Enforcement and Network Capacity in Spectrum Sharing: Quantifying the Benefits of Different Enforcement Scenarios

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Abstract

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.

Spectrum sharing has moved from being a radical notion to a principal policy focus in the past decade. Enabling spectrum sharing regimes means that sharing agreements must be implemented. To have meaning, those agreements must be enforceable. The focus of this paper is to determine the relationship between enforcement methodologies and benefits of spectrum sharing through sharing between government and commercial users. 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, the FCC, and the PCAST report. To address this problem, we build a model to quantitatively examine the relationships between different enforcement scenarios and sharing benefits. We model two case studies, 1695-1710 MHz band and 3550-3650 MHz band.

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][3]. 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 [3] [1]. Most recently, the President’s Council of Advisors on Science and Technology (PCAST) report address this issue intensively [4]. In addition, the National Telecommunications and Information Administration (NTIA) has proposed several bands to facilitate spectrum sharing between different level of users such as Primary Users (PUs) and Secondary Users (SUs) [5].

It is clear that mobile broadband is the great infrastructure challenge for wireless operators, particularly with the existence of several evidences of significant increase in mobile broadband traffic [4]. 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 5-10 years [1] [6] [7].

The focus of this work is to determine the relationship between enforcement methodologies and additional benefits of spectrum sharing through sharing between government and commercial users. 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, the FCC, and the PCAST report. There are many scenarios where spectrum sharing can take place, so the emphasis of the paper is on government and commercial spectrum sharing. The government incumbent will be the PUs; on the other hand, the commercial users be the SUs.

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 paper will try to do reasoning about enforcement of spectrum sharing and will demonstrate and examine diverse scenarios, which can be implemented, at different spectrum sharing environments. We model two case studies, 1695-1710 MHz band and 3550-3650 MHz band. For more information about the PUs and expected SUs of these two bands, please refer to previous work [8] [9].

2.0 Enforcement and Spectrum sharing

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) 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 [10], [11].

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 [12]. 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.

Ex ante and ex post approaches work in tandem, not in isolation. Thus, the choice of ex ante approach affects ex post strategies [12]. The choice of how to design the enforcement mechanism directly and indirectly impacts the design and costs of usage rights enforcement. In particular, the costs of inducing good behaviors (avoiding bad ones) 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).

This paper 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 settings toward ex post enforcement settings in our model.

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 [7] [13]. 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.

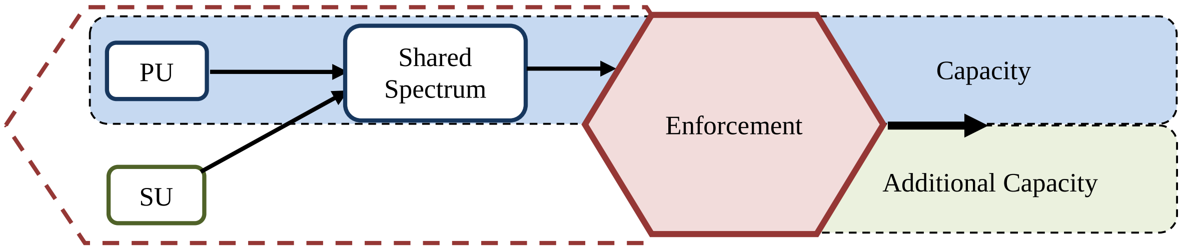


Figure 2-1 Illistration of enforcemnts effect on spectrum sharing

3.0 Spectrum Sharing Model

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. The proposed modeling of geographical exclusion zones moves from a purely ex ante approach (large exclusion zone only) towards ex post enforcement, see Figure 3-1. The model includes these additions:

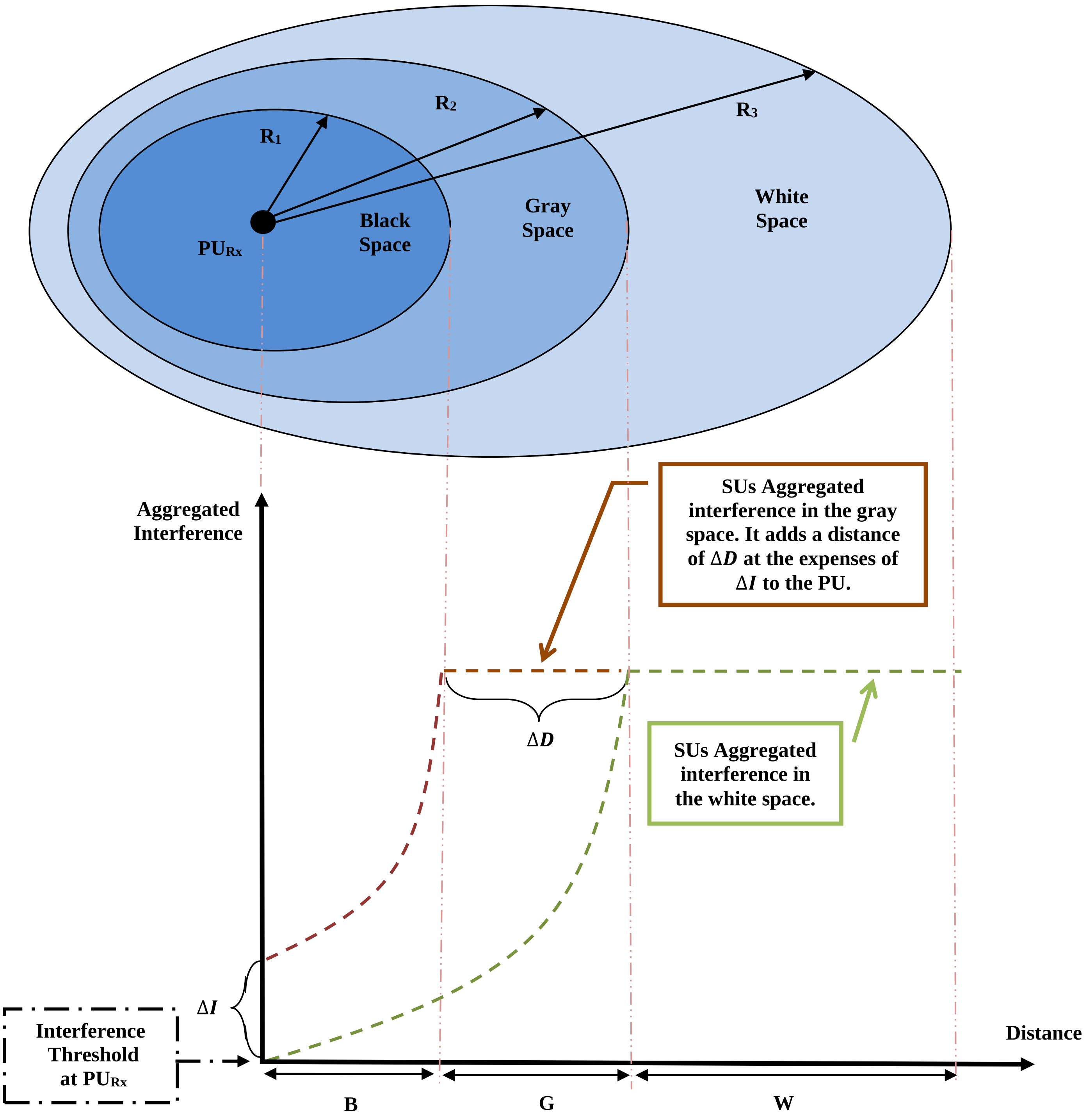
- Evaluation the benefits of spectrum sharing within the exclusion zone.
    - Model of a “Gray space” area.
    - Model of a “Black space” area.
- Evaluation the benefits of spectrum sharing outside the exclusion zone.
    - Model of a “White space” area.

3.1 Main Idea

In Figure 3-1, 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”.

- ➢ R_1: proposed radius of Back space.
- ➢ R_2: proposed radius of Gray space areas. R_1 and R_2 are the key variables affecting the function of sharing utilization.
- ➢ R_3: the radius of PU usage right area. It is the total area where the PU is originally licensed to use the spectrum. For simplicity propose, we set this radius to be 100km during the simulation.

Figure 3-1 Model Summary



3.1.1 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 any interference to the PU.
- A smaller enforcement effort is needed to facilitate sharing in this area compared to the other proposed areas.
    - In special cases where the cost of ex post enforcement is higher than the benefits of sharing G and B spaces, we probably need ex ante enforcement only, 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 compared to other areas.
- 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).

3.1.2 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 noise floor 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.

3.1.3 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. Thus, enforcing SU behavior will be achieved through this single interface. For more information about the differences between centralized and decentralized enforcement, please refer to [12] [9].
- In special cases, the black 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.

3.2 Simulation Main Function

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. In this paper, 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 utilization.

In this model, each 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).

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

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

Table 3-1 Equations (1) and (2) description.

	Description	**Unit**
I	SU's power (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. indoor factor)	dB
I_{AGG}	Aggregated interference at PU receiver	dBm
N	Number of SUs	N

Since the number of simulated SUs is very large (i.e., tens of thousands) around the PU location, the transmitted power should be modeled in a more accurate way. To do this, we follow a probability distribution function for the transmitted power of SUs.

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 [14]. Figure 3-2 shows the azimuth and elevation antenna pattern from the simulation model when maximum antenna gain equals 43 dBi and the minimum elevation angle for PU antenna is 27 degrees.

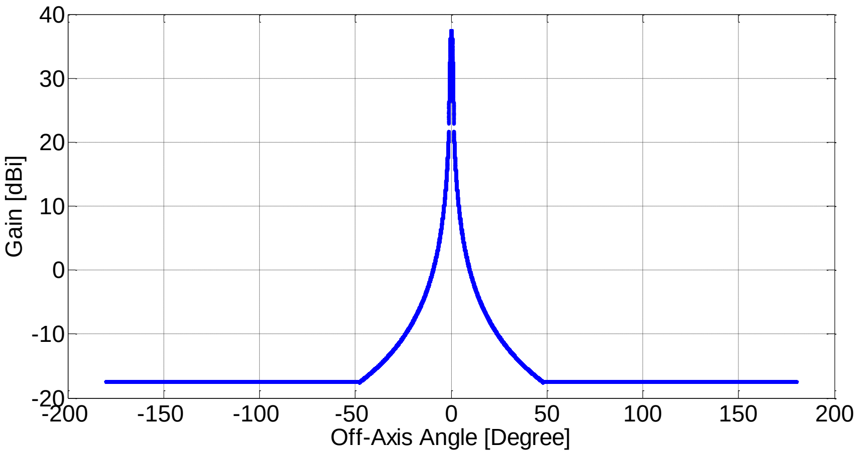


Figure 3-2 PU antenna gain pattern

Per the ITU[1] and NTIA documents [15], "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 victim receiver". Although FDR is has been built into the simulator, in this paper, we ignore its effects in both 1.7 GHz and 3.5 GHz cases to simplify the exposition.

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

3.3 Model Design and Findings

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.

3.3.1 Settings

- A single PU receiver that is bounded by three types of zones: W, G and B spaces.
- The external radius (i.e., simulation area) is 100km.
- We will assume the noise floor level of the PU is G_{boundary} .
- 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]
    - $G_{\text{boundary}} < B_{\text{boundary}} \quad or \quad |G_{\text{boundary}}| > |B_{\text{boundary}}|$
- From these distances, we can find out the additive area that can be added to the sharing scenario.

3.3.2 Research Assumptions

In this paper, certain assumptions are taken into consideration:

- 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.

- We assume 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 paper :
    - 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.
    - 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.

3.3.3 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 3-3 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 density of population 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.

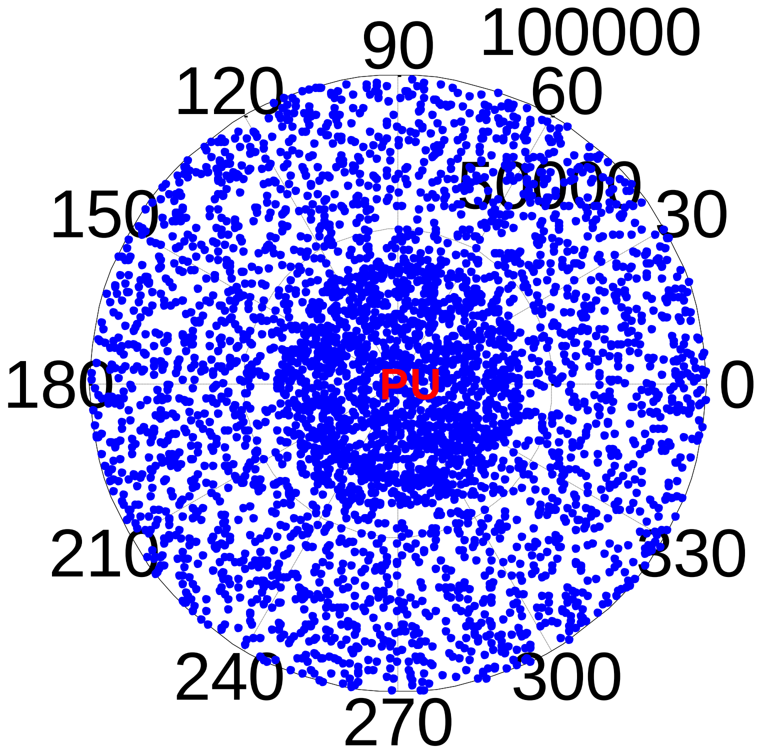

Figure 3-3 Area of simulation. The PU receiver is located in the center.

3.3.4 Findings

In this section, we will examine the main inputs and variables in this model; the rest will be covered through the real case scenarios that follow in the next sections. The major inputs to this model analysis are listed in Table 3-2.

Table 3-2 Major model inputs used in this section

Frequency		2 GHz
"PU Antenna" azimuth angle		360 Degree
Minimum "PU Antenna" elevation angle		20 Degree [2]
SU transmitted power (I_{SU})		Standard LTE-UE
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
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.		

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[2] The minimum elevation angle is consider as fixed input 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.

3.3.4.1 SUs Density

This section examines the relationship between the level of SU 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 SU density. Figure 3-4 summarize these relationships.

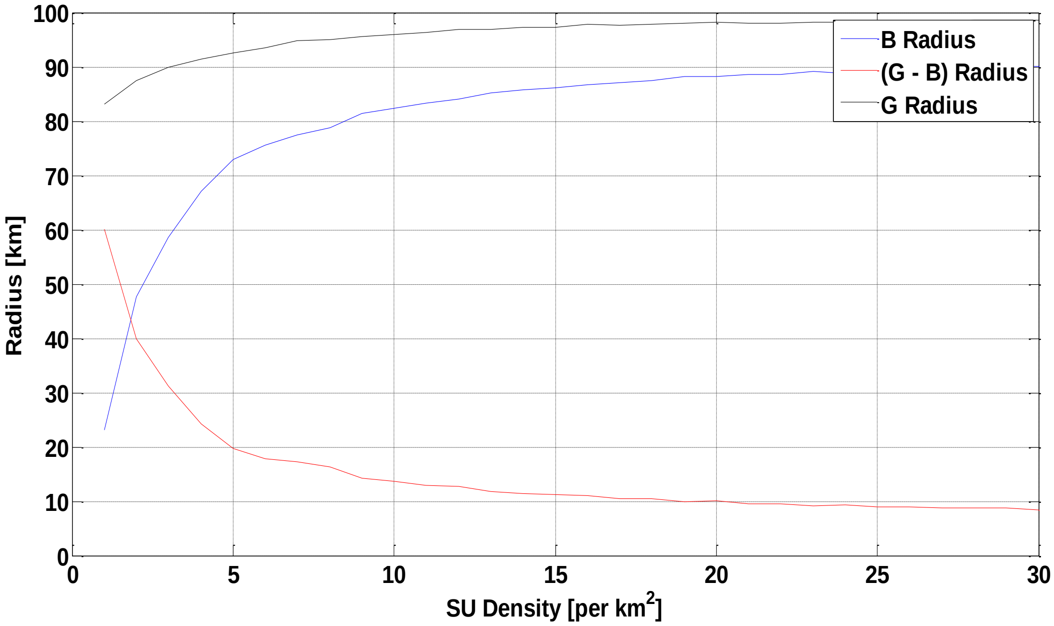

Figure 3-4 Relationship between SU density and Black and Gray radiuses.

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

- Interestingly, the G radius is almost the same the for any SU density greater than 6 users per km^2.
  - This suggest that the W space is not sensitive to SU density above 6 users per km^2.
- Due to the difference in G and B boundaries (in dBm), it is obvious that B radius is more sensitive to density compared to G radius.

3.3.4.2 Frequency

In this section, we will try to see how the simulated model reacts to different frequency bands. The frequency will vary from 0.5 GHz to 5 GHz. The major variable is still the same as in Table 3-2, where the frequency is the variable. From Figure 3-5, and Figure 3-6, we can conclude the following:

- The effect of SU 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.
- At higher SUs density, the differences between the B radius (for example) at different frequencies is minimized.
    - Frequency effect on B radius is minimal for $SU_{density} > 10/km^2$
- For example, if a regulator wants to assign two different SUs service with two different expected densities of SUs, all else being equal, then the service with less SUs density should be assigned to a higher frequency, and the other to a lower frequency.

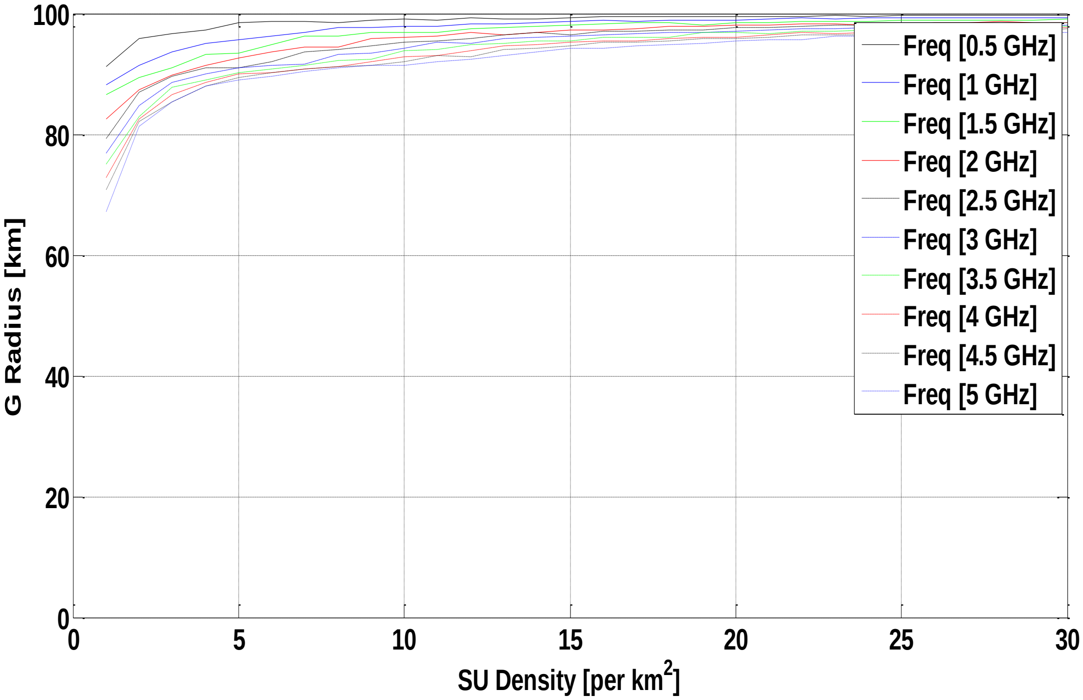

Figure 3-5 Illustration of frequency band effect on G radius. SU/km^2 is between 1 and 30.

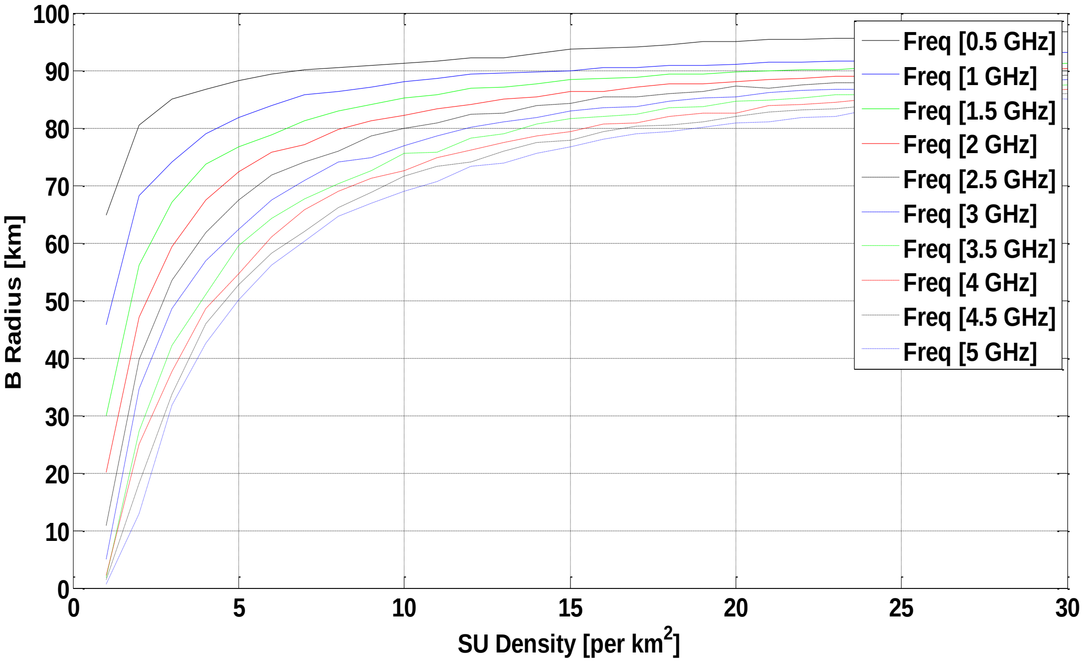

Figure 3-6 Illustration of frequency band effect on B radius. SU/km^2 is between 1 and 30

3.3.4.3 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 bands.

In Figure 3-7, the G radius remains at approximately 100km till reaching -130dBm, for all different SUs density. Also, the G radius reaches zero around -70dBm. That leads to these findings:

- If the PU antenna noise floor is less than (-130dBm), it is very sensitive to interference, and the exclusion zones will be very large.
- If the noise floor 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.

In Figure 3-8, the inner area density is 6 SUs/km^2 and the outer area density is 2 SUs/km^2. We can conclude the followings:

- At any specific point on the G boundary (x-axis), as the frequency decreases, the G radius increases.
- 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.
- The bending on the curves at radius=40km is due to the different SUs densities between inner and outer areas.

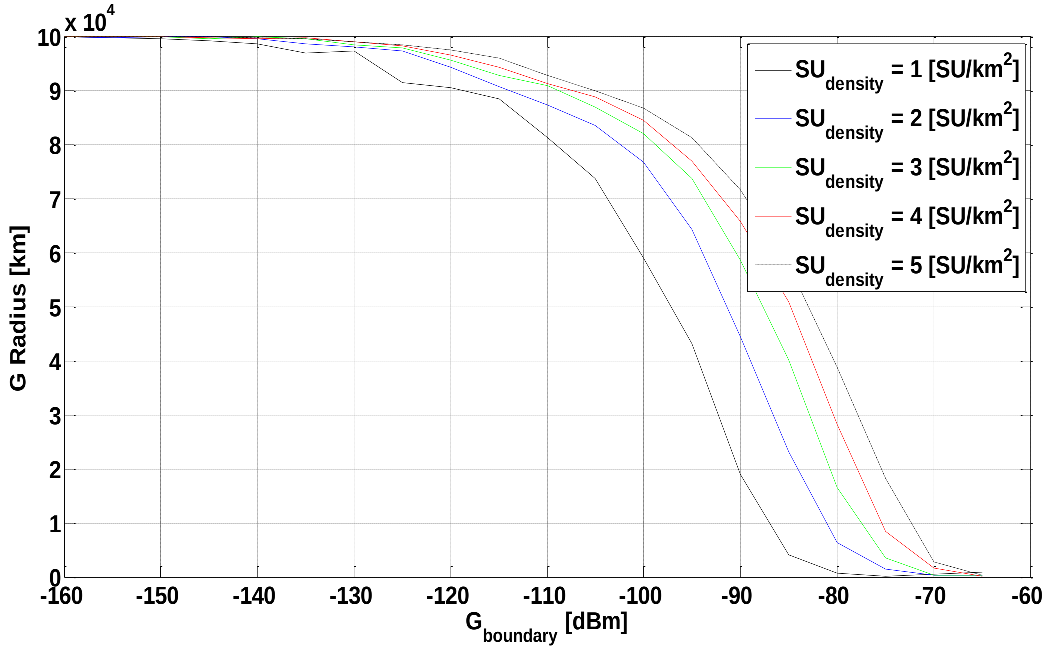

Figure 3-7 Effects of interference threshold on G radius over five different SUs densities.

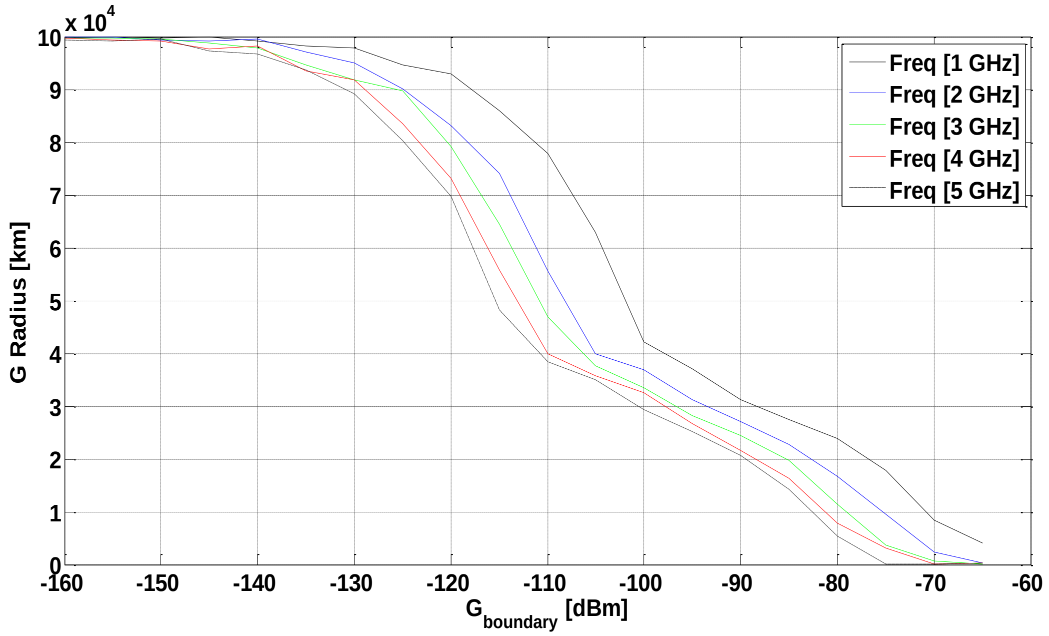

Figure 3-8 Effects of interference threshold on G radius over five different frequency bands.

4.0 Case Studies of Government-Commercial Sharing

4.1 Spectrum Sharing in 1.7GHz band

The 1695-1710 MHz frequency range (15MHz) is allocated to Meteorological-Satellite (MetSat; space-to-earth) and meteorological aids (MetAids; radiosondes) services. According to the Commerce Spectrum Management Advisory Committee (CSMAC) report [15], sharing in the 1695-1710 MHz band should be limited to commercial systems operations (LTE mobile uplink use only). That is because, in part, the1695-1710 MHz is immediately adjacent to the AWS-1 uplink band (which will maximize its usefulness for commercial services) and because mobile uplinks transmit at much lower power than downlinks. Please refer to [9] and [8] for more information about the PU and SU in this proposed band for sharing.

4.1.1 Simulation Setting

The published information about MetSat earth-stations (by NTIA) is only for the original 18 earth stations. Therefore, we will illustrate our simulation methodologies using these 18 MetSat stations and that could be generalized to any additional stations.

The specifications of the 18 earth-stations are summarized in Appendix A (Table A1). 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.

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. Appendix A (Table A2) 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).

These population analyses provide a powerful tool to evaluate the “opportunity cost” of B, G and W space areas. Figure 4-1 shows 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.

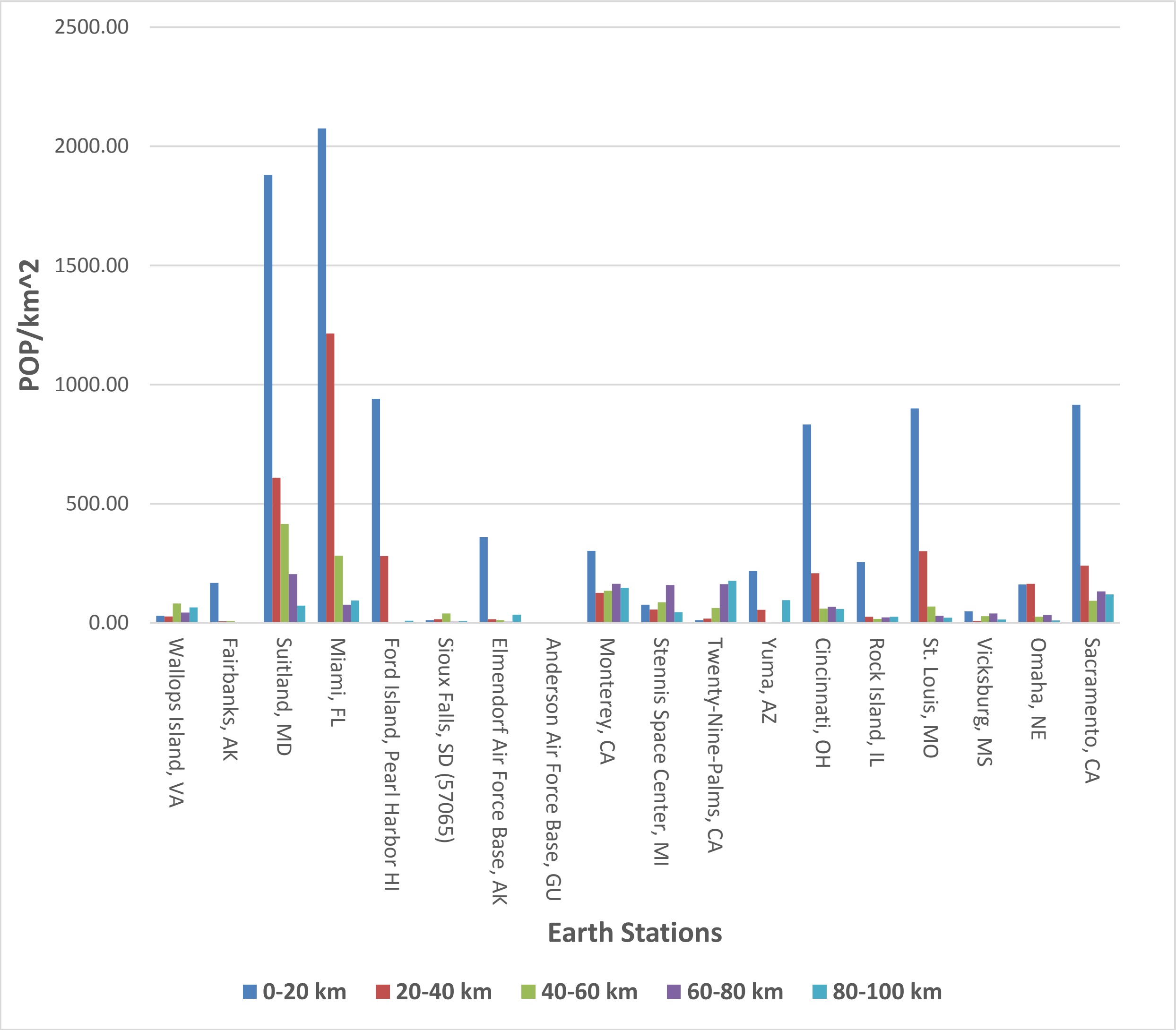

Figure 4-1 Population density for all 18 earth-station based on the five different areas.

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” [3] at the PU antenna specification.
  - In the MetSat case, it is in the range of -120 dBm. Appendix A lists the interference protection threshold at each earth-station.
- $B_{boundary}$
  - This is a new approach to be used to define B space area.
  - It’s value 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 noise floor threshold as part of sharing enforcement procedure.

4.1.2 Spectrum Sharing Benefits Evaluation

To show the benefits of enforcement scenarios, we get the real cost 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.

The following tables summarize our analysis for each earth-station. Table 4-1 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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[3] In this paper, the “interference protection threshold” and “the noise floor” for an antenna are used interchangeably.

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, we can evaluate the additive gain of the additional proposed areas shared as B, G, or W spaces.

Table 4-1 Analysis results based on average spectrum auction pieces of block A,B, and C.

Station #	Earth Station Name	$/MHz-POP
1	Wallops Island, VA	0.03
2	Fairbanks, AK	0.14
3	Suitland, MD	0.88
4	Miami, FL	0.54
5	Ford Island, Pearl Harbor HI	0.18
6	Sioux Falls, SD	0.09
7	Elmendorf Air Force Base, AK	0.14
8	Anderson Air Force Base, GU	0.00
9	Monterey, CA	0.44
10	Stennis Space Center, MI	0.41
11	Twenty-Nine-Palms, CA	0.60
12	Yuma, AZ	0.60
13	Cincinnati, OH	0.50
14	Rock Island, IL	0.12
15	St. Louis, MO	0.33
116	Vicksburg, MS	0.15
17	Omaha, NE	0.32
18	Sacramento, CA	0.19

These $/MHz-POP numbers are the final output of this analysis, and the input to the simulation model.

4.1.2.1 Black Space Area

The summary of black space analysis is listed in Appendix B (Table B1). The total B space area worth $193 million. Some black spaces are very small in area and impacted relatively large populations; the value, then, depends more on the population density more than on the size of the geographic area.

According to our definition, the black space boundary occurs when the PU receiver will accept more than 20dBm as additional aggregated interference above the noise floor 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.

4.1.2.2 Gray Space Area

The summary of gray space analysis is listed in Appendix B (Table B2). The total G space area is worth $52 million. The percentage of total area impacted at both B and G space are similar. However, the percentage of total populated impacted at G space is almost half the B space case.

4.1.2.3 White Space Area

This information listed at Table 4-2 is very critical and clearly shows the benefits of sharing the band with the PU. Where USs share the band, and aggregated interference falls below the noise floor of the PU (W space sharing), that will give $2.3 billion worth of spectrum.

This will incur a lower enforcement cost compared to G or B space sharing. It is most likely that the enforcement cost at this W space will be less than the benefits. That gives more incentive to share the band at this space type.

Table 4-2 Benefits evaluation suammary of B, G, and W Spaces

	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 ($ million)	193	52	245	2,327

4.1.3 Relocation of Earth-stations

In this section, we assess the benefits of relocating earth-stations that cause the most impacted percentage on sharing utilization. The following Table 4-3 lists the stations inputs. We can see that the first five earth-stations account for 90% of the benefits gained from sharing. In addition, the first three earth-stations account for 79% of the benefits.

The idea here is to relocate the earth-stations with the highest sharing benefits to another area with less population. If we assume the total cost (including the cost of the impacted population in the new location) of relocating an earth-station would be \$3 million, then the value of the spectrum based on the affected population exceeds the cost of relocation for the first eight earth-stations. This suggests that there may be a social benefit to their relocation.

Table 4-3 Relocation Benefits of the 18 earth-station, based on B+G values.

Station #	Earth Station Name	Value ($)	Order #	Grouping	
				Method #1	Method #2
3	Suitland, MD	134,976,113	1	**90%**	**79%**
4	Miami, FL	34,320,545	2		
11	Twenty-Nine-Palms, CA	23,971,324	3		
13	Cincinnati, OH	13,797,514	4		**21%**
9	Monterey, CA	13,316,321	5		
10	Stennis Space Center, MI	9,530,951	6	**10.00%**	
18	Sacramento, CA	3,434,079	7		
15	St. Louis, MO	3,101,571	8		
5	Ford Island, Pearl Harbor HI	2,727,747	9		
12	Yuma, AZ	1,770,843	10		
16	Vicksburg, MS	1,174,559	11		
7	Elmendorf Air Force Base, AK	747,481	12		
14	Rock Island, IL	631,456	13		
1	Wallops Island, VA	466,638	14		
17	Omaha, NE	417,872	15		
6	Sioux Falls, SD	398,119	16		
2	Fairbanks, AK	139,170	17		
8	Anderson Air Force Base, GU	-	18		

4.2 Spectrum Sharing in 3.5GHz 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” [16]. 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 [17].

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) [5]. To get more information about PUs and SUs discussion, please refer to [9].

4.2.1 Simulation Setting

As mentioned in a recent report from the FCC [17], many services/technologies have been proposed to share the band with PUs. The most common feature is that it is expected to be “small cell” topology(s). Even the PCAST report goes in this direction, recommending small cells in 3.5GHz band [4]. In this paper, we will consider the following two types of technologies to demonstrate our model:

1. LTE network
2. Femtocells and WiFi

All the PU technical specifications used in this model are based on the NTIA analysis [5]. Some necessary information is missing; however, we have made certain assumptions as detailed below. Table 4-4 summarizes the specifications about the shipborne radars.

Table 4-4 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

Based on Census Bureau data [18], the average population density of the coastal shoreline counties (excluding Alaska) is 172 person per km^2. The density in the US as a whole averages 40 people per km^2. To capture those data in the model:

- Inner area density (0 to 50km) = 172 person per km^2
- Outer area density (50 to 100km) = 40 person per km^2

4.2.2 Spectrum Sharing Benefits Evaluation

4.2.2.1 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 all possible scenario in this research.

The relation of LTE base stations to each other is completely independent. Both LTE base stations and LTE-UE are randomly and uniformly distributed over the simulated area, since we examine aggregated interference effect to the PU antenna, not the performance of LTE network; see Table 4-5. From Appendix C (Table C1), we can notice the following:

- Shipborne 1 still has the largest radiuses.
- Once the SUs active factor changes over 0.05%, 0.1%, and 0.5%; the percentage of change in radiuses is different from radar to another. That due to the different characteristics of each one of these five radars.
- 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)
- Since shipborne 1 causes the largest exclusion zones among the five radars, Table 4-6 summarize the benefits of W, G, and B spaces over the US.

Table 4-5 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.
- At the NTIA-CSMAC analysis [15]; 1 to 18 ratio had been used over all different terrain types.

Table 4-6: W, G, and B 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

4.2.2.2 Femtocells and WiFi Scenario

In this scenario, it is assumed both the transmitter and receiver have the same probability distribution function (PDF). The PDF is same as LTE-UE in urban area, where the transmitted power is relatively less since the distance between the transmitter and receiver is short. We ignore the factor or different type of traffic been carried over this scenario, we simulate a PDF of transmitted power (dBm) regardless if it is Femtocells or WiFi users.

The SU density has been examined over three cases (Active factor = 0.5%, 0.1%, and 0.05%) to study the sensitivity of that over the result. From Appendix C (Table C2)Table, we can notice the following:

- Since these type of technologies are small cell, there is huge reduction in G and B radiuses. Which gives advantage to small cell technologies over LTE to share this band, which increase the sharing utilization.
    - The majority of the cases list in this Table C2 show that, in large cities, the radii will be minimal. That is an interesting finding since the highest SUs density located in large cities.

Table 4-7: W, G, and B 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	662	186	13	14	219
	Gray	50	305	42	47	111
	Black + Gray	712	491	55	61	330
	White	2,376	2,596	3,033	3,026	2,758

5.0 Conclusion

Spectrum sharing has gone from an idea to a serious policy focus in one decade. As with many new and possibly disruptive technologies, spectrum sharing poses challenges for stakeholders, which include incumbents, regulators and entrants. 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 courts that is 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 paper, we have sought to provide some specific insight into some techno-economic aspects of cooperative spectrum sharing in two particular scenarios.

The main goal of his paper is to develop a relationship between enforcement methodologies and benefits of spectrum sharing through sharing between government and commercial users. In particular, we sought to shed light on the relationship between common enforcement strategies and their economic consequences in terms of lost value for two bands that are actively being considered for government-commercial sharing by the NTIA. While the results reported here are specific to these particular sharing scenarios, the approach (and some of the lessons) may be generalizable to other bands and other sharing scenarios as well.

One of the aims of this research is to develop some recommendations for principal stakeholders to facilitate spectrum sharing. In particular, we develop some recommendations for the sharing enforcement authority/agency that are drawn from the simulation model. This analysis is valuable because it will help regulators/governments prepare for possible future scenarios in solving wireless capacity crunch. In addition, it can give government users (Federal and non-Federal) more insight into expected future 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 of the economic benefits of different spectrum sharing market and opportunities.

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Appendix (A): Specifications of MetSat earth-stations

Table A1: The specification of the MetSat 18 earth-stations.

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

TableA2: Detailed specifications for each MetSat 18 earth-station.

Earth Station Number	POP within Radius=100 km (Population)	Minimum Elevation Angle (Degree)	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	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

Appendix (B): 1.7GHz Band Analysis

Table B1: Benefits evaluation sammary of B Spaces

station #	**Black Space Analysis**			
	Radius (km)	Population Affected	Population Impacted (%)	Value ($)
1	56.73	175,304	0.06%	187,945
2	3.55	7,894	0.00%	19,223
3	78.55	7,707,479	2.50%	123,248,661
4	40.12	3,310,138	1.07%	23,856,598
5	29.52	913,032	0.30%	2,612,780
6	5.41	1,579	0.00%	2,261
7	25.54	268,289	0.09%	579,678
8	15.48	-	-	-
9	63.53	775,494	0.25%	4,333,835
10	83.00	1,015,651	0.33%	6,000,135
11	98.49	2,610,050	0.85%	23,402,738
12	13.81	114,054	0.04%	1,040,131
13	21.65	1,036,004	0.34%	7,473,844
14	2.20	14,867	0.00%	27,861
15	0.99	26,937	0.01%	146,598
16	4.28	7,128	0.00%	17,466
17	1.27	2,819	0.00%	9,453
18	0.82	19,001	0.01%	60,152
Total Area Impacted (%)			0.70%	
Total Population Impacted (%)			5.83%	
Total Value ($)			193,019,360	

Table B2: Benefits evaluation summary of G Spaces

station #	Gray Space Analysis			
	Radius (km)	Population Affected	Population Impacted (%)	Value
1	92.20	259,949	0.08%	278,693
2	12.75	49,258	0.02%	119,948
3	97.62	733,388	0.24%	11,727,452
4	90.51	1,451,888	0.47%	10,463,947
5	39.48	40,175	0.01%	114,967
6	62.44	276,428	0.09%	395,858
7	60.37	77,663	0.03%	167,802
8	78.67	-	-	-
9	91.21	1,607,321	0.52%	8,982,486
10	95.10	597,666	0.19%	3,530,816
11	99.70	63,413	0.02%	568,586
12	36.44	80,125	0.03%	730,711
13	46.20	876,570	0.28%	6,323,670
14	32.30	322,087	0.10%	603,595
15	13.44	542,969	0.18%	2,954,973
16	70.57	472,218	0.15%	1,157,093
17	10.19	121,799	0.04%	408,420
18	21.39	1,065,758	0.35%	3,373,926
Total Area Impacted (%)				0.87%
Total Population Impacted (%)				2.80%
Total Value ($)				51,902,943

Appendix (C): 3.5GHz Band Analysis

Table C1: Black and Gray 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	91.5	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	67.7	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 C2: Black and Gray space radius for Femtocell-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	93.8	47.1	15.1	14.5	97.8	77.2	41.1	40.4
Shipborne 2	48.3	1.7	0.0	0.0	75.5	23.7	0.8	1.0
Shipborne 3	48.3	1.9	0.0	0.0	77.5	25.2	0.9	1.0
Shipborne 4	79.4	26.0	1.1	1.0	92.9	46.4	13.2	13.6
Shipborne 5	77.3	23.2	1.2	1.0	92.3	44.2	10.4	11.1
	SUs Active Factor = 0.1%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	71.5	15.4	1.1	1.2	89.2	40.8	4.5	5.1
Shipborne 2	16.4	0.0	0.0	0.0	41.9	2.0	1.8	1.8
Shipborne 3	16.5	0.0	0.0	0.0	42.4	1.8	1.7	1.7
Shipborne 4	43.6	2.4	0.0	0.0	66.4	13.0	1.8	2.1
Shipborne 5	42.4	1.9	0.0	0.0	63.8	10.9	1.8	1.8
	SUs Active Factor = 0.05%							
	Open	Suburban	Small City	Large City	Open	Suburban	Small City	Large City
Shipborne 1	52.0	3.4	0.0	0.0	81.2	27.2	2.5	2.5
Shipborne 2	4.6	0.0	0.0	0.0	23.7	2.8	2.2	2.8
Shipborne 3	4.7	0.0	0.0	0.0	26.8	2.5	2.7	2.7
Shipborne 4	29.8	0.0	0.0	0.0	51.5	2.8	2.3	2.4
Shipborne 5	28.1	0.0	0.0	0.0	50.7	3.7	2.7	2.0