97.62	95.6
4	98.4	90.51	83.0
5	68.2	39.48	38.3
6	85.6	62.44	41.3
7	89.3	60.37	42.4
9	98.0	91.21	87.9
10	99.1	95.10	93.2
11	99.9	99.70	99.3
12	64.7	36.44	30.2
13	89.1	46.20	38.5
14	57.0	32.30	23.3
15	29.1	13.44	4.5
16	91.7	70.57	51.9
17	30.0	10.19	3.3
18	49.2	21.39	8.2

6.4.3 Black Space Boundary

The G space boundary is given in this analysis as a constant (i.e. it is one of the PU's antenna specifications that define the interference threshold). The focus on in this section is to examine the effect of the difference between G and B boundaries. Figure 6-8 shows that at the Miami FL earth-station, and we notice the following:

- If the G and B boundary are the same, the radius will be around 90km (matches the results listed at Table 6-12).
- By increasing the difference between the G and B boundaries by moving along the x-axis, the radius of B space decreases.
    - At difference equal 20dBm (as the classical scenario) between G and B boundary, the B radius is 40km which match also the result at Table 6-11.
- The sensitivity of this factor will vary based on the characteristic of sharing environment. In this figure (Miami, FL earth-station), we reduce the exclusion zone radius by 50km by making the PU accept additional 20dBm of aggregated interference.

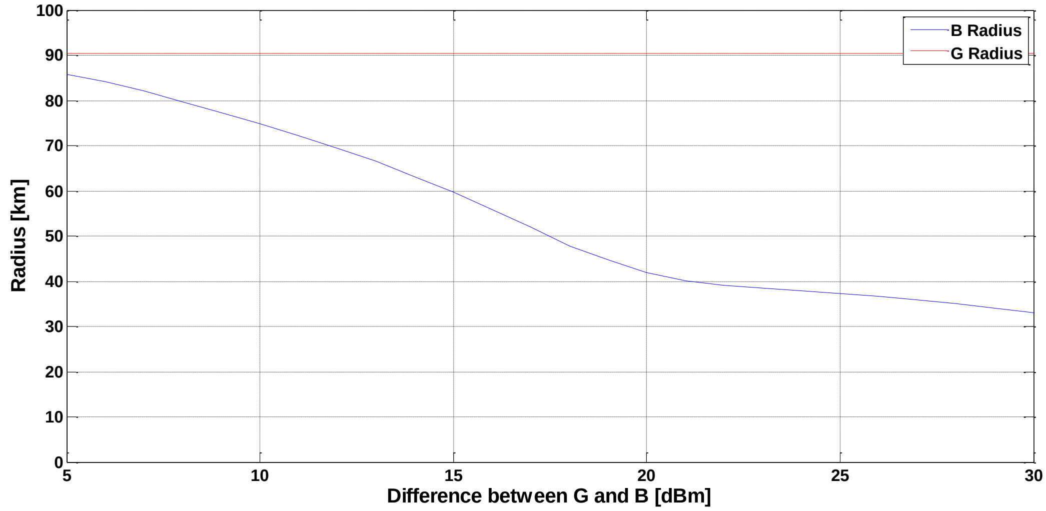

Figure 6-8 Aggregate interference and B space radius

6.4.4 Relocation Benefits

In this section, we assess the benefits of relocating earth-stations that cause the most impacted percentage on sharing utilization (based on classical scenario). The following Table 6-17 lists the stations based on the classical scenario inputs. We can see that the first five earth-stations account for 90% of the benefits gained from sharing.

The idea here is to relocate the earth-stations with the highest sharing benefits to another locations with less population. If we assume the total cost (including the cost of the impacted population in the new locations) of relocating an earth-station would be $10 million, then the value of the spectrum based on the affected population exceeds the cost of relocation for the first five earth-stations. This suggests that there may be a social benefit to their relocation.

Table 6-17 Relocation benefits analysis of the 18 earth-stations

<table>
<tr><th rowspan="2">Station #</th><th rowspan="2">Earth Station Name</th><th rowspan="2">Value ($)</th><th rowspan="2">Order #</th><th colspan="2">Relocation Suggestion</th></tr>
<tr><th>Option A</th><th>Option B</th></tr>
<tr><td>3</td><td>Suitland, MD</td><td>134,976,113</td><td>1</td><td rowspan="5">90%</td><td rowspan="3">79%</td></tr>
<tr><td>4</td><td>Miami, FL</td><td>34,320,545</td><td>2</td></tr>
<tr><td>11</td><td>Twenty-Nine-Palms, CA</td><td>23,971,324</td><td>3</td></tr>
<tr><td>13</td><td>Cincinnati, OH</td><td>13,797,514</td><td>4</td><td rowspan="14">21%</td></tr>
<tr><td>9</td><td>Monterey, CA</td><td>13,316,321</td><td>5</td></tr>
<tr><td>10</td><td>Stennis Space Center, MS</td><td>9,530,951</td><td>6</td><td rowspan="12">10%</td></tr>
<tr><td>18</td><td>Sacramento, CA</td><td>3,434,079</td><td>7</td></tr>
<tr><td>15</td><td>St. Louis, MO</td><td>3,101,571</td><td>8</td></tr>
<tr><td>5</td><td>Ford Island, Pearl Harbor HI</td><td>2,727,747</td><td>9</td></tr>
<tr><td>12</td><td>Yuma, AZ</td><td>1,770,843</td><td>10</td></tr>
<tr><td>16</td><td>Vicksburg, MS</td><td>1,174,559</td><td>11</td></tr>
<tr><td>7</td><td>Elmendorf Air Force Base, AK</td><td>747,481</td><td>12</td></tr>
<tr><td>14</td><td>Rock Island, IL</td><td>631,456</td><td>13</td></tr>
<tr><td>1</td><td>Wallops Island, VA</td><td>466,638</td><td>14</td></tr>
<tr><td>17</td><td>Omaha, NE</td><td>417,872</td><td>15</td></tr>
<tr><td>6</td><td>Sioux Falls, SD</td><td>398,119</td><td>16</td></tr>
<tr><td>2</td><td>Fairbanks, AK</td><td>139,170</td><td>17</td></tr>
</table>

6.4.5 NTIA Analysis VS Simulation Results

The NTIA did two analyses of the 1.7GHz band in 2010 and 2013 [4] [67]. By excluding exceptional cases, there is a relative similarity between the NTIA analysis and our results; see Table 6-18. It should be noted that the NTIA analysis used different settings, such as the network topology of SUs, density of SUs, and the assumption of the terrain model, which result the variance between NTIA and our results.

In 2010 analysis [4], the NTIA used LTE networks (both LTE base-stations and LTE-UE) to represent the SUs. In 2013, the NTIA used LTE-UE only (similar to our simulation). LTE base-stations added more interference, which explains that our results are more comparable to the 2013 analysis.

The NTIA 2013 analysis [67] considered 18 SUs (i.e. LTE-UE) in each LTE cell with a cell-radius of either 0.93km or 3.76km. However, in our simulation, we used real population analysis where we did not assume the population. As a result, each earth-station simulated based on real population around it (the population analysis in a level of “zip-code area”).

If we take “Miami, FL” earth-station as an example (station #4), the NTIA 2013 analysis shows that the radius is 46km, whereas our result shows that it is 90.5km with zero additional losses being considered. The population density in our simulation is 1592.63 SUs/km^2 at inner area and 126.86 SUs/km^2 at outer area. We believe, the NTIA 2013 report underestimated the population at the “Miami, FL” earth-station.

In the “Yuma, AZ” earth-station case (station #12), the NTIA 2013 analysis shows that the radius is 95km, whereas our result shows that it will be 36.4km. At this station, the population density in our simulation is 123.63 SUs/km^2 in the inner area and 7.61 SUs/km^2 in the outer area. The real population is very low in the outer area (i.e. 40km $\leq$ radius $\leq$ 100km).

Finally, in the NTIA 2013 analysis [67], the percentage of population (based on 2010 Census) impacted by the 18 exclusion zone is 8.96%. In my analysis, the percentage of impacted population is 8.63%, 6.63%, and 5.22% for addition losses equal to 0, 10, and 20dB; respectively. For more details, please refer to Appendix (E).

Table 6-18 Comparison between NTIA analysis VS simulation results

station #	Radius of Exclusion Zone (G radius) [km]				
	NTIA Analysis		Dissertation Analysis (Active SUs Factor=0.1%)		
	2010	*2013*	Addition Loss =0 dB	Addition Loss =10 dB	Addition Loss =20 dB
1	*90*	*29*	92.2	82.3	56.9
2	*90*	*81*	12.7	6.2	4.1
3	*121*	*91*	97.6	91.9	77.8
4	*110*	*46*	90.5	73.6	40.4
5	*110*	*25*	39.5	36.9	29.1
6	*80*	*40*	62.4	18.9	4.4
7	*110*	*14*	60.4	35.6	25.9
8	*110*	*42*	Not included (unpopulated island); see section 6.3.3.1		
9	*110*	*85*	91.2	84.1	65.1
10	*110*	*58*	95.1	92.6	83.6
11	*110*	*80*	99.7	99.2	98.4
12	*110*	*95*	36.4	24.4	14.8
13	*96*	*32*	46.2	34.9	22.1
14	*78*	*10*	32.3	8.3	1.8
15	*76*	*34*	13.4	2.2	0.7
16	*72*	*14*	70.6	37.6	3.9
17	*76*	*30*	10.2	1.8	1.6
18	*72*	*55*	21.4	2.9	1.1

6.5 HYPOTHESES TEST

This chapter examines and quantifies the benefits gained from spectrum sharing through three levels of sharing/enforcement scenarios (W, G, and B spaces). It also tests the four hypotheses that are listed at chapter#3 of this dissertation.

There are enormous benefits to sharing the spectrum at 1.7GHz band. For example, there is an approximately around $2.3 billion benefit out of sharing the W space at this spectrum band. These sharing benefits prove valuable opportunity cost is lost by having exclusive usage right at 1.7GHz band. Therefore, the opportunity cost is getting larger in the case where the spectrum utilization is less, which means that we can accept H1.

If we consider that the most stringent ex ante enforcement position is to prevent any sharing in this band, the next step towards ex post enforcement is to allow sharing in W spaces. The aggregated interference will be below the PU interference threshold and the enforcement-cost will be at its lowest (compare to other cases). By moving towards ex post enforcement, we will allow sharing in the G space and then the B space. Both need more enforcement costs since the PU should agree to tolerate additional aggregated interference. In this classical scenario, the W benefits are $2.3 billion, whereas both G and B benefits together are $244 million. Throughout all 18 earth-stations, the benefits are higher and the expected costs are lower in W space sharing. Spectrum utilization increases by sharing the G and then the B space (moving towards ex post enforcement). This led to the acceptance of both H2 and H4.

To evaluate H3, we will illustrate the cumulative benefits versus the radius of the simulated area. Figure 6-9 shows a different perspective by relating the radius (in km) with the sharing benefits (in $) at “Cincinnati. OH” earth-station. For all other MetSat earth-stations, please see

Appendix (F). The y-axis illustrated in the figure shows the cumulative benefits starting from the boundary of the simulated area (100km) to the earth-station location.

In our example (Table 6-11 and Table 6-12) of the Cincinnati earth-station, the B radius is 21.7km with a benefit value equivalent to \$7.5 million. We can see this benefit clearly from the cumulative curve, between 0 and 21.7km. Similarly, the G radius is 46.2km with G space area worth \$6.3 million. Both these results and the analysis in section 0 match identically.

We can summarize this in the following functions for "Cincinnati, OH" earth-station:

$$W_{benefit} = \int_{46}^{100} Cumulative\ Curve\ \ dr$$

$$G_{benefit} = \int_{22}^{46} Cumulative\ Curve\ \ dr$$

$$B_{benefit} = \int_{0}^{22} Cumulative\ Curve\ \ dr$$

The W benefit case shows the benefits of W space sharing in the simulated area (R=100km) only. This does not take into consideration the W spaces between the simulated earth-stations as total.

In G benefit case, this is the upper bound of the reasonable cost for enforcement at this scenario. This enforcement-cost include, but not limited to, the amount that probably been paid to the PU to accept additional aggregated interference and shifting the threshold from $G_{boundary}$ to $B_{boundary}$ (additional 20 dBm). If the enforcement-cost exceeds the benefits (enforcement cost ≥ \$6.3 million), the sharing at G space does not worth it.

The B benefit case is the total gain from sharing the spectrum without any type of exclusion zones. In this case, the SU will determine the optimal protection zone where there will be a balance between enforcement penalty and sharing gain out of this additional area.

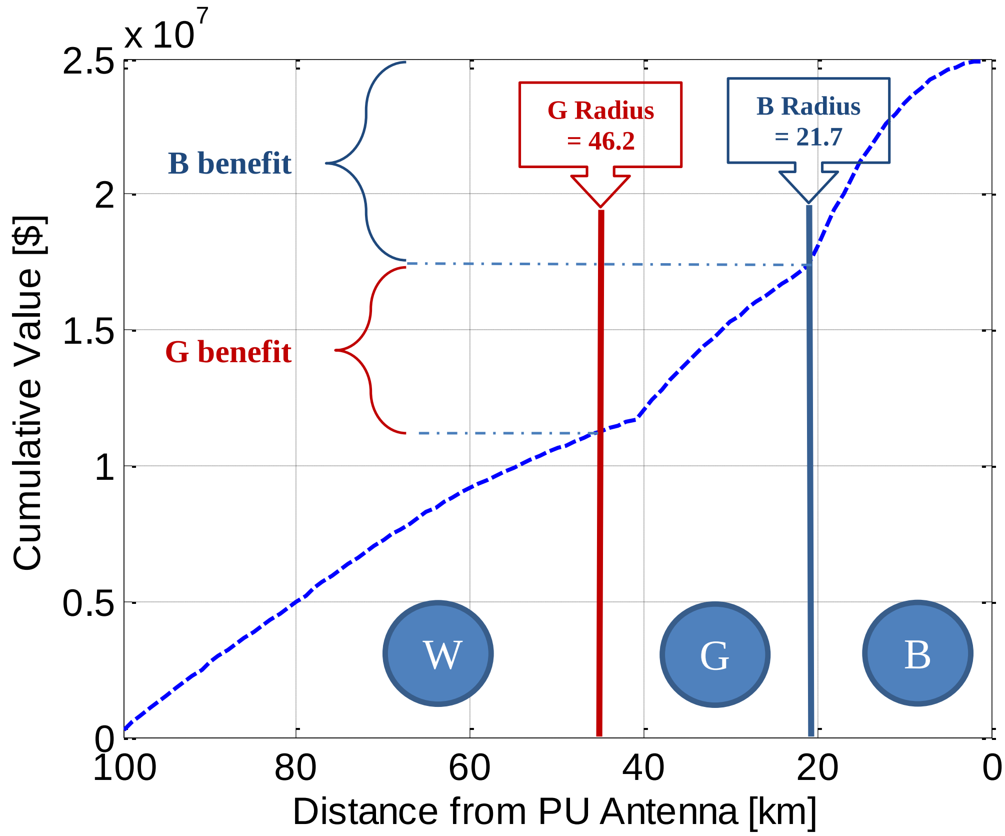

Figure 6-9 Cumulative value of spectrum sharing benefits in "Cincinnati, OH"

As we can see in Appendix (F), each earth-station has its own curve that represents the benefits of sharing by moving from the ex ante towards ex post enforcement scenario. For example, Figure 6-10 illustrates this for Ford Island, Pearl Harbor, HI earth-station. We can see that the exclusion zone is worthless between 100km to 40km. After that, however, there is a significant increase in benefits by shrinking the zone towards the PU location. This led to the acceptance of H3, where there is more than one relationship-curve by moving from the "ex ante" towards the "ex post" enforcement approaches, which varies by changing the sharing environment characteristics.

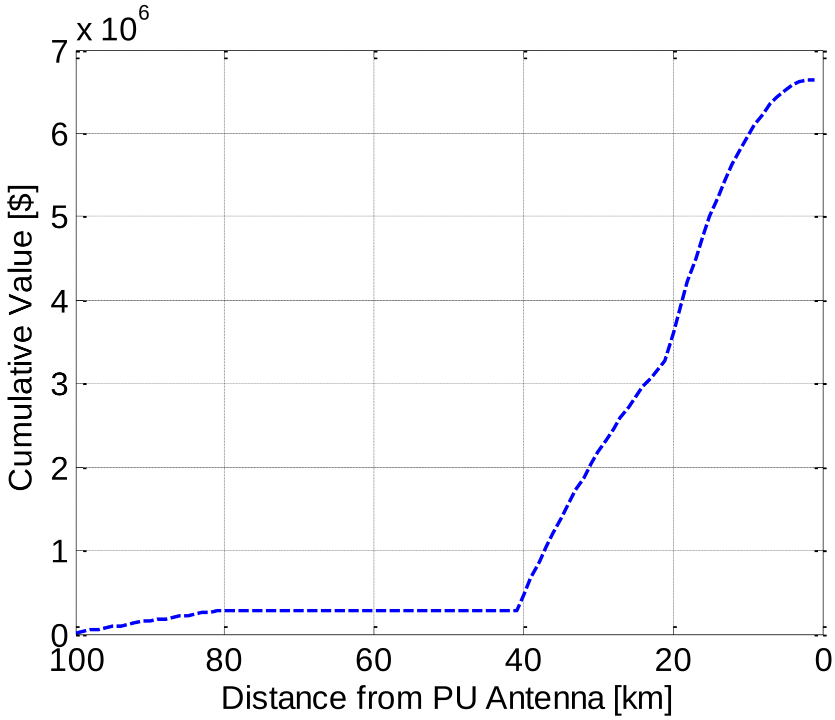

Figure 6-10 Cumulative value of spectrum sharing benefits in "Ford Island, HI"

7.0 SPECTRUM SHARING IN THE 3.5 GHZ BAND

The FCC proposes specific rules for a "Citizens Broadband Radio Service" in the 3.5 GHz band that would make the 3.5 GHz sharing regime, originally described by the PCAST report, a reality. In December 2012, the FCC published the first "Notice of Proposed Rulemaking", which was followed by a revised proposed framework described in the "Licensing Public Notice" [32]. In April 2014, the FCC issued the most recent notice (called "Further Notice of Proposed Rulemaking"), which was developed based on responses to a series of prior proposals and workshops [33].

The 3500-3650 MHz frequency range is divided into the 3500-3600 and 3600-3650 MHz bands in the US National frequency table. These two frequency bands include allocations to Federal radio-location and radio navigation services. Therefore, since the bands represent similar uses throughout the 3500-3650 MHz band, the 3500-3600 and 3600-3650 MHz bands have been addressed as a single frequency band in the NTIA analysis.

Originally, the NTIA in the Fast Track report recommended reallocating 100 megahertz of the 3550-3650 MHz band for wireless broadband use within five years (Fast Track report published in October 2010) [4]. In this chapter, we will describe the recommended sharing scenarios and examine the expected sharing benefits.

7.1 PRIMARY AND SECONDARY USERS

7.1.1 Primary User

The 3500-3650 MHz band (150MHz) is used by DoD radar systems with installations on land, ships, and aircraft. Based on the NTIA [4], most of the aircraft and land-based systems are operated at military training areas and test ranges. Functions performed by these systems include search for near-surface and high altitude airborne objects, sea surveillance, tracking of airborne objects, air traffic control, formation flight, and multi-purpose test range instrumentation.

To share this band, the NTIA Fast Track Report recommends geographic separation to mitigate interference. NTIA recommends exclusion zones around ground-based and shipborne radar systems[28]. With respect to shipborne radars, NTIA has determined that extremely large geographic exclusion zones are necessary, reaching a maximum of 310km. That is estimated to exclude approximately 60% of the United States population that falls within that exclusion zone[29]. As a result, our focus in this dissertation will be on shipborne radars only, as the main PU antenna type reducing sharing utilization. For more information about PU types at this band, please refer to Appendix (G).

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[28] For airborne radar systems, there is no need for exclusion zones. The NTIA has concluded that a frequency offset of approximately 40 MHz is needed to eliminate the need for exclusion zones for airborne radar systems. This is one of the rationales for limiting the sharing band to 3550-3650MHz instead of the full 3500-3650MHz.

[29] NTIA analysis considers WiMAX technology for shared use of the 3.5 GHz band.

7.1.2 Secondary User

As mentioned in a recent report from the FCC [33], many services/technologies have been proposed to share the band with the PUs. The most common feature is expected to be "small cell" topology(s). Even the PCAST report goes in this direction, recommending small cells in the 3.5GHz band [3].

We believe that both Femtocells and WiFi have almost the same effect on the PU antenna, especially given that both have the same maximum standardized transmit power and that both are used mainly indoors. Thus, we group them together in this analysis. In this dissertation, we will consider the following three types of technologies to demonstrate our model:

1. LTE-UE: uplink only.
2. LTE network: both LTE base stations and LTE-UE.
3. Femtocells-WiFi networks.

7.2 SIMULATION SETTINGS

7.2.1 PU Characteristics

The technical specifications used in this model are based on the NTIA report [4]. Some necessary information is missing from that report; however, we have made certain assumptions as detailed below. Table 7-1 summarizes the specifications about the shipborne radars. Please refer to Appendix (H) for more details.

Table 7-1 Specifications of shipborne radars

	Antenna Gain (dBi)	Antenna Losses (dB)	Antenna Height (m)	$G_{boundary}$ (dBm) {Interference Threshold}	$B_{boundary}$ (dBm) {$G_{boundary}$ + 10}
Shipborne 1	32	2	50	-114	-104
Shipborne 2	47	2	30	-101	-91
Shipborne 3	41.8	3.4	30	-100	-90
Shipborne 4	38.9	2	30	-110	-100
Shipborne 5	43.3	2	30	-110	-100

One critical characteristic that is not available is the minimum elevation angle for each of these five types of shipborne radars. As a result, the PU elevation angle is assumed to be 10 degrees as a classical input in this case[30], and we will include this assumption in our sensitivity analysis at

[30] We believe that "10 degrees" is a very reasonable assumption for the worst possible scenario, given the fact that these radars are used to track objects flying over the ground.

the end of this chapter. In addition, the PU azimuth angle is between -180 and 180 degrees, and the center frequency in this case is 3600MHz.

7.2.2 SUs Characteristics

7.2.2.1 Area of Simulation The shipborne radars run along the East, Gulf, and West coasts of the US. For an illustration of an exclusion zone around the coast lines, please see Figure 7-1. In this figure, the red line represents the boundary of an exclusion zone. The radius of the simulated area is 100km.

In the NTIA analysis [4], they expect the PU antennas (shipborne radars) to be 10km away from the coast line. However, that assumption is not binding. Thus, we chose to assume the location of the PU antennas in this simulation model to be right at the coast line to represent a conservative strategy to protect the PU.

Figure 7-1 Depiction of exclusion zones around the East, Gulf, and West coasts of the US

7.2.2.2 SUs Density In the case of 3.5GHz, we are dealing with a very large area of sharing with a very large exclusion zone proposed to protect the PUs. Based on the NTIA analysis, in order to protect the shipborne radars along the three coastal lines, the proposed exclusion zone area causes the exclusion of around 60% of the population. This very large proportion of the population will lower the value of sharing in this critical band.

Based on Census Bureau data [75], the average population density of the coastal shoreline counties (excluding Alaska) is 172 persons per km^2. The density in the US as a whole averages 40 persons per km^2. To capture those data in the model, and in similar way we did the setting at the 1.7GHz band analysis, the SUs densities as follow:

- Density1 (0 to 50km) = 172 person per km^2

- Density2 (50 to 100km) = 40 person per km^2

To reflect the terrain effect on the path loss, four of the Hata models are simulated for each type of shipborne radars (i.e. open, suburban, small city, and large city). The radius of G and B spaces varies widely over these four path loss models due to differences in the PU antenna characteristics of each shipborne radar.

7.3 ANALYSIS AND RESULTS

Three SUs types, which share this band, will be examined. Each of them will be simulated over three different SUs active factors: 0.5%, 0.1% and 0.05%, to represent different SUs density scales. In addition, W, G, and B space are evaluated for each shipborne radar.

There is 100MHz of spectrum to be shared over a very large area along the US coasts. There is no benchmark which to base the spectrum price at 3.5GHz band ($ per MHz-POP)[31]. Therefore, we use a value of $0.1 per MHz-POP in this band (3.5GHz).

[31] Based on the ITU broadband report [73], since 2002, the global average for 2.1 GHz spectrum has been $1.33 per MHz POP. However, the global average of spectrum auction for 2.6 GHz has been $0.07 per MHz POP since 2005.

7.3.1 LTE-UE Scenario

In this scenario, the SUs is considered to be LTE-UE (uplink only). The technical characteristics and probability distribution function of these LTE-UE devices is the same as that described in section 6.2.2. From Table 7-2, we notice the following:

- The order from largest to smallest exclusion zone radius[32] is as follows:
  - Shipborne 1,
  - Shipborne 4,
  - Shipborne 5,
  - Shipborne 2 and Shipborne 3 are almost the same.
- In some cases, there is no need for B space. For example, where the SUs active factor = 0.1%, there is no need for B space in the small and large city terrain model.

[32] In this chapter, the distance from the coast line to boundary of G or B space is called "radius" of the exclusion zone.

Table 7-2 B and G space radius for LTE-UE scenario

	Black Space (km)				Gray Space (km)			
	SUs Active Factor = 0.5%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	94.2	47.1	30.7	30.6	98.1	76.6	42.1	41.3
Shipborne 2	48.3	16.3	1.7	1.0	77.7	34.9	7.6	5.8
Shipborne 3	47.5	16.1	1.1	0.9	76.7	34.9	7.6	5.8
Shipborne 4	77.8	35.8	8.4	6.8	92.2	46.1	29.8	29.1
Shipborne 5	74.1	33.5	6.0	5.3	90.6	44.9	28.5	28.2
	SUs Active Factor = 0.1%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	70.1	32.8	4.9	4.4	90.2	41.7	23.3	23.0
Shipborne 2	27.0	1.8	0.0	0.0	42.8	7.7	1.6	1.5
Shipborne 3	29.9	0.7	0.3	0.0	42.3	4.7	2.4	1.8
Shipborne 4	42.0	10.0	0.9	0.7	60.9	31.4	2.9	2.3
Shipborne 5	42.7	9.2	0.5	0.1	64.1	28.9	2.6	2.2
	SUs Active Factor = 0.05%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	48.7	20.6	1.6	1.6	76.1	34.5	8.9	7.7
Shipborne 2	22.5	0.7	0.0	0.0	36.0	3.8	3.0	1.4
Shipborne 3	21.5	0.2	0.0	0.0	36.1	3.8	3.2	1.3
Shipborne 4	39.4	4.1	0.6	0.4	52.1	20.1	2.8	2.8
Shipborne 5	36.7	2.3	0.0	0.0	46.5	15.5	2.4	2.8

To show the benefits of sharing the band with each shipborne radar independently, please see Table 7-3 till Table 7-7. The SUs active factor in these tables is 0.1% (the classical value). Four terrain models have been simulated, where the radius decreases by moving from “open” area towards “large city” area. Therefore, by assuming that each terrain type has 25% of the terrain topography along the coast lines, we can determine the average value of W, G, and B spaces at each shipborne radar. The difference in W space value between shipborne 1 and shipborne 4 (the second largest radiuses) is around $176 million.

Table 7-3 B, G, and W space value for Shipborne 1 in LTE-UE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	**Suburban**	**Small City**	**Large City**	
Space Type	**Black**	658	394	59	53	291
	Gray	56	107	222	224	153
	Black + Gray	715	502	281	277	444
	White	2,373	2,586	2,807	2,810	2,644

Table 7-4 B, G, and W space value for Shipborne 2 in LTE-UE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	**Suburban**	**Small City**	**Large City**	
Space Type	**Black**	325	21	0	0	87
	Gray	189	71	19	18	74
	Black + Gray	515	92	19	18	161
	White	2,573	2,995	3,068	3,070	2,926

Table 7-5 B, G, and W space value for Shipborne 3 in LTE-UE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	361	8	3	0	93
	Gray	149	48	26	22	61
	Black + Gray	510	56	29	22	154
	White	2,578	3,031	3,058	3,065	2,933

Table 7-6 B, G, and W space value for Shipborne 4 in LTE-UE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	505	120	10	8	161
	Gray	127	258	25	19	107
	Black + Gray	632	378	35	27	268
	White	2,455	2,710	3,052	3,060	2,819

Table 7-7 B, G, and W space value for Shipborne 5 in LTE-UE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	514	111	6	2	158
	Gray	127	237	26	25	104
	Black + Gray	641	349	31	27	262
	White	2,446	2,739	3,056	3,060	2,825

7.3.2 LTE Scenario

Here, a full LTE network is considered (both LTE base stations and LTE-UE), although, this scenario is not consistent with the direction of having only small cell technologies in this band. However, we want to examine several possible scenarios in this research.

The relation of LTE base stations to each other is completely independent. Both LTE base stations and LTE-UE are randomly distributed over the simulated area, since we are examining the aggregated interference effect on the PU antenna and not the performance of the LTE network. Table 7-8 summarizes the assumed ratio which is used between LTE base stations and LTE-UE. In dense areas (i.e. large and small cities), we assume that there is 1 base station for each 22 LTE-UE, whereas in suburban and rural areas, there is 1 for each 6. In the NTIA-CSMAC analysis [67], 1 to 18 ratio has been used over all different terrain types.

From Table 7-9, we can notice the following:

- The radius of G and B spaces is larger compared to the LTE-UE, due to the addition of LTE base stations.
    - Shipborne 1 still has the largest radii.
    - By comparing LTE-UE and LTE scenarios (Table 7-2 and Table 7-9), if G or B radius is relatively small, the variance between LTE and LTE-UE cases is large due to the sensitivity of both G and B boundaries. For example:
        - At Shipborne 5 with “large city” terrain and (0.5%) active factor, the B radius is 5.3km and 38.4km for LTE-UE and LTE cases, respectively.

    - At Shipborne 5 with open terrain and (0.5%) active factor, the G radius is 90.6km and 97.3km for LTE-UE and LTE cases, respectively.
- In some cases (e.g. the terrain type of "large city" at Shipborne 2 and 3), the B and G radius is very small.
  - NTIA assumes that the shipborne radar will be at a distance of 10km from the coast line. If we consider that in our analysis, we will end up with some cases where the B and G radius is zero. (We considered the shipborne radars on the coast line as the worst case scenario in our model).

The SUs active factor in Table 7-10 till Table 7-14 is (0.1%). These tables show the benefits of sharing the band with each shipborne radar independently. G and B space value at Shipborne 1 case is worth an average of $645 million, compared to 444 million in LTE-UE scenario. This benefit shows the existence of more incentive to share G and/or B space at this scenario.

Table 7-8 LTE network topology

Terrain Type	Ratio
Small and large city areas	{1 to 22} One LTE base station for each 22 active LTE-UE
Suburban and open areas	{1 to 6} One LTE base station for each 6 active LTE-UE
• All the LTE base station transmit at fixed power = 46 dBm. • LTE-UE transmit based on the PDF listed in section 6.2.2	

Table 7-9 B and G space radius for LTE scenario

	Black Space (km)				Gray Space (km)			
	SUs Active Factor = 0.5%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	95.5	87.4	57.9	54.9	99.2	94.5	84.3	83.2
Shipborne 2	67.3	42.4	24.7	25.9	93.5	60.8	37.9	38.5
Shipborne 3	70.1	43.3	26.5	25.6	94.5	60.9	39.6	38.5
Shipborne 4	88.2	66.6	40.2	39.7	97.7	85.6	55.5	51.8
Shipborne 5	77.7	56.7	38.4	38.4	97.3	84.2	51.0	50.1
	SUs Active Factor = 0.1%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	72.0	52.3	36.8	36.3	93.3	79.4	51.3	47.2
Shipborne 2	41.9	19.0	2.0	2.8	66.2	40.9	12.2	13.6
Shipborne 3	34.5	24.8	3.4	2.5	69.5	37.8	15.2	17.5
Shipborne 4	61.7	36.7	18.2	13.3	89.3	55.3	34.5	32.7
Shipborne 5	69.0	34.1	12.3	17.7	87.6	50.0	32.1	33.7
	SUs Active Factor = 0.05%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	63.9	46.7	26.4	26.2	93.0	65.9	42.5	39.3
Shipborne 2	31.6	8.7	1.3	1.0	53.7	33.4	9.1	5.2
Shipborne 3	35.3	8.6	0.9	1.4	57.3	28.7	5.7	8.0
Shipborne 4	52.0	22.2	7.3	4.6	78.3	44.9	22.5	26.0
Shipborne 5	51.2	25.0	4.6	5.3	75.6	46.8	21.0	19.9

Table 7-10 B, G, and W space value for Shipborne 1 in LTE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	664	608	443	437	538
	Gray	60	76	162	131	107
	Black + Gray	723	684	606	568	645
	White	2,364	2,403	2,482	2,519	2,442

Table 7-11 B, G, and W space value for Shipborne 2 in LTE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	504	229	24	33	198
	Gray	143	263	122	130	165
	Black + Gray	647	492	147	164	362
	White	2,440	2,596	2,941	2,924	2,725

Table 7-12 B, G, and W space value for Shipborne 3 in LTE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	415	299	41	31	197
	Gray	241	157	142	180	180
	Black + Gray	657	455	183	210	376
	White	2,431	2,632	2,905	2,877	2,711

Table 7-13 B, G, and W space value for Shipborne 4 in LTE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	635	442	219	160	364
	Gray	77	175	196	234	171
	Black + Gray	712	617	415	394	535
	White	2,375	2,470	2,672	2,693	2,553

Table 7-14 B, G, and W space value for Shipborne 5 in LTE Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	655	410	148	213	357
	Gray	52	192	238	193	169
	Black + Gray	707	602	386	406	525
	White	2,380	2,485	2,701	2,682	2,562

7.3.3 Femtocells and WiFi Scenario

In this scenario, it is assumed that both the transmitter and receiver have the same probability distribution function (PDF); therefore, we will not differentiate between an access point or user equipment. We assume that the PDF for transmit power is the same as LTE-UE in urban areas, where the transmit power is relatively less given the short distance between the transmitter and receiver[33].

We ignore traffic type differences that have been carried over SUs network, we simulate a PDF of transmit power (dBm) whether for Femtocells or WiFi users. The SU density has been examined over three cases (Active factor = 0.5%, 0.1%, and 0.05%) to compare their sensitivity.

Since Femtocells and WiFi applications are mainly indoor, and based on ITU recommendation (please refer to section 5.2.5.2), the ITU recommend power loss coefficient for indoor transmission calculation to be around (27 dB). To be in the conservative side, we will add only 10dB as additional losses in this scenario. From Table 7-15, we conclude the following:

- Since these types of technologies are small cell, there is a huge reduction in G and B radii compare to previous two scenarios, which gives an advantage to small cell technologies over LTE in sharing this band. This in turn will increase sharing utilization.

[33] At 3.5GHz, there is no official standards yet that we can base the "transmit power" on them for either Femtocells or WiFi. Therefore, it is reasonable to set it to be similar to LTE-UE PDF.

- The majority of the cases at either small or large city terrain model, listed in Table 7-15, show that G and B radii will be zero.
    - This will decrease the benefits of sharing the G and/or B spaces. So, we can conclude that the incentive to share G and B space will be less at this scenario.
    - However, the W space benefits will be at its largest compare to other scenarios.
- These findings are consistent with the FCC recommendations of using “small cell” technology in this type of spectrum sharing environment.

Table 7-15 B and G space radius for Femtocells-WiFi scenario

	Black Space (km)				Gray Space (km)			
	SUs Active Factor = 0.5%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	50.6	2.2	0.0	0.0	81.0	27.3	0.8	0.0
Shipborne 2	3.8	0.0	0.0	0.0	28.6	0.7	0.6	0.0
Shipborne 3	2.9	0.0	0.0	0.0	28.4	0.8	0.7	0.0
Shipborne 4	30.9	0.0	0.0	0.0	48.9	1.9	0.8	0.0
Shipborne 5	28.0	0.0	0.0	0.0	47.3	2.0	0.8	0.0
	SUs Active Factor = 0.1%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	21.4	0.0	0.0	0.0	44.3	2.0	0.0	0.0
Shipborne 2	0.0	0.0	0.0	0.0	2.6	1.7	0.0	0.0
Shipborne 3	0.0	0.0	0.0	0.0	2.2	1.6	0.0	0.0
Shipborne 4	2.4	0.0	0.0	0.0	18.5	1.9	0.0	0.0
Shipborne 5	2.3	0.0	0.0	0.0	16.1	1.9	0.0	0.0
	SUs Active Factor = 0.05%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	6.3	0.0	0.0	0.0	32.5	0.0	0.0	0.0
Shipborne 2	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
Shipborne 3	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Shipborne 4	1.3	0.0	0.0	0.0	6.2	0.0	0.0	0.0
Shipborne 5	0.0	0.0	0.0	0.0	4.7	0.0	0.0	0.0

The previous table list the radii for all simulated scansions, now, how about evaluating the benefits? WiFi technology commonly deployed at unlicensed band, which means the spectrum is free of cost. LTE-Femtocells commonly utilize the same spectrum as the mobile operator. This dissertation does not undertake a comprehensive analysis of the benefits to society that may result from making spectrum sharing available. So, under Femtocells-WiFi scenario, it is likely that SUs may share this band without paying for the spectrum.

If there will be a price for it, there is no benchmark which to base the spectrum price ($ per MHz-POP). Therefore, we use a value of $0.1 per MHz-POP in this band (3.5GHz), same as previous two scenarios. Table 7-16 and Table 7-17 show sharing benefits for only two shipborne (since the radii is very small for G and B space) for active factor equals (0.1%). Shipborne 1, which product the largest exclusion zone, and Shipborne 2, which product the smallest exclusion zone. We conclude that G and B space values on all shipborne radars are relatively small and W space value is greatest. This shows the advantage of this type of small cell over other scenarios.

Table 7-16 B, G, and W space value for Shipborne 1 in Femtocells and WiFi Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	258	0	0	0	64
	Gray	275	24	0	0	75
	Black + Gray	533	24	0	0	139
	White	2,555	3,063	3,087	3,087	2,948

Table 7-17 B, G, and W space value for Shipborne 2 in Femtocells and WiFi Scenario

($ Million)		Terrain Type				Average (25% each)
		Open	Suburban	Small City	Large City	
Space Type	Black	0	0	0	0	0
	Gray	0	0	0	0	0
	Black + Gray	0	0	0	0	0
	White	3087	3087	3087	3087	3087

7.4 SENSITIVITY ANALYSIS

In this section, we discuss the sensitivity of the results to potential variance of critical input data. To avoid prolixity, unless mentioned otherwise, all analysis is based on the LTE-UE scenario for 0.1% SUs active factor and for Shipborne 1.

7.4.1 SUs Active Factor and Density

The above section shows that changing the SUs active factor results in a significant change in the G and B radii. For example, Table 7-18 summarizes the variance among three different densities.

Sensitivity in small and large city terrain areas is higher than in open or suburban areas because the total aggregated interference in the “open” terrain area is higher than in the “large city” area, which makes it less sensitive to SUs density changes compared to the second one. For example, if we increase the active factor from (0.1%) to (0.5%) in the open terrain case, the B radius increases by 34%, and the G radius increases by 9%. On the other hand, the B radius increases by 599%, and the G radius increases by 80% in the large terrain case.

Table 7-18 Sensitivity analysis for SUs density in Shipborne 1

Active Factor (*)	**Black Space**				**Gray Space**			
	Open	**Suburban**	**Small City**	**Large City**	**Open**	**Suburban**	**Small City**	**Large City**
0.5% (Change %)	34%	44%	531%	599%	9%	84%	81%	80%
0.1% (km)	70.1	32.8	4.9	4.4	90.2	41.7	23.3	23.0
0.05% (Change %)	-30%	-37%	-67%	-64%	-16%	-17%	-62%	-67%

(*) This is the percentage of active SUs among the total simulated population

7.4.2 Minimum Elevation Angle

As previously mentioned, the elevation angle of PU antenna (i.e. shipborne radars) was not known; and we assume it to be 10 degrees as the minimum elevation angle. From the MetSat case, it is clear that the elevation angle of the PU antenna is very sensitive input. Thus, to examine its effect, we plot how the G and B radii will change based on the variance of the minimum elevation angle from 0 to 40 degrees; please see Figure 7-2. This figure is based on the Shipborne 1 specifications for a suburban terrain type.

Clearly, this input is critical, and the radius becomes very small after 40 degrees. If we consider that 43 degrees is the minimum elevation angle, which is similar to some MetSat earth-stations, the G and B space will decrease significantly, leading to a larger W space area. This figure matches the result listed in Table 7-2 at angle=10 degrees, where G radius is 41km and B radius is 32km.

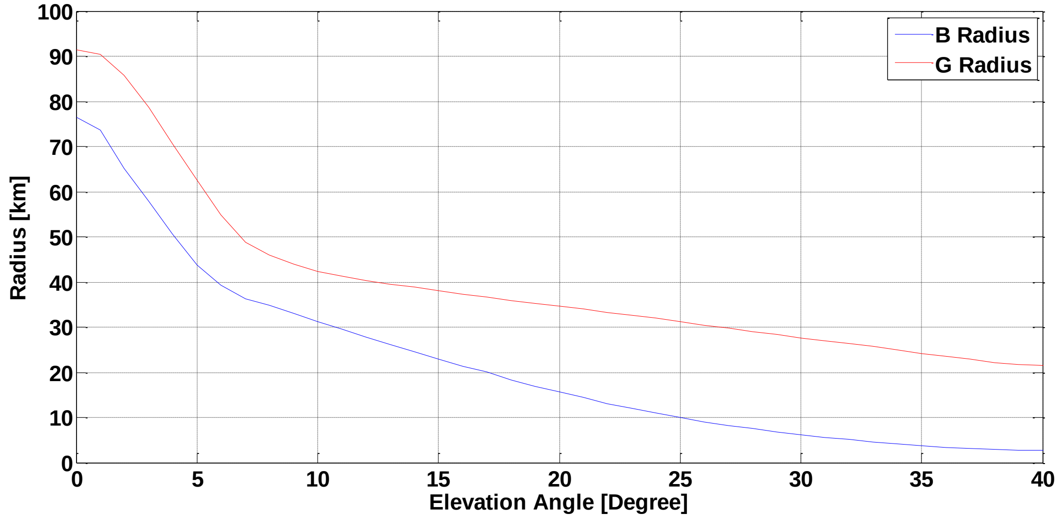

Figure 7-2 Effect of PU minimum elevation angle over G and B radiuses

7.4.3 Black Space Boundary

The G space boundary in this analysis (i.e. interference threshold listed in Table 7-1) is given as (-114dBm) for Shipborne 1. Hence, we will examine the effect of changing the B boundary to B radius. At a difference of 10 dBm (the classical value), the B radius is 32km, which matches the previous result. The B boundary can be negotiated between the PU and SU, which will affect both G and B space areas.

From the figure, we can also see that if B boundary is set below -89 dBm (-114+25), the B radius will be zero. From this fact and the above tables, it is clear that the B space is diminished in many cases, especially if the terrain area is the “small city” or “large city” model.

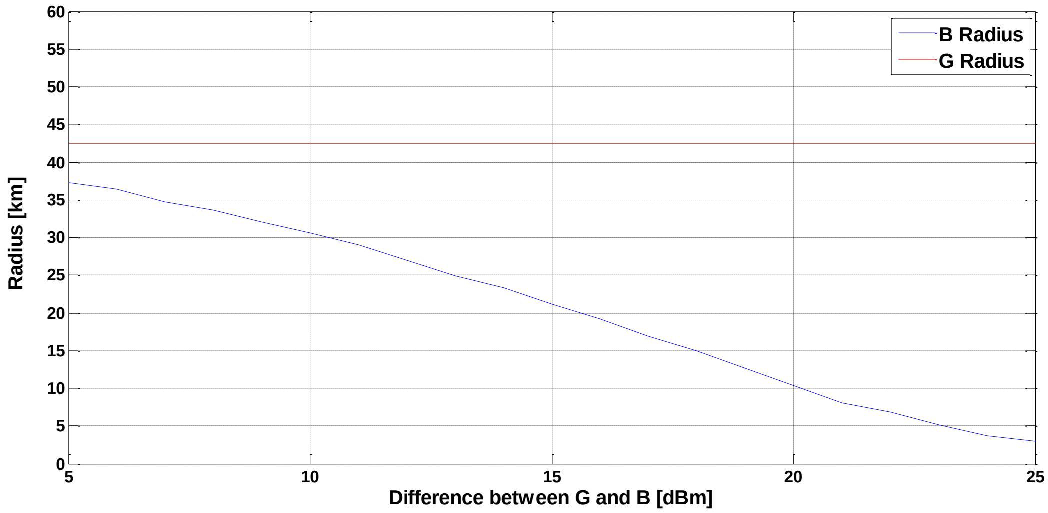

Figure 7-3 Aggregate interference and B space radius

7.5 HYPOTHESES TEST

In the LTE-UE scenario, the average value of G+B space is worth $444 million in the Shipborne 1 case, $645 million in the LTE scenario and $204 million in the Femtocells-WiFi scenario. We can say clearly that the Femtocells-WiFi scenario gives the highest opportunity cost to share this band compared to the other two scenarios. The W space is worth around $3 billion in the Femtocells-WiFi scenario, and it is expected to be shared with the minimal cost of enforcement compare to the other G and B enforcement. These findings let us accept H1.

If we only consider Shipborne 2, there are different findings based on four different terrain types. In the LTE scenario, for example, the value of G+B space in "open terrain" type is worth $647 million. However, in "large city terrain", it is worth $164 million. In the same analogy we used in the last chapter, if we consider these benefits as the upper and reasonable enforcement-cost curves for each scenario, There are different curves link the path between the two extreme sides: ex ante and ex post enforcement scenario; which led to the acceptance of H3.

Overall, according to these three scenarios, if we share only W space, the benefit is huge. Also, it is possible to share more (i.e. G and/or B spaces), albeit with less benefits, but it is still worth it if the benefits exceed the enforcement cost. More sharing means additional and higher spectrum utilization, as well as more dependency on ex post enforcement; which means we can accept H2 and H4.

All our analyses are based on the assumption that the spectrum value is based on 0.1$ per MHz-POP. However, if we change that number to 0.3, for example, we have to multiply all our final findings by 3, and so on. In addition, this simulation considers the shipborne radars to be right on the coast lines, with zero distance, although, the NTIA analysis suggests a 10km distance. If we add that to this model, many B spaces will be eliminated from the results, and G spaces will decrease. The Femtocells-WiFi scenario is very likely to be at least one of the technology types to share this band. We expect significant advantages in this sharing since the G and B radii are relatively small. These assumptions will not affect the acceptance of the Hypotheses.

8.0 CONCLUSIONS AND FUTURE WORK

Spectrum sharing has gone from an idea to a serious policy focus in one decade. It has become one of the most expected approaches to expand mobile wireless capacity due to the predicted high growth rate of mobile broadband traffic over the coming years. Enabling spectrum sharing regimes on a non-opportunistic basis means that sharing agreements must be implemented. To have meaning, those agreements must be enforceable, and the enforcement-cost supposed to be less than the benefits we are getting out of this sharing

As with many new and possibly disruptive technologies, spectrum sharing poses challenges for stakeholders, which include incumbents (i.e. PUs), regulators and entrants (i.e. SUs). Incumbents have made investments that are often sunk costs to utilize the spectrum for which they have a license. Over the course of nearly a century, regulators have developed regulations that have been tested in the field and in the courts and are based on the “command and control” licensing regime. Entrants are being pressed by the marketplace and enabled by new technologies to develop new approaches to exploiting the resource that is RF spectrum. Thus, it is no wonder that the specter of spectrum sharing has political, economic, technical, and legal implications.

In this dissertation, we have sought to provide specific insight into some techno-economic aspects of non-opportunistic spectrum sharing. This analysis is valuable because it will help regulators prepare for possible future scenarios in solving the wireless capacity crunch. In addition, it can give government users more insight into the expected future of sharing. It is also of value to commercial users and operators in that they can use the results of this work to make more informed decisions about the economic benefits of different spectrum sharing market and opportunities.

The main goal of this dissertation is to examine and quantify the benefits of spectrum sharing. Given the inherent uncertainty of any quantifying model of future benefits, the goal of this analysis is not to reach definitive numeric findings of spectrum sharing value and economic benefits, but to shed light on the relationship between common enforcement strategies and their economic consequences in terms of lost value for bands that are actively being considered for government-commercial sharing.

There are four hypotheses in this dissertation which had been tested throughout two spectrum bands cases. We believe that the first hypothesis hold in majority of expected spectrum sharing bands, where the opportunity cost of exclusive spectrum is high at low spectrum utilization. For other hypotheses, we believe that they hold in all spectrum bands. The complexity of "ex post" enforcement approach is higher than "ex ante" enforcement approach. In addition, there is more than one relationship-curve by moving from the "ex ante" towards the "ex post" enforcement approaches. Furthermore, spectrum utilization will increase by raising the dependency on the "ex post" enforcement approach.

8.1 CONCLUSIONS

One of the contributions of this dissertation is to demonstrate enforcement concepts in the spectrum sharing domain (***chapter 4***). Traditionally, in the spectrum field, the enforcement process is heavily based on preventing an "interference event" before it happens, such as having geographical or spectral (i.e. guard band) separation between licensees, and transmitters' specifications. This dissertation propose the idea of an interactive rule of enforcement that changes the spectrum utilization bar by moving from "ex ante" towards "ex post" enforcement. The enforcement regime is comprised of technical and non-technical elements, where the latter includes business processes, market norms, and policy institutions and frameworks that reinforce and interact with the technical enforcement solutions. Thus, developing effective approach to protect the rights of incumbents and entrants is important, and it is equally important that this approach be adaptive.

As the main contribution of this dissertation, we propose a "sharing model" that is customized to examine and quantify the benefits of different sharing scenarios (***chapter 5***). It is a centerpiece of this dissertation in which main factors that affect the sharing scenarios can be examined and highlighted. The current approach to spectrum sharing using exclusion zones (as suggested by NTIA) is based primarily on ex ante enforcement by setting very large exclusion zones to protect the PUs. In this dissertation, however, the role of ex post enforcement is expected to increase. The proposed modeling of geographical exclusion zones moves from the ex ante approach (large exclusion zone) towards ex post enforcement. The evaluation criteria of sharing benefits spans three levels of sharing: Black, Gray, and White space sharing.

The key component of this simulation is a methodology that has been used to determine the aggregated interference level at a PU location with many SUs sharing the band. In this work, we have created a reasonable representation of the aggregate interference in the spectrum sharing environment where multiple SUs cause interference to a single PU. Based on our model settings, the major findings can be summarized as follows:

- The variance at the expected W area (by sharing the W space) is less when the density of SUs increases. This indicates that if we plan to share the spectrum in W space only, the density of SUs will not have much effect over the W space area above a certain level of SUs per km^2.

- The incentive to share G space will decrease by increasing the density of SUs. Therefore, G area will be smaller if the density increase.
- "Frequency sensitivity" of both B and G space area decrease as SUs density increases. For example, sharing at 1GHz or 5GHz will lead to the same B and G sharing areas at high SUs density.
- The sensitivity analysis for the interference threshold boundary (in dBm) shows the following:
    - At a specific interference threshold of PU antenna, the exclusion zone radius (either B or G space) will increase in nonlinear relationship with SUs density.
    - The variance of the exclusion zone radius, by changing the interference threshold of the PU antenna, has a nonlinear relationship with SUs density. For example, by changing the interference threshold by (+10dBm), the gain at G space area will be higher at lower SUs density compared to higher ones.

In the spectrum sharing case of the 1.7GHz band (***chapter 6***), sharing between MetSat (18 fixed earth-stations) and LTE-UE has be studied. The results show high lost value if we keep the exclusive rights (i.e. no sharing) at this band. In addition, this analysis has ultimately led to a priority list of stations that are recommended to be relocated to better utilize the band. A level of "zip-code area" analysis was done to determine the population density affected by each exclusion zone (i.e. B, G, and W) to increase the accuracy of the benefits analysis. In addition, on the basis of the FCC auction-database of comparable spectrum bands (AWS-1 bands), spectrum pricing analysis was performed. Based on the setting of our model and the analysis we did, we can conclude the following:

- For each specific sharing environment, there is a unique sharing-benefits function. Frequency band, SUs density, transmit power of SUs, and other common factors are not enough to evaluate the sharing benefits in each specific environment or to give recommendations regarding the preference of each band to be shared by which SUs service. As a result, the enforcement strategy will vary and its cost will not be reasonable if it is above the expected benefits from each sharing case.
- There is huge lost value in having exclusive usage rights MetSat stations only. Our analysis indicates high benefits by moving from pure ex ante enforcement (the current case by not allowing the sharing) towards ex post enforcement through different levels of sharing (i.e. B, G, W spaces). Based on our classical scenario:
    - W space is worth approximately $2.4 billion and covers an area of 98% of the area of the US land.
    - G+B space is worth approximately $245 million. However, not all the 18 earth-stations are worth sharing in G and/or B space. It totally depends on the benefit function at each station and whether that benefit exceeds the expected enforcement cost. For example, the G+B space is worth $135 million at one of the stations, whereas it is worth only $0.4 million at another.
    - These sharing benefits prove to be a valuable opportunity cost that is lost by having exclusive usage right at the 1.7GHz band.

- One critical item in this simulation is the difference between the G and B boundaries. It is assumed to be (20dBm) in our classical scenario. We expect the PU will tolerate this additional level of interference provided that it will be paid back from the G space benefit.
- We also deliver a relocation-table for the 18 earth-stations, where the station with the highest sharing benefits is recommended to be relocated to another area with less population. So, if spectrum sharing be limited to W space only, we reduce the opportunity cost by relocate the highest G+B benefits stations.
- W space sharing gives the highest benefits with less expected enforcement-cost. G space sharing gives different levels of benefits which vary based on the sharing environment and it is expected to cost more to enforce sharing in this space. B space sharing also shows benefits, which may give a positive total gain at some scenarios.
- Each earth-station has its own curve which represents the benefits of sharing by moving from the ex ante towards ex post enforcement scenario.
- The percentage of impacted population due to G+B exclusion zone is 8.63%, 6.63%, and 5.22% for addition loss equal to 0, 10, and 20dB; respectively.

In the spectrum sharing case of the 3.5GHz band (***chapter 7***), the NTIA has determined that extremely large geographic exclusion zones are necessary; in addition, it was estimated to exclude approximately 60% of the United States population. In our analysis, we examine three different scenarios: LTE-UE, LTE, and Femtocells-WiFi. On one side, the most impactful scenario (LTE scenario, for Shipborne 1) is estimated to exclude approximately 38% of the United States population. On the other side, for the least impactful scenario (Femtocells-WiFi scenario, for Shipborne 2) is estimated to exclude only 6.2%.

This chapter discusses the benefits of spectrum sharing over different enforcement scenarios in the 3.5GHz band. The SU is modeled in three types, each of which has its own characteristics and findings. Although there are some other PU types using this band, the focus in this dissertation is on the main PU usages (i.e. shipborne radars) which cause the highest reduction in spectrum utilization. Based on our analysis:

- In the LTE-UE scenario with 0.1% active factor:
    - Shipborne 1 radar gives the largest exclusion zone compared to the other four radars; the G+B space is worth $444 million.
    - Shipborne 2 and 3 radars give the smallest exclusion zone. The G+B space in each is worth approximately $160 million.
- In the LTE scenario with 0.1% active factor:
    - The G+B space is worth $645 million in the Shipborne 1 case.
- In the Femtocells-WiFi scenario with 0.1% active factor:
    - The G+B space is worth $330 million in the Shipborne 1 case.
- The elevation angle of the PU antenna (i.e. shipborne radars) is unknown; we assumed it to be 10 degrees as the minimum elevation angle. The sensitivity analysis shows that this is a critically sensitive input to model results.
- The NTIA analysis suggests 10km distance between the shipborne radars and the coast line, we consider zero distance in the analysis. If we add that to this model, many B spaces will be eliminated from the results, and there will be a significant decrease of G spaces.

Finally, we want to highlight that most of the settings of the simulation model are conservative. The intent of this approach was to that the PUs are protected by considering worst case settings in some of the inputs to the model. We ignore the effects of "indoor propagation losses" over the propagation model in all the analyses cases except at Femtocells-WiFi scenario. In addition, at 3.5GHz, we consider the shipborne radars to be at the coast line while we aggregate the interference. If we add all that to the model, it is expected that W benefits will dominate other benefits, especially in the 3.5GHz case.

8.2 GENERALIZATIONS AND SPECULATIONS

While the results reported here are specific to some particular sharing bands, the approach (and some of the lessons) may be generalizable to other bands and other sharing scenarios as well. One of the lessons from this study is that spectrum sharing benefits (as well as the enforcement applicability) are quite situation-specific. Sharing W space is expected to have higher incentives with high benefits and low enforcement-cost. Sharing G or B space, however, runs the risk of having enforcement-cost greater than the sharing benefits in some situations. Further, it is as yet not possible to determine a "best" approach to share a spectrum band as the enforcement-cost (including the costs of adjudication) are highly uncertain and dependent on the particulars of the sharing circumstances.

In the 1.7GHz band, there are many reasons to expect that there will be one LTE operator sharing the band. First, reduction in enforcement-cost by having a centralized SU (i.e. single interface managing all the secondaries; see section 4.1.2). Second, the adjudication process as part of ex post enforcement will be easier. Thus, demodulation of the LTE signal to uniquely identify the SU causing an interference event may not be necessary reducing ex post enforcement-cost. If multiple LTE operator exist to share the 15MHz band, the LTE signal would have to be demodulated to identify the source of the interference, which is more costly.

This dissertation does not undertake a comprehensive analysis of the benefits to society that may result from making spectrum sharing available, which some economists estimate as multiples of the private value. There may be a sharing scenarios where the SUs will use the band under pre-registration processes and spectrum-license-free (similar to unsilenced band), for example, WiFi sharing of the 3.5GHz band. Since there are no direct benefits from the spectrum auction, however, there probably huge benefits to society that will compensate any enforcement-cost.

Performing additional case studies, such as the ones presented here, will help build a “catalog” of enforcement approaches and expected benefits bounds. Such a collection may enable the development of recommended initial approaches for various spectrum sharing circumstances. These recommendations/lessons together will help analyzing and understating any future sharing scenario.

The focus of this dissertation is to study the spectrum sharing between government (as PUs) and commercial users (as SUs). We believe there are many lessons that can be taken from this towards other sharing scenarios such as government-government sharing or commercial-commercial sharing (see Figure 3-1). Frequency effects and SUs density analyses and findings are examples of lessons that can be taken from this dissertation and applied to other sharing scenarios.

In the case of government-government sharing, the trust between the PUs and SUs is high, and that will reduce the enforcement-cost substantially. For example, the SUs (i.e. government agencies) may gain access to more information about the PUs. The feedback level between the PUs and SUs will increase, especially if that contains information within government security domain. In the case of commercial-commercial sharing, it is expected that the opportunity cost of sharing will be less, since the PU has higher spectrum utilization compare to government users. Network topology and usages of commercial PU is different than governments PU, which led to the expectation that the sharing enforcement-cost will be higher in this case.

8.3 FUTURE WORK

There is a great potential for future research. This simulation model and the two case studies for examining spectrum sharing open the doors for future ideas and questions, including:

- This dissertation quantifies the benefits of different levels of sharing. In other words, it sets the upper bound of the reasonable cost of enforcement for sharing the spectrum in specific scenarios. Although there is significant uncertainty in estimating enforcement costs at this early stage of spectrum sharing practice, it will be very interesting to see how benefits will intersect with cost to define the optimum point to do the enforcement and represent the ideal sharing utilization. Thus, finding the cost model for enforcement between "ex ante" and "ex post" enforcement approaches is another interesting area of research.

- Due to spectrum sharing, both PUs and SUs expect that interference may occur from one to the other. This dissertation concentrates on a “PUs as victim” approach and assumes that the SUs will consider the PUs interference as a fact of life that needs to be coexisted with it. However, how will that affect the benefits evaluation from the SUs perspective? Is there an advantage of small-cell over large-cell SUs’ service (since small-cell is most likely to be indoors and less affected by PU interference)?
- Chapter 5 of this dissertation shows a very interesting relationship between “sharing benefits” and “some key model inputs”. By considering additional new SUs services that could share the spectrum with PUs, such as Machine to Machine technologies, how will that change the findings of sharing benefits in G and/or B spaces?

APPENDIX (A)

SPECTRUM OPPORTUNITY COST

Opportunity cost can be described as "the basic relationship between scarcity and choice"[34]. In microeconomic theory, opportunity cost is defined as the highest value alternative forgone; in a situation in which a choice needs to be made between several mutually exclusive alternatives given limited resources. The New Oxford American Dictionary defines it as "the loss of potential gain from other alternatives when one alternative is chosen". The efficient market clearing price is equal to the opportunity cost of the marginal unit of the good or service in that market[35].

Accordingly, spectrum opportunity cost is:

- In the exclusive spectrum domain:
    - Allocating the spectrum to the highest value user should be considered in the band allocation process. That can be done in many forms, such as spectrum auctions.
    - In theory, the last remaining bidder, after all others have dropped out, will be the one best prepared to make the optimal use of that particular spectrum[36].

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[34] James M. Buchanan; "*Opportunity cost*". The New Palgrave Dictionary of Economics; 2008.

[35] American Case Management Association; "Opportunity Cost Pricing of Spectrum"; Public Consultation; April 2009.

[36] ITU; "Exploring the Value and Economic Valuation of Spectrum"; ITU reports on broadband; April 2012.

- In the shared spectrum domain:
    - What we are trying to do in this research can be described as studying and discovering “alternatives” of utilizing the spectrum in specific bands under two level of usage rights: primary rights (i.e. PUs) and secondary rights (i.e. SUs).
    - If the value of those “alternatives” is higher than the current case, this means that we have incentive to introduce spectrum sharing in that band.

“Only if the sharing arrangement increases the value to all other sharing users by a greater amount than is lost to the highest valued user will the total value of the band of spectrum increase. If the total value of the spectrum for all shared uses is less than the value for a single user, then spectrum sharing diminishes the potential value of the spectrum”[37].

[37] McHenry, Giulia and Bazelon, Coleman, “The Economics of Spectrum Sharing” The 41st Research Conference on Communication, Information and Internet Policy; 2013.

APPENDIX (B)

MIMO EFFECTS AND TRANSMIT POWER

In this appendix, we will illustrate in brief some research that supports the argument that characterizes MIMO over SISO systems in power efficiency (i.e. less interference to PU). As in the assumption in the simulation model, at long distance transmission, an SU using MIMO transmits less power than SISO. As a result, the amount of Gray and Black spaces will be less in the MIMO scenario. In other words, the sharing utilization will be better when SUs use the MIMO, where everything else is the same, including the data rate between SUs.

From Figure A 1, we want to highlight two different distances. The distance between two SUs (transmitter and receiver) is “d”. The distance between SU transmitter and PU receiver is “R”. Distance “d” influences the transmit power between SUs. Distance “R” influences the spectrum utilization in our simulation model, and it is the key variable in this dissertation.

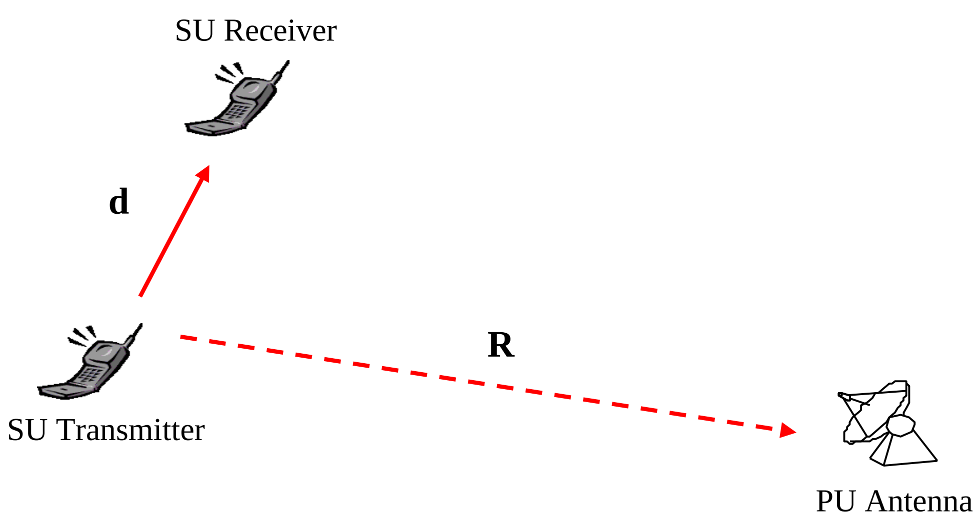

Figure A 1 Differentiate between two types of distances affect SUs power

Most research relates the distance “d” to MIMO and the power efficiency level. However, this distance is not considered in our work; we rather consider “R” as directly affecting the exclusion zone size and the aggregated interference level.

Based on Figure A 2 (from [71]), under the same throughput (data rate = 5 bit/s/Hz), transmit power will drop from 92 mW to 26mW by changing the antenna configuration from 1x1 to 2x2. The transmit power will be around 7mW at 4x4 and 8x8. This figure is based on a simulated IEEE 802.11n network. In this case, SISO will cause more aggregated interference at the PU receiver, if they share the same spectrum band. Therefore, by adding MIMO factor to the SUs topology in our simulation model, the aggregate interference to the PU receiver is expected to be either less or at least the same as SISO, and we expect that utilization will increase and that Gray and Black spaces will be smaller.

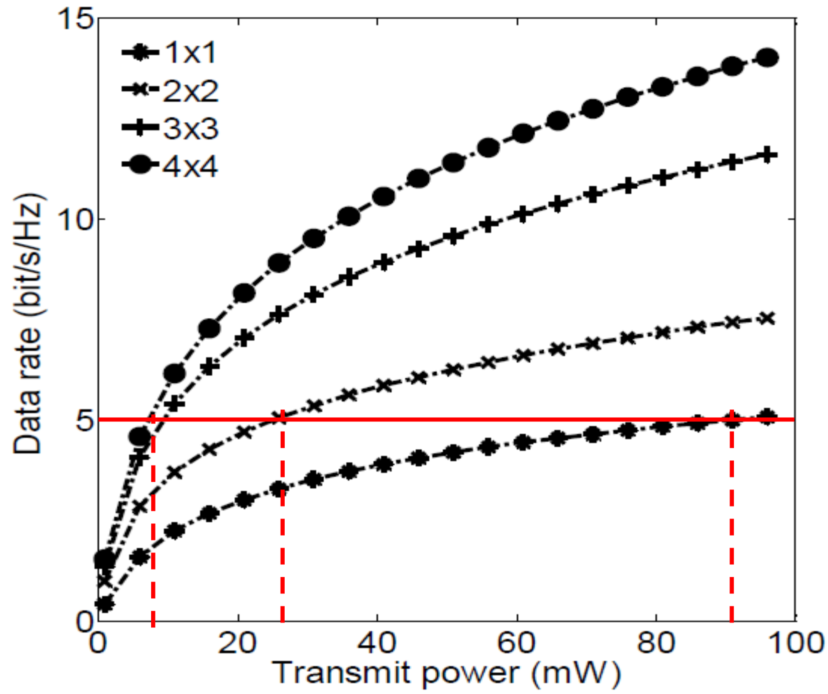

Figure A 2 Mapping from transmit power to data rate

APPENDIX (C)

POPULATION CHARACTERISTICS CHART

In section 6.2.1, we illustrate the population characteristics chart for Miami, FL earth-station only. This appendix list the rest of them[38].

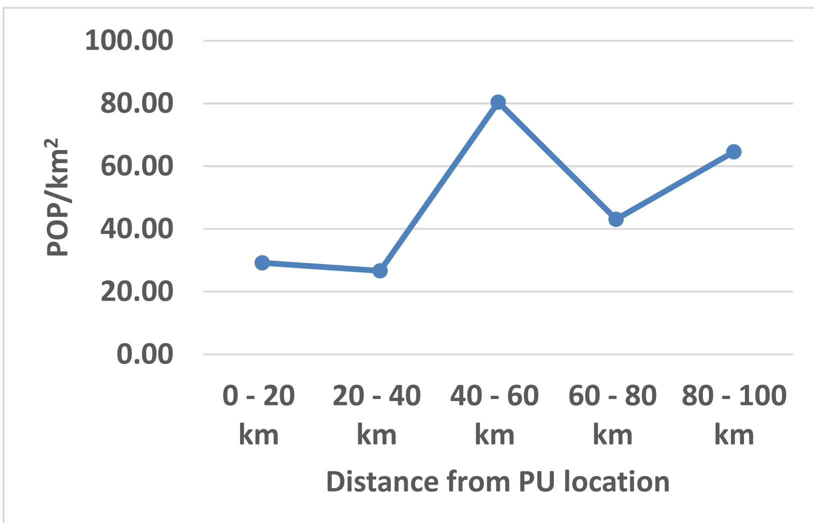

Figure A 3 Population characteristics chart: Wallops Island, VA

[38] Note:"Anderson Air Force Base, GU" earth-station is not listed here, since it is located in non-populated area.

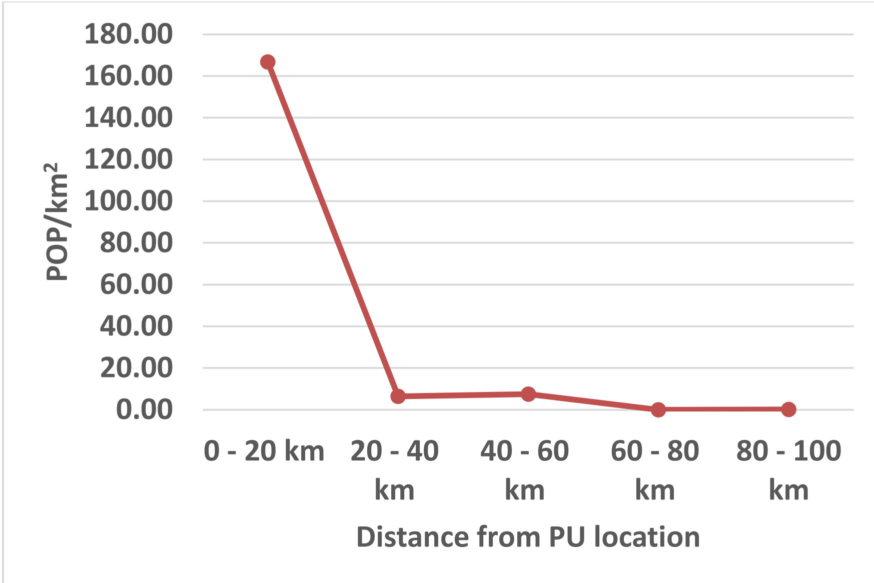

Figure A 4 Population characteristics chart: Fairbanks, AK

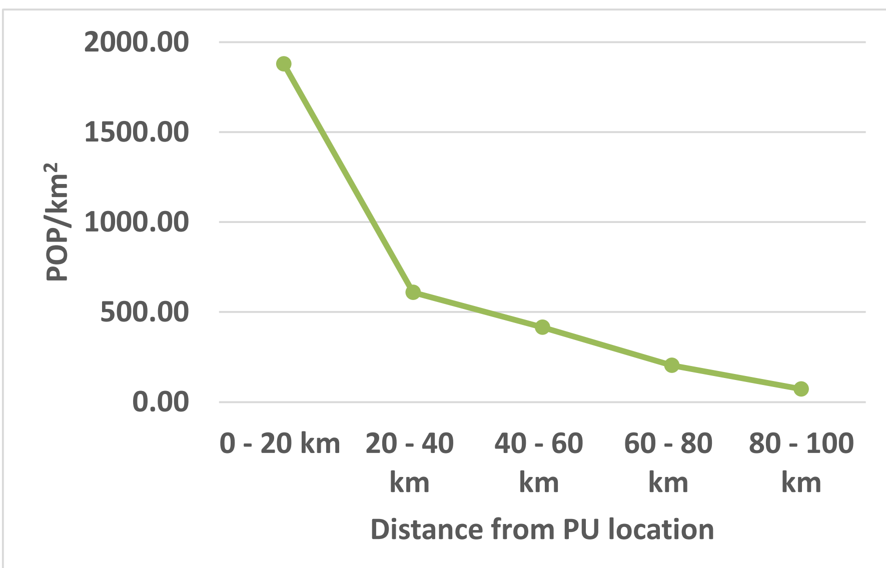

Figure A 5 Population characteristics chart: Suitland, MD

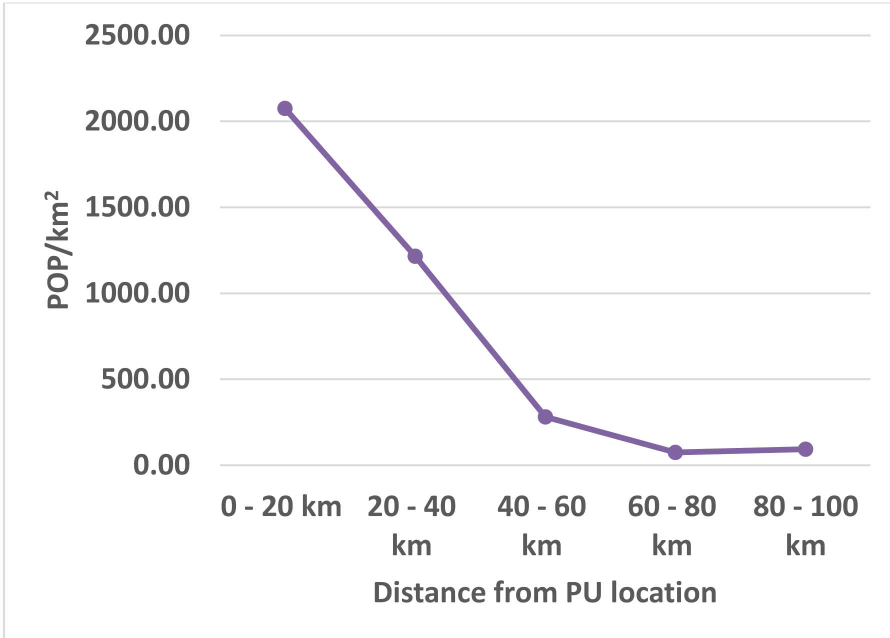

Figure A 6 Population characteristics chart: Miami, FL

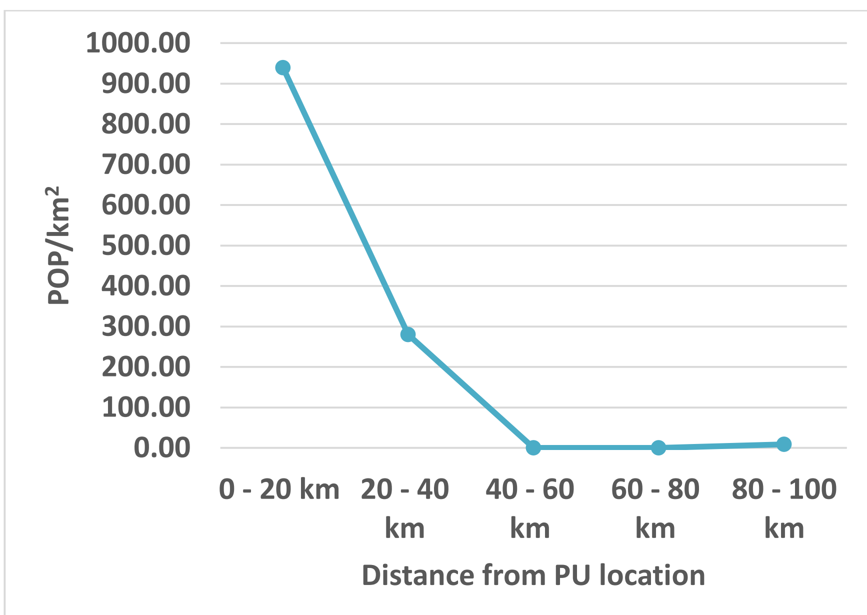

Figure A 7 Population characteristics chart: Ford Island, Pearl Harbor HI

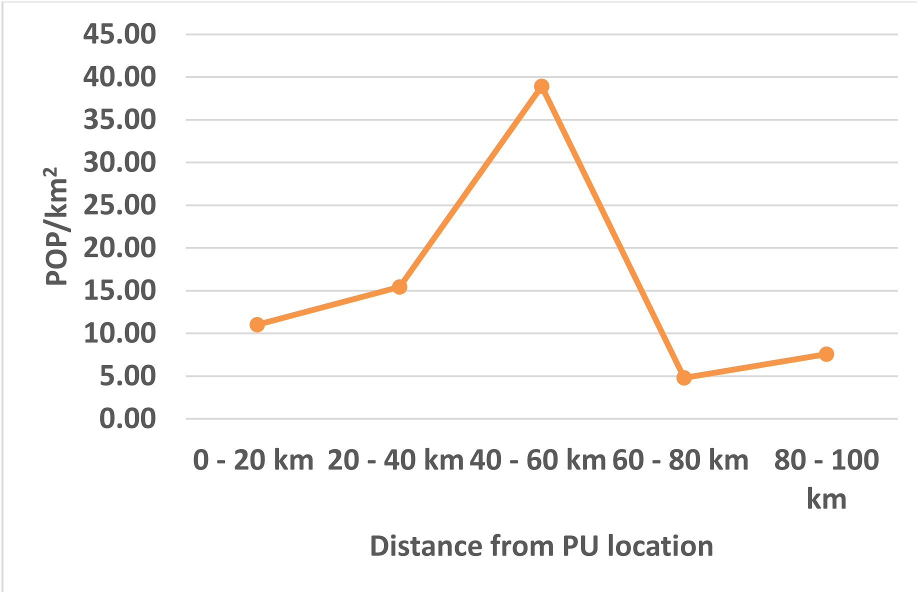

Figure A 8 Population characteristics chart: Sioux Falls, SD

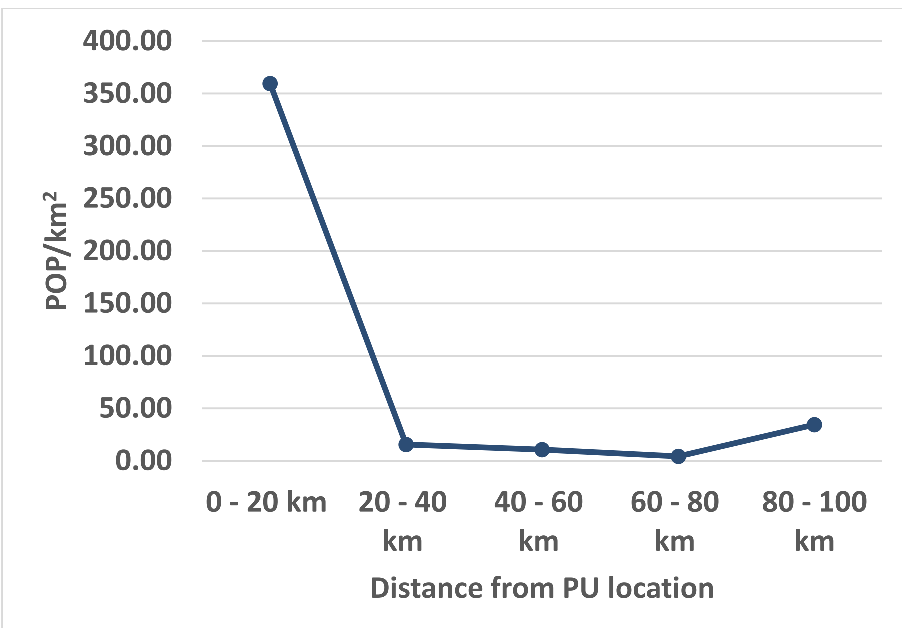

Figure A 9 Population characteristics chart: Elmendorf Air Force Base, AK

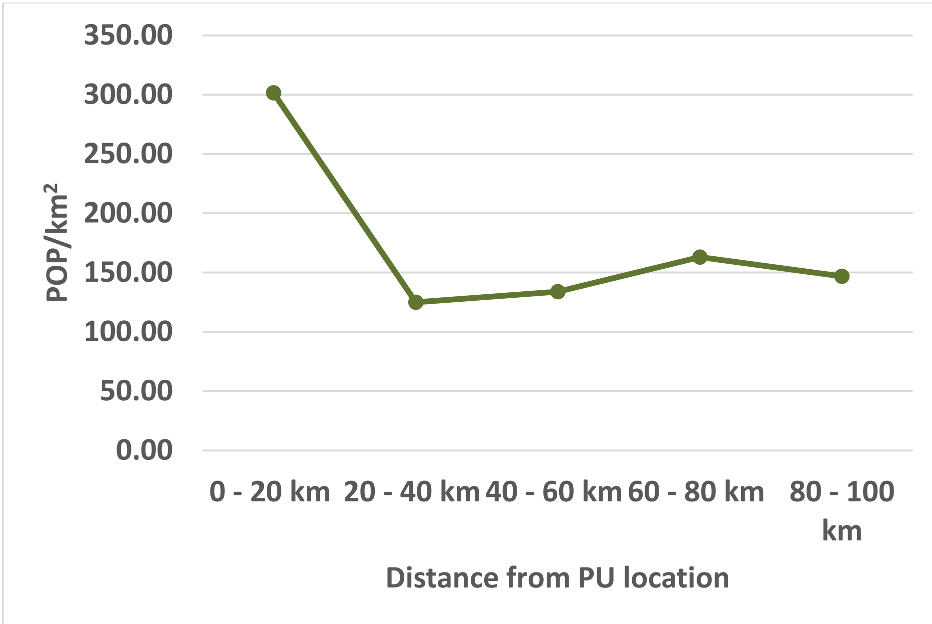

Figure A 10 Population characteristics chart: Monterey, CA

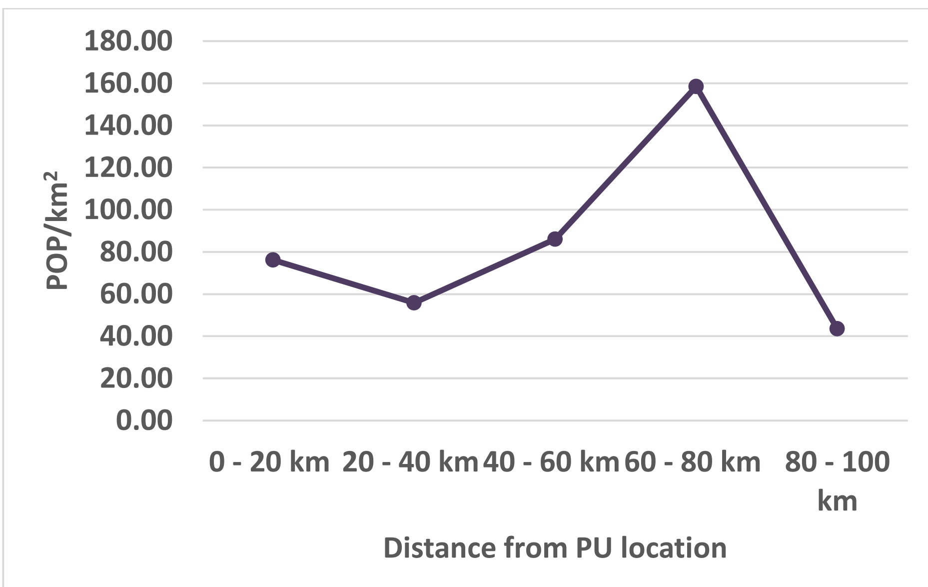

Figure A 11 Population characteristics chart: Stennis Space Center, MS

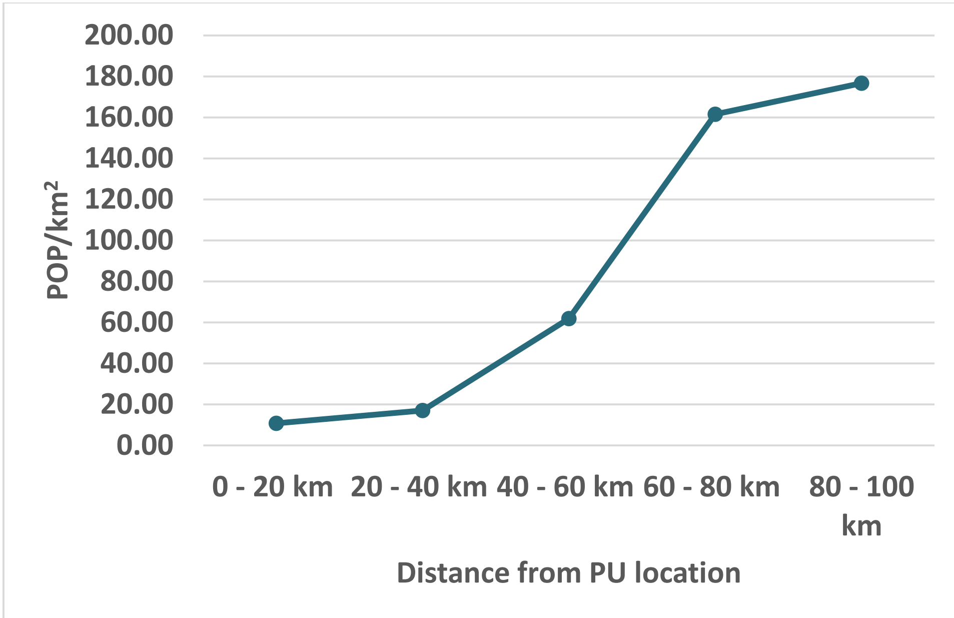

Figure A 12 Population characteristics chart: Twenty-Nine-Palms, CA

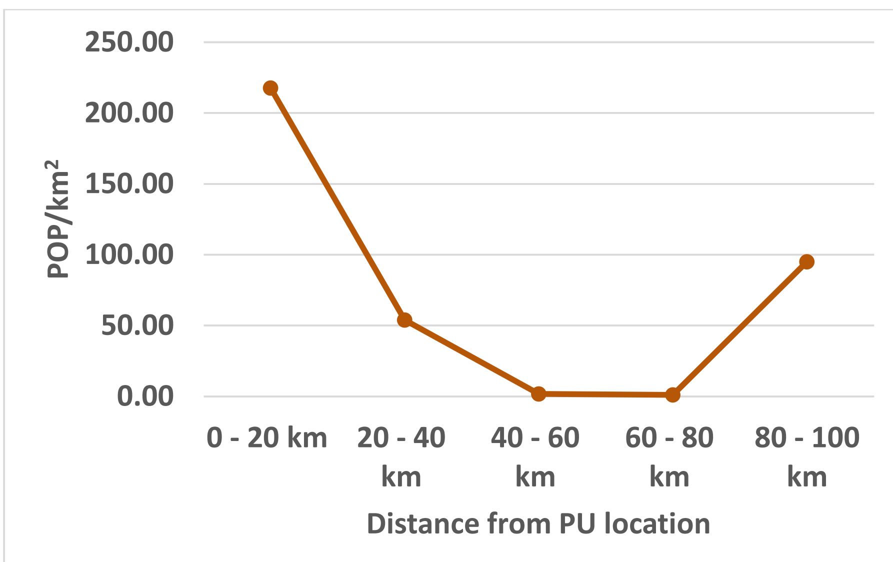

Figure A 13 Population characteristics chart: Yuma, AZ

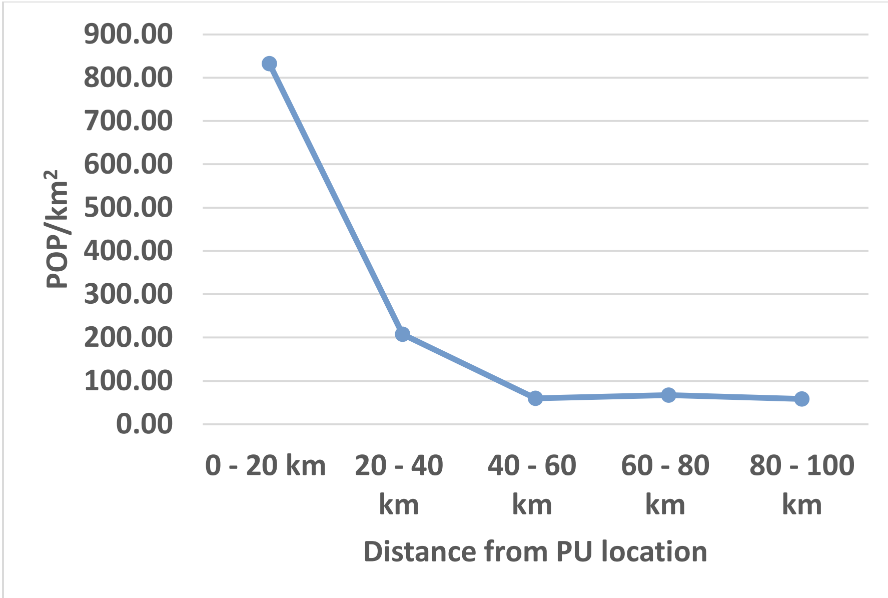

Figure A 14 Population characteristics chart: Cincinnati, OH

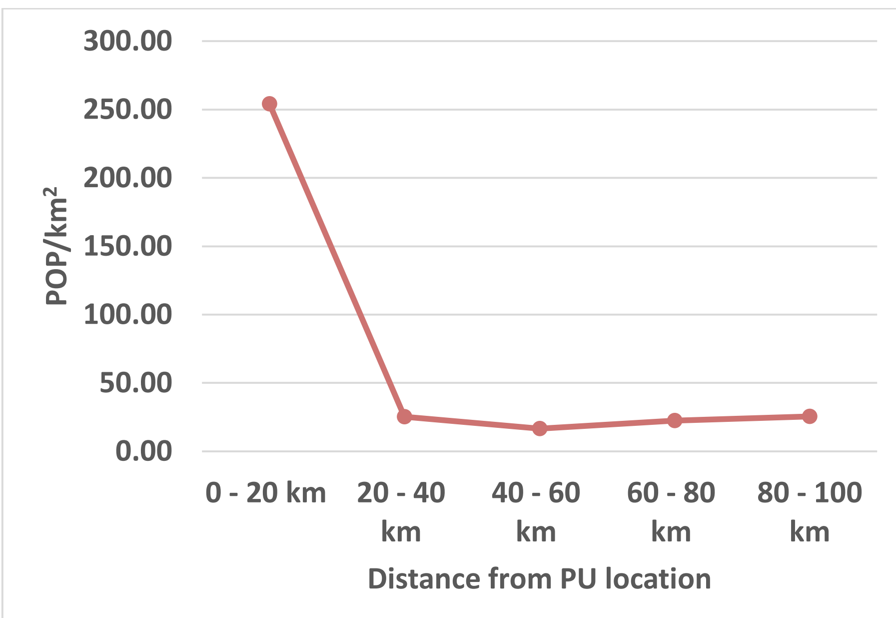

Figure A 15 Population characteristics chart: Rock Island, IL

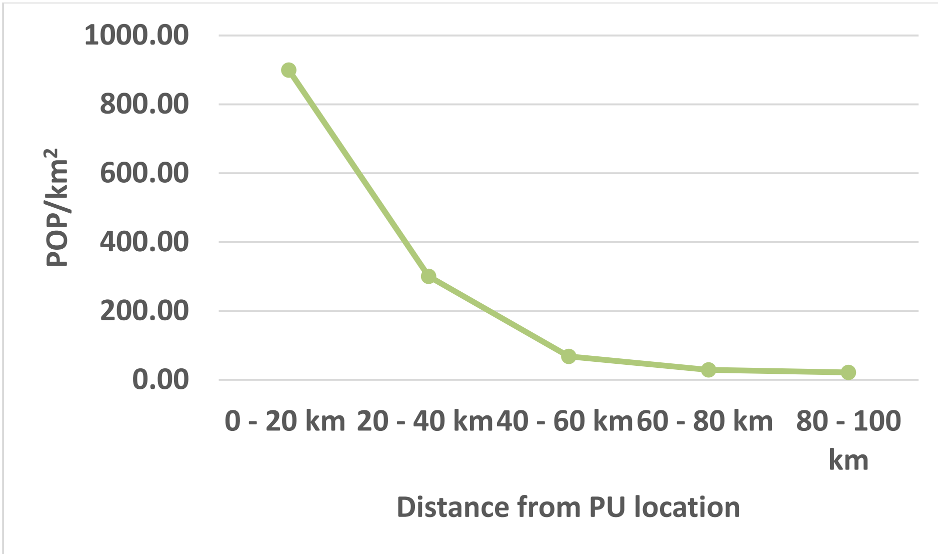

Figure A 16 Population characteristics chart: St. Louis, MO

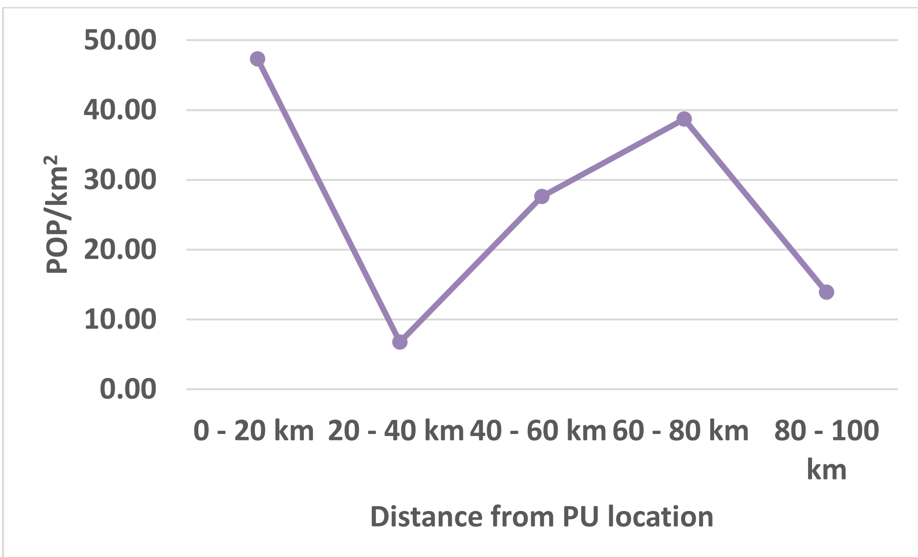

Figure A 17 Population characteristics chart: Vicksburg, MS

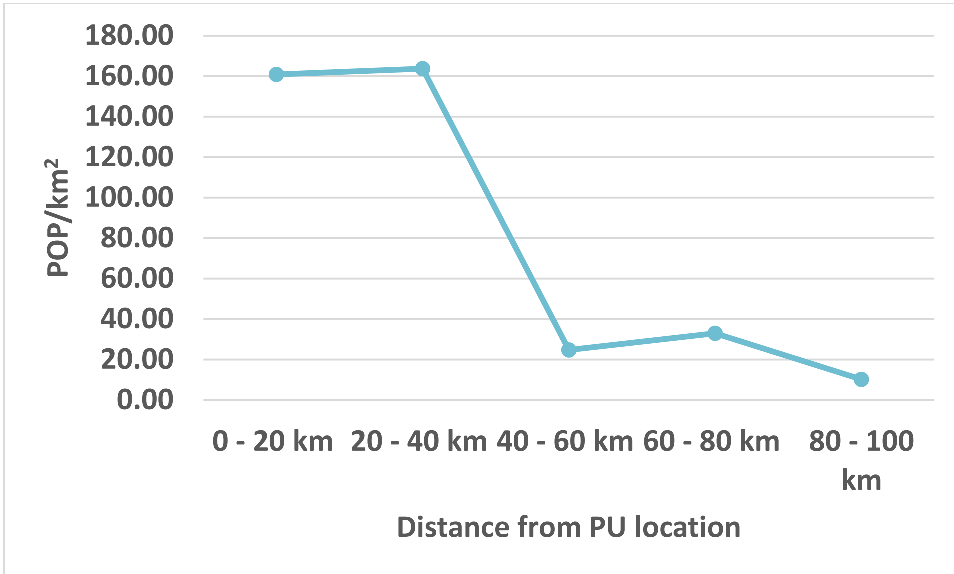

Figure A 18 Population characteristics chart: Omaha, NE

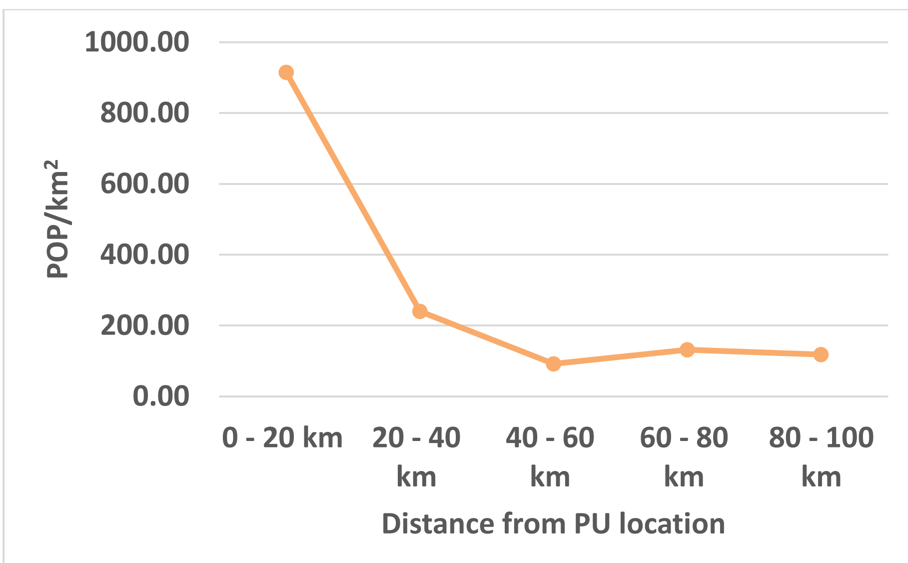

Figure A 19 Population characteristics chart: Sacramento, CA

APPENDIX (D)

ANALYSIS OF THE FCC AUCTION-DATABASE

Table D1 Summary of AWS-1 band analysis [39]

Block	Total ($)	Bandwidth	Licenses Type	$US per MHz-POP	Applied in MetSat Case
A	2,246,977,800	20 MHz (1710-1720 / 2110-2120)	Cellular Market Area (CMA)	0.40	yes
B	2,437,092,750	20 MHz (1720-1730 / 2120-2130)	Economic Area (EA)	0.43	yes
C	1,461,386,350	10 MHz (1730-1735 / 2130-2135)	Economic Area (EA)	0.51	yes
D	1,669,642,750	10 MHz (1735-1740 / 2135-2140)	Regional Economic Area Grouping (REAG)	0.59	no
E	1,710,488,250	10 MHz (1740-1745 / 2140-2145)	Regional Economic Area Grouping (REAG)	0.60	no
F	4,174,486,000	20 MHz (1745-1755 / 2145-2155)	Regional Economic Area Grouping (REAG)	0.73	no
Gross Bids for all AWS-1 band = $13.7 billion				**0.54 (average)**	

Note:

- *These numbers are summary of this band analysis based on FCC auction-database. It is not the inputs to the simulation model.*
- *For each station area, we perform separate analysis.*

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[39] This is the auction number (66), which began on 8/9/2006 and closed on 9/18/2006.

Table D2 Earth-Stations basic information in the FCC auction-database

No	County Name (State)	Economic Area Number (EA)	Cellular Market Area Number (CMA)
1	Accomack (VA)	14	692
2	Fairbanks North Star (AK)	171	315
3	Prince Georges (MD)	13	8
4	Miami-Dade (FL)	31	12
5	Honolulu (HI)	172	50
6	Minnehaha (SD)	116	267
7	Anchorage (AK)	171	187
9	Monterey (CA)	163	126
10	Hancock (MI)	82	173
11	San Bernardino (CA)	160	2
12	Yuma (AZ)	160	321
13	Hamilton (OH)	49	23
14	Rock Island (IL)	102	98
15	Saint Louis City (MO)	96	11
16	Warren (MS)	77	497
17	Douglas (NE)	118	65
18	Yolo (CA)	164	35

APPENDIX (E)

SHARING BENEFITS DETAILS

Table E1 Benefits evaluation summary of G+B Space at Losses=0 (Classical Scenario)

station #	Black + Gray Space				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	92.20	8,653	435,253	0.14%	466,638
2	12.75	487	57,152	0.02%	139,170
3	97.62	25,415	8,440,867	2.73%	134,976,113
4	90.51	13,534	4,762,026	1.54%	34,320,545
5	39.48	1,549	953,207	0.31%	2,727,747
6	62.44	12,368	278,007	0.09%	398,119
7	60.37	8,192	345,952	0.11%	747,481
9	91.21	14,689	2,382,815	0.77%	13,316,321
10	95.10	18,415	1,613,317	0.52%	9,530,951
11	99.70	21,282	2,673,463	0.87%	23,971,324
12	36.44	1,570	194,179	0.06%	1,770,843
13	46.20	6,899	1,912,574	0.62%	13,797,514
14	32.30	3,199	336,954	0.11%	631,456
15	13.44	497	569,906	0.18%	3,101,571
16	70.57	15,269	479,346	0.16%	1,174,559
17	10.19	290	124,618	0.04%	417,872
18	21.39	1,386	1,084,759	0.35%	3,434,079
Total Area Impacted (%)					1.56%
Total Population Impacted (%)					8.63%
Total Value ($)					244,922,303

Table E2 Sensitivity analysis in B space: additional losses = 10 dB

station #	Black Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	7.85	161	4,759	0.00%	5,102
2	1.70	3	3,263	0.00%	7,946
3	46.17	6,049	4,921,052	1.59%	78,691,498
4	32.85	1,604	2,895,056	0.94%	20,865,048
5	13.13	352	469,010	0.15%	1,342,143
6	3.80	34	1,023	0.00%	1,465
7	15.43	370	244,784	0.08%	528,892
9	25.49	777	265,882	0.09%	1,485,877
10	58.18	7,699	455,459	0.15%	2,690,703
11	96.55	24,891	621,028	0.20%	5,568,382
12	3.01	31	1,415	0.00%	12,904
13	2.55	28	72,582	0.02%	523,614
14	1.47	8	14,867	0.00%	27,861
15	0.59	0	0	0.00%	0
16	3.84	28	2,533	0.00%	6,207
17	0.27	0	0	0.00%	0
18	0.39	0	0	0.00%	0
Total Area Impacted (%)			0.43%		
Total Population Impacted (%)			3.23%		
Total Value ($)			111,757,643		

Table E3 Sensitivity analysis in G space: additional losses = 10 dB

station #	Gray Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	82.25	6,723	322,650	0.10%	345,916
2	6.20	124	19,758	0.01%	48,112
3	91.93	15,920	3,321,680	1.08%	53,116,280
4	73.63	6,707	1,564,918	0.51%	11,278,569
5	36.91	1,192	484,151	0.16%	1,385,472
6	18.93	1,140	19,833	0.01%	28,402
7	35.56	1,881	40,219	0.01%	86,899
9	84.15	11,482	1,574,709	0.51%	8,800,235
10	92.59	9,438	1,080,955	0.35%	6,385,929
11	99.23	80	67,975	0.02%	609,491
12	24.36	1,635	160,492	0.05%	1,463,629
13	34.86	3,829	1,600,551	0.52%	11,546,547
14	8.35	184	135,087	0.04%	253,155
15	2.20	8	26,937	0.01%	146,598
16	37.63	4,067	67,047	0.02%	164,288
17	1.78	8	2,819	0.00%	9,453
18	2.90	0	0	0.00%	0
Total Area Impacted (%)			0.66%		
Total Population Impacted (%)			3.40%		
Total Value ($)			95,668,974		

Table E4 Sensitivity analysis in G+B space: additional losses = 10 dB

station #	Black + Gray Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	82.25	6,883	327,409	0.11%	351,018
2	6.20	127	23,021	0.01%	56,058
3	91.93	21,969	8,242,732	2.67%	131,807,779
4	73.63	8,311	4,459,974	1.44%	32,143,617
5	36.91	1,544	953,161	0.31%	2,727,615
6	18.93	1,174	20,856	0.01%	29,867
7	35.56	2,251	285,003	0.09%	615,791
9	84.15	12,259	1,840,591	0.60%	10,286,112
10	92.59	17,137	1,536,414	0.50%	9,076,633
11	99.23	24,972	689,003	0.22%	6,177,873
12	24.36	1,666	161,907	0.05%	1,476,534
13	34.86	3,858	1,673,133	0.54%	12,070,161
14	8.35	192	149,954	0.05%	281,015
15	2.20	8	26,937	0.01%	146,598
16	37.63	4,096	69,580	0.02%	170,494
17	1.78	8	2,819	0.00%	9,453
18	2.90	0	0	0.00%	0
Total Area Impacted (%)					1.08%
Total Population Impacted (%)					6.63%
Total Value ($)					207,426,617

Table E5 Sensitivity analysis in B space: additional losses = 20 dB

station #	Black Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	3.44	31	1,536	0.00%	1,647
2	0.12	0	0	0.00%	0
3	34.80	3,707	3,507,253	1.14%	56,083,739
4	22.18	1,088	2,171,110	0.70%	15,647,474
5	3.03	26	44,200	0.01%	126,485
6	0.00	0	1,579	0.00%	2,261
7	3.16	34	45,873	0.01%	99,115
9	1.99	5	6,623	0.00%	37,013
10	6.52	127	4,914	0.00%	29,030
11	90.99	22,917	441,774	0.14%	3,961,120
12	1.55	8	578	0.00%	5,271
13	0.84	8	20,763	0.01%	149,787
14	0.00	0	0	0.00%	0
15	0.00	0	0	0.00%	0
16	0.13	0	0	0.00%	0
17	0.11	0	0	0.00%	0
18	0.00	0	0	0.00%	0
Total Area Impacted (%)					0.28%
Total Population Impacted (%)					2.02%
Total Value ($)					76,142,942

Table E6 Sensitivity analysis in G space: additional losses = 20 dB

station #	Gray Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	56.86	3,751	172,143	0.06%	184,556
2	4.14	78	16,621	0.01%	40,474
3	77.83	11,495	4,121,944	1.34%	65,913,132
4	40.36	990	1,139,028	0.37%	8,209,124
5	29.10	1,212	870,665	0.28%	2,491,540
6	4.42	73	0	0.00%	0
7	25.91	1,080	226,117	0.07%	488,559
9	65.15	6,487	791,956	0.26%	4,425,833
10	83.57	14,513	1,076,051	0.35%	6,356,958
11	98.36	2,021	205,050	0.07%	1,838,559
12	14.76	580	118,128	0.04%	1,077,285
13	22.10	1,549	1,106,421	0.36%	7,981,840
14	1.76	8	14,867	0.00%	27,861
15	0.72	0	0	0.00%	0
16	3.89	28	2,533	0.00%	6,207
17	1.56	8	2,819	0.00%	9,453
18	1.08	0	0	0.00%	0
Total Area Impacted (%)					0.45%
Total Population Impacted (%)					3.20%
Total Value ($)					99,111,533

Table E7 Sensitivity analysis in G+B space: additional losses = 20 dB

station #	Black + Gray Space Analysis				
	Radius (km)	Land Area (km^2)	Population Affected	Population Impacted (%)	Value ($)
1	56.86	3,782	173679	0.06%	186,203
2	4.14	78	16621	0.01%	40,474
3	77.83	15,202	7629197	2.47%	121,996,871
4	40.36	2,078	3310138	1.07%	23,856,598
5	29.10	1,238	914865	0.30%	2,618,025
6	4.42	73	1579	0.00%	2,261
7	25.91	1,114	271990	0.09%	587,675
9	65.15	6,492	798579	0.26%	4,462,845
10	83.57	14,640	1080965	0.35%	6,385,989
11	98.36	24,938	646824	0.21%	5,799,679
12	14.76	588	118706	0.04%	1,082,556
13	22.10	1,557	1127184	0.37%	8,131,626
14	1.76	8	14867	0.00%	27,861
15	0.72	0	0	0.00%	0
16	3.89	28	2533	0.00%	6,207
17	1.56	8	2819	0.00%	9,453
18	1.08	0	0	0.00%	0
Total Area Impacted (%)					0.73%
Total Population Impacted (%)					5.22%
Total Value ($)					175,254,475

APPENDIX (F)

THE CUMULATIVE VALUE FOR EACH EARTH-STATIONS

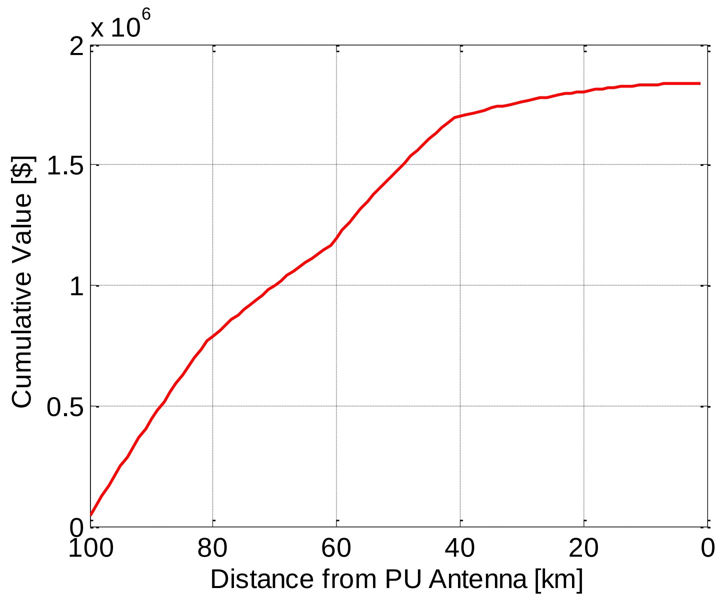

Figure A 20 Cumulative value of Wallops Island, VA

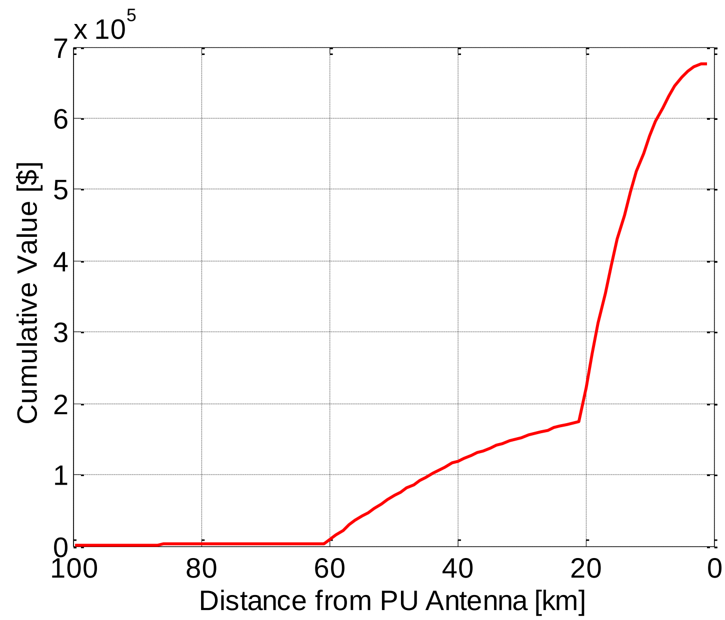

Figure A 21 Cumulative value of Fairbanks, AK

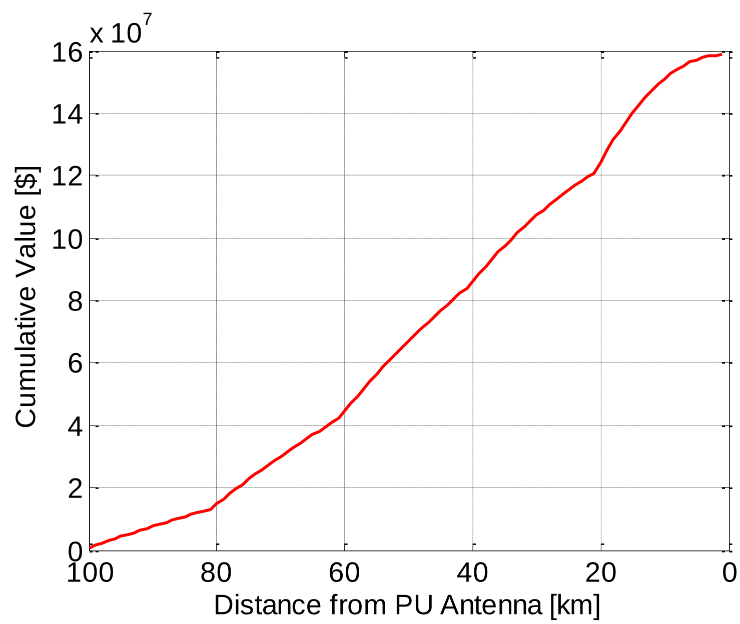

Figure A 22 Cumulative value of Suitland, MD

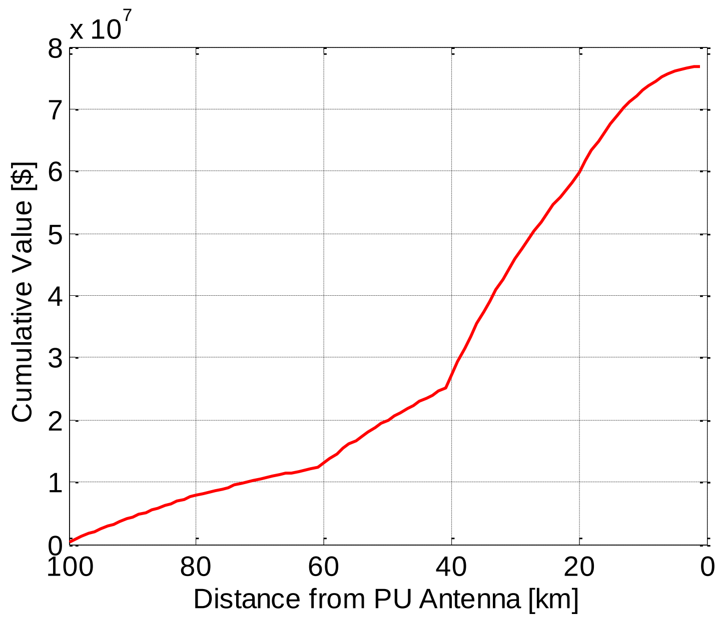

Figure A 23 Cumulative value of Miami, FL

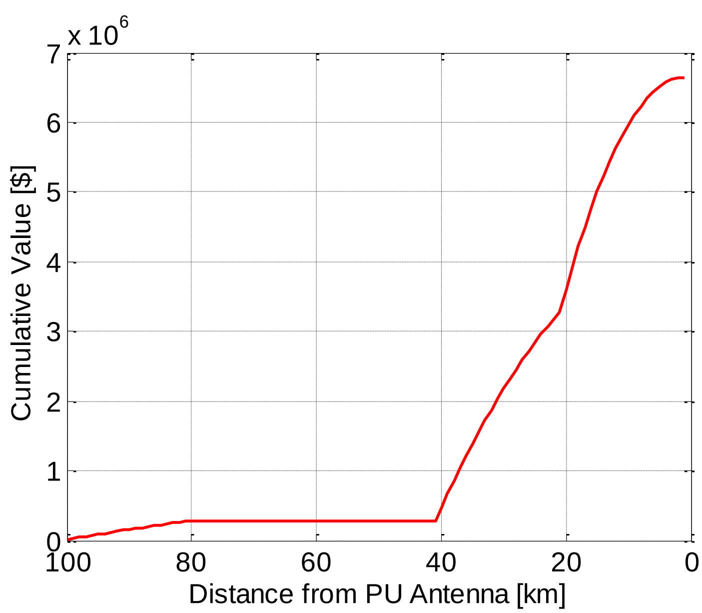

Figure A 24 Cumulative value of Ford Island, Pearl Harbor HI

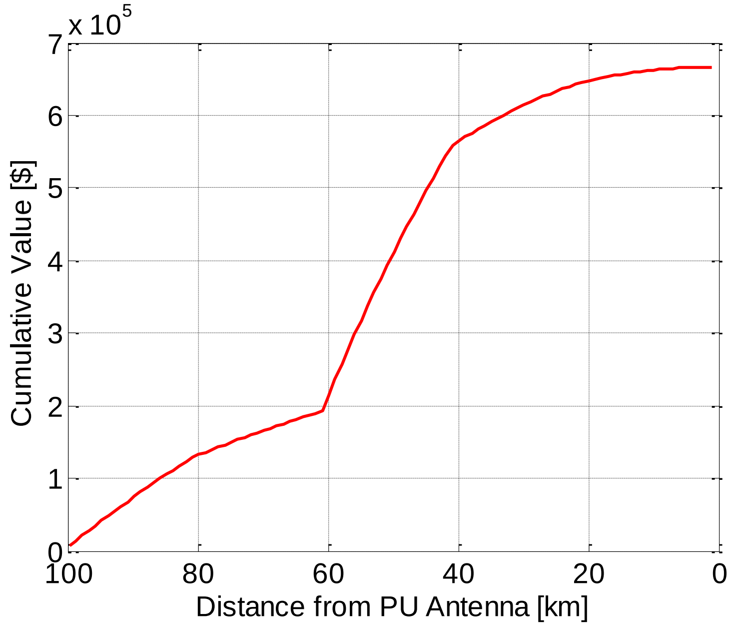

Figure A 25 Cumulative value of Sioux Falls, SD

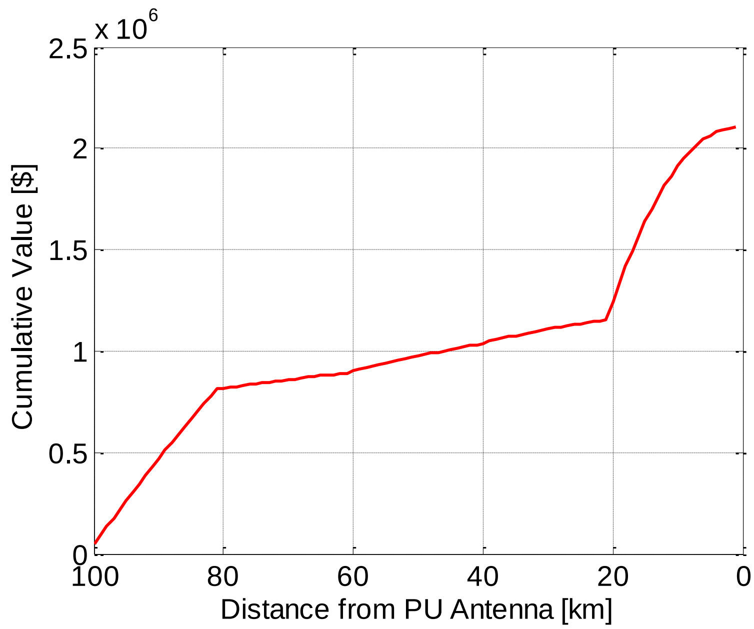

Figure A 26 Cumulative value of Elmendorf Air Force Base, AK

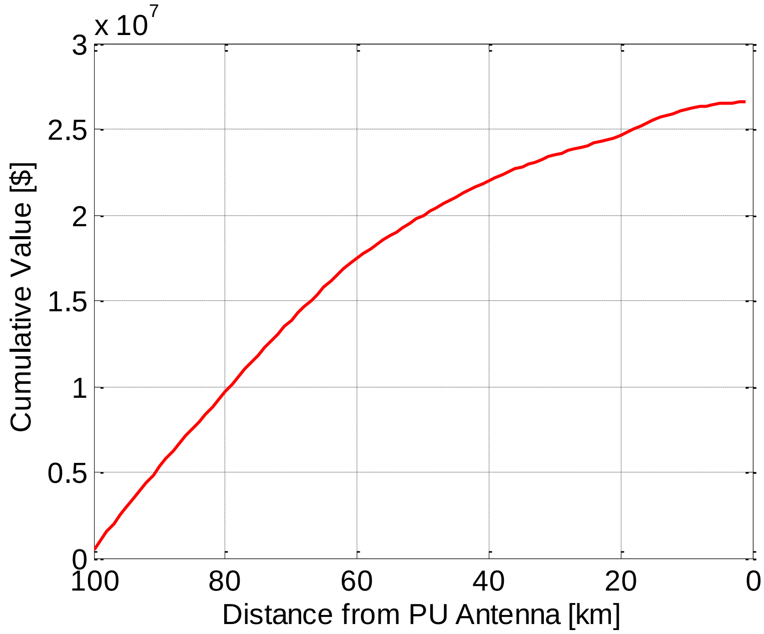

Figure A 27 Cumulative Value of Monterey, CA

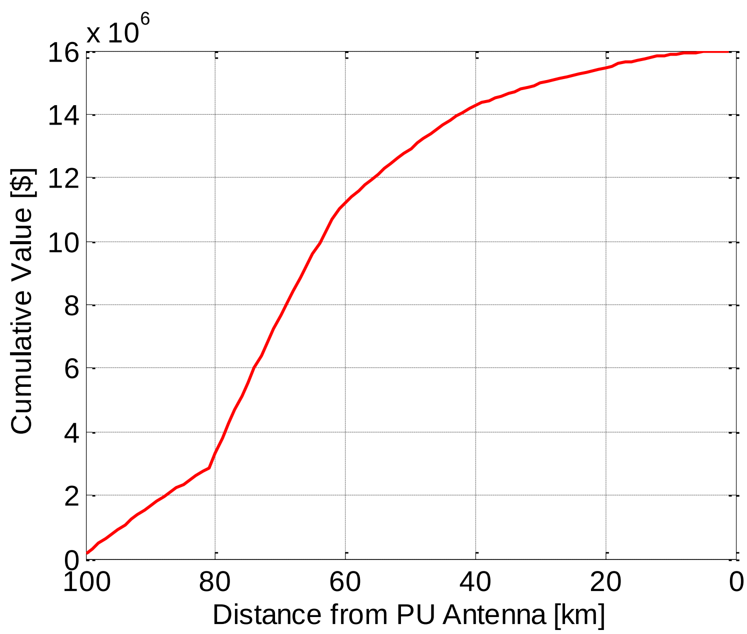

Figure A 28 Cumulative value of Stennis Space Center, MS

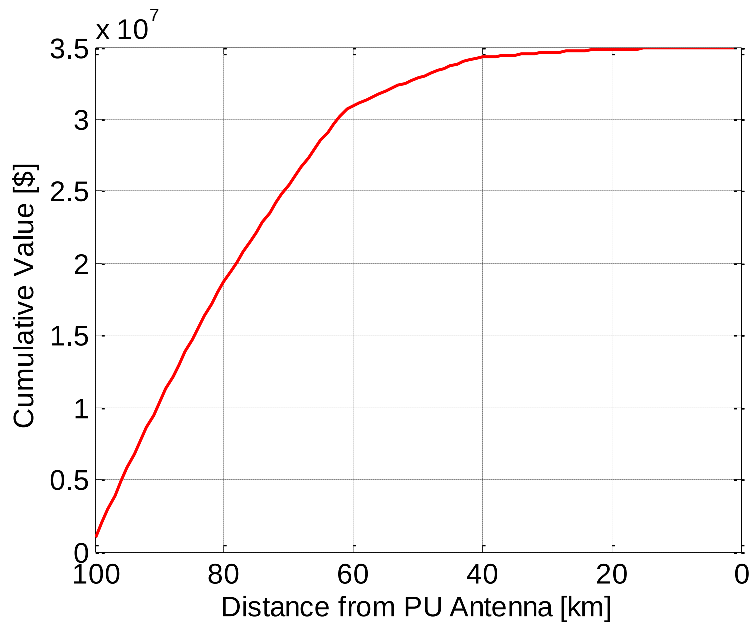

Figure A 29 Cumulative value of Twenty-Nine-Palms, CA

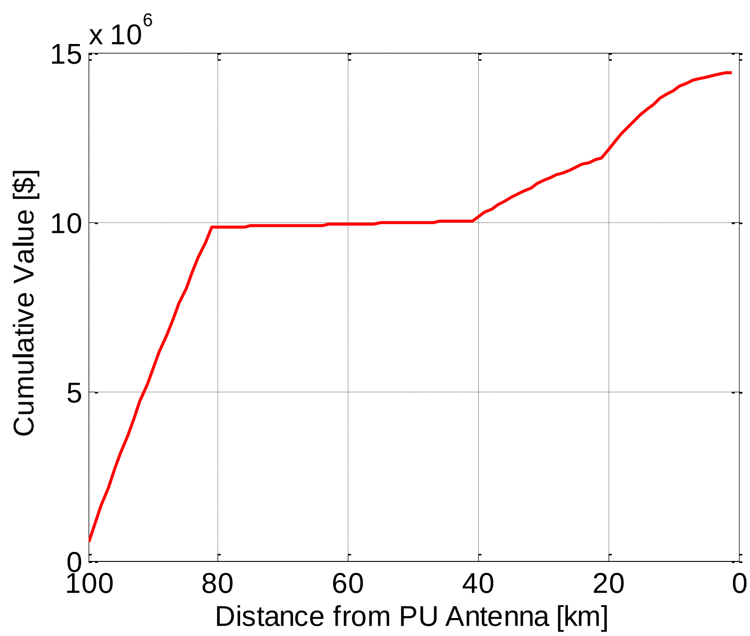

Figure A 30 Cumulative value of Yuma, AZ

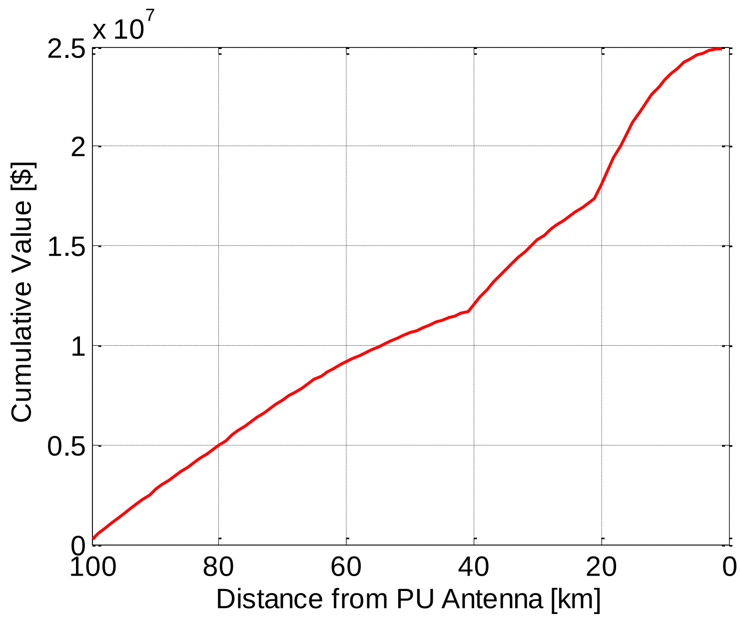

Figure A 31 Cumulative value of Cincinnati, OH

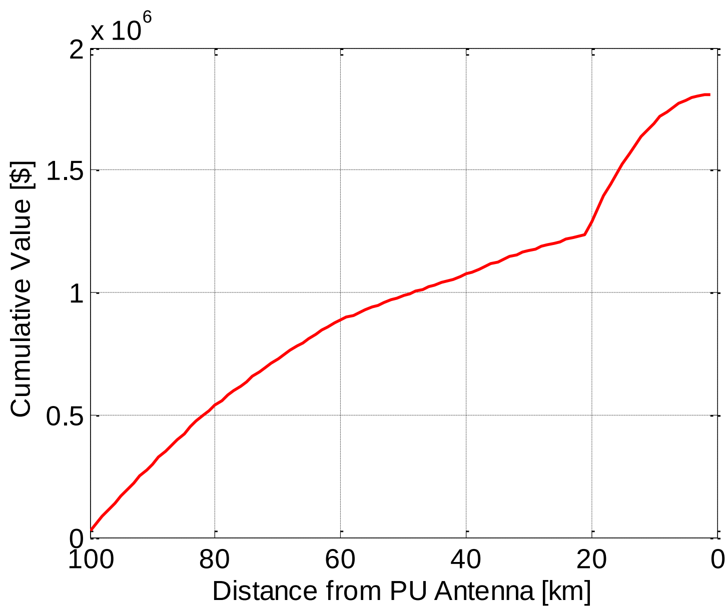

Figure A 32 Cumulative value of Rock Island, IL

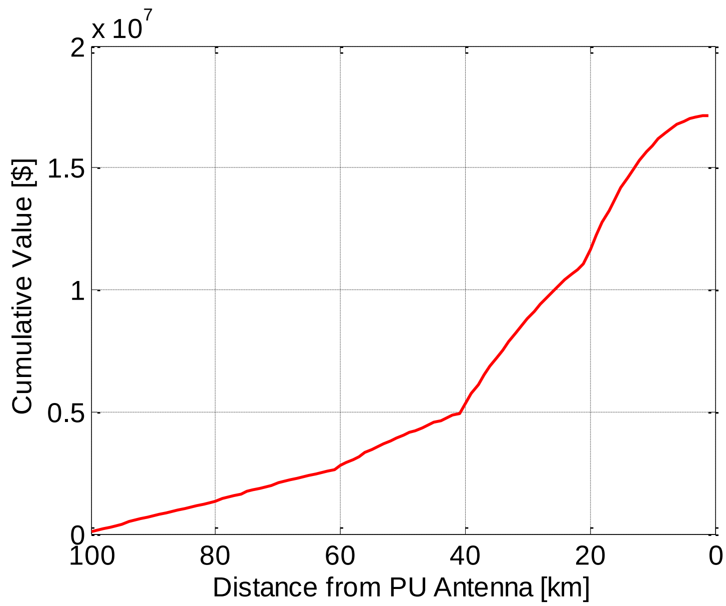

Figure A 33 Cumulative value of St. Louis, MO

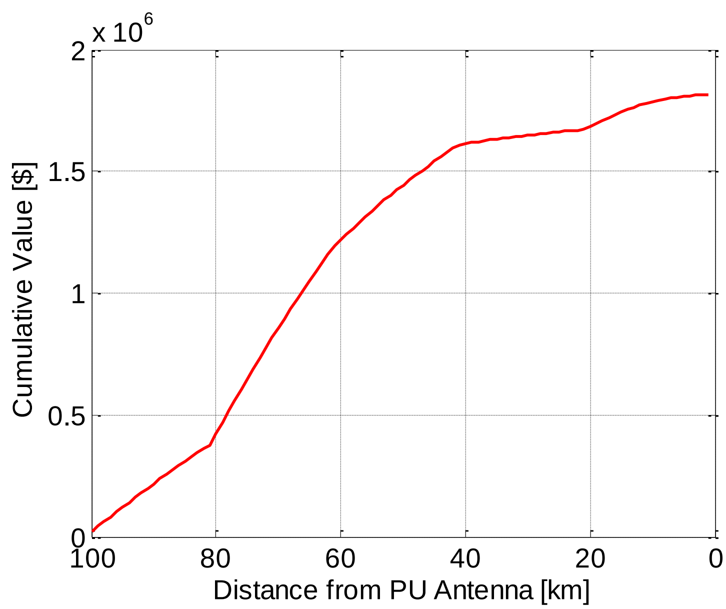

Figure A 34 Cumulative value of Vicksburg, MS

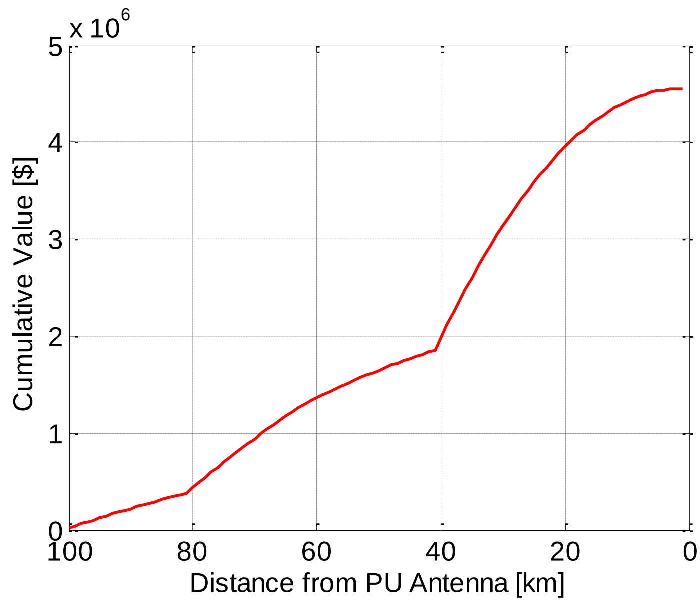

Figure A 35 Cumulative value of Omaha, NE

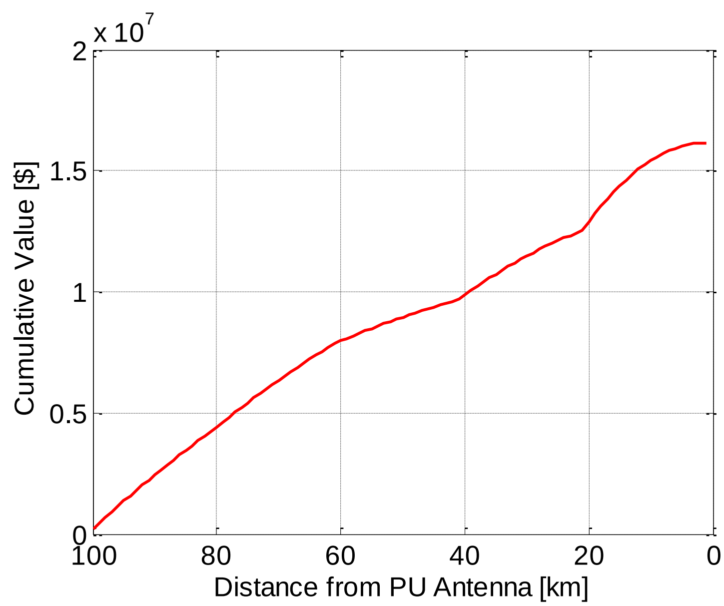

Figure A 36 Cumulative value of Sacramento, CA

APPENDIX (G)

TYPES OF THE PUS AT THE 3.5GHZ BAND

All these information are from the NTIA Fast Track report [4].

Ground-Based Radar Systems

DoD has two mobile ground based radar systems. The first is Ground Based Radar One (GB-1) which is specifically designed to locate the firing positions of both rocket and mortar launchers. The Army operates GB-1 radar at many locations within the U.S. However, the sites requiring exclusion zones provided in Table G1 was limited to the locations where the radar requires use of its full tuning range. The radar does not require use of the upper portion of its tuning range at the many other locations. Ground Based Radar Three (GB-3) is a multi-function system that provides surveillance, air traffic control and fire quality data. The Ground-Based Radar Two (GB-2) are interference limited systems (as opposed to noise limited systems) and are associated with Airborne Radars.

Based on the NTIA analysis, it was concluded that there is a need for an exclusion zone to protect the ground-based radars. The exclusion zone creates separation distances on the order of several hundred kilometers. It should be noted that a number of "GB-1" and "GB-3" sites required limited exclusion zones protection. To accommodate this much-reduced number of exclusion zones, the radio frequency filter of the base stations would need to provide 30 to 40 dB of attenuation at 3500 MHz (approximately 50 MHz below the band of interest, 3550-3650 MHz) to mitigate the potential of high-power interference effects. The radius of the exclusion zones around the ground-based radar systems are given in Table G2.

Table G1 Ground-Based Radar 1 and 3 Installation Locations

GB-1 Installation Name	GB-3 Installation Name
Fort Stewart, Georgia	MCB Camp Pendleton, California
Fort Carson, Colorado	MCAS Miramar, California
Fort Hood, Texas	MAGTFTC 29 Palms, California
Fort Riley, Kansas	MCMWTC Bridgeport, California
Fort Polk, Louisiana	MCAS Yuma, Arizona
Fort Knox, Kentucky	MCB Camp Lejeune, North
Fort Drum, New York	MCB Quantico, Virginia
Fort Bragg, North Carolina	MCAS Cherry Point, North
Fort Wainwright, Alaska	Bogue Field, North Carolina
Fort Lewis, Washington	MCAS Beaufort, South Carolina
White Sands Missile Range	Virginia Beach, Virginia
Yuma Proving Ground	Fort Worth, Texas
Fort Irwin, California	Cheyenne, Wyoming
	Ft Sill, Oklahoma
	Aurora, Colorado
	Pensacola, Florida
	Ft Bliss, Texas

Table G2 Summary of Exclusion Zones based on NTIA analysis

Radar to Wireless System Interaction	Ground-Based Radar – 1		Ground-Based Radar – 2		Ground-Based Radar – 3	
	Frequency Offset (MHz)	Radius of Exclusion Zone (km)	Frequency Offset (MHz)	Radius of Exclusion Zone (km)	Frequency Offset (MHz)	Radius of Exclusion Zone (km)
Radar to Base (Single Entry)	50	40	40	< 1	50	63
Radar to Mobile (Single Entry)	50	< 1	40	< 1	50	3.5
Base and Mobile to Radar (Aggregate)	50	24	40	< 1	50	32

Airborne Radar Systems

The NTIA concluded that, a frequency offset of 50 MHz was needed in order to minimize the required separation distances. As shown in the analysis, co-frequency operation with the airborne radar systems would require large exclusion zones (in excess of 300 km). Furthermore, establishing exclusions is generally not a practical approach to sharing with airborne systems. Therefore, NTIA concluded that a frequency offset of approximately 40 MHz was needed to eliminate the need for exclusion zones for airborne radar systems[40] ; see Table G3.

Table G3 Summary of Exclusion Zones based on NTIA analysis, Airborne Radar Systems

Radar to Wireless System Interaction	Airborne Radar – 1		Airborne Radar – 2	
	Frequency Offset (MHz)	Radius of Exclusion Zone (km)	Frequency Offset (MHz)	Radius of Exclusion Zone (km)
Radar to Base (Single Entry)	40	< 1	40	< 1
Radar to Mobile (Single Entry)	40	< 1	40	< 1
Base and Mobile to Radar (Aggregate)	40	< 1	40	< 1

[40] This is one of the rationales for limiting the sharing band to 3550-3650MHz instead of the full 3500-3650MHz. For airborne radar systems, there is no need for exclusion zones.

Shipborne Radar Systems

In shipborne radar case, the exclusion zone is defined by a distance from the coast line considering interference to and from the shipborne radar. In developing the exclusion zone distance (i.e. NTIA analysis), it was assumed that the shipborne radar was operating 10 km from the coastline.

To share this band, the NTIA Fast Track Report recommends geographic separation to mitigate interference. NTIA recommends exclusion zones around ground-based and shipborne radar systems. With respect to shipborne radars, NTIA has determined that extremely large geographic exclusion zones are necessary, reaching a maximum of 310km. That is estimated to exclude approximately 60% of the United States population that falls within that exclusion zone. As a result, our focus in this dissertation is on shipborne radars only, as the main PU antenna type reducing sharing utilization.

APPENDIX (H)

SHIPBORNE RADARS SPECIFICATIONS

Table H1 Shipborne Radars Specifications

	Antenna Gain (dBi)	**Losses**	**Transmitted Power**			**Height**	**FDR**
			Transmitted (dBm)	Duty Cycle	Average (dBm)		
S1	32	2	90	0.1%	60	50	0
S2	47	2	83	15%	75	30	0
S3	41.8	3.4	98	1.6%	80	30	0
S4	38.9	2	84	-	84	30	-
S5	43.3	2	93.3	-	93.3	30	-

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