EX-POST ENFORCEMENT FOR COOPERATIVE SPECTRUM SHARING

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Spectrum sharing policy was introduced to overcome spectrum limitations and inefficient use of spectrum. Spectrum sharing is a reorganization of rights between the spectrum sharing entities. The sharing entities are the Primary User (PU) who holds the spectrum license, and the Secondary User(s) (SU) who uses the spectrum temporarily. Any rights management system requires a set of strategies and technologies to enforce the rights; the timing of the enforcement action (ex-ante and ex-post) also plays a significant role in the rights management system.

In general, ex-ante enforcement measures are designed to prevent stakeholders' rights from being violated, while ex-post enforcement mechanisms deal with addressing the consequences of violating the usage rights policy. From the regulatory and economic perspective, the ex-ante measures are divided into two folds which are: 1) prevention-only measures (monitor-care) and prevention and detection measures (monitor-harm). Current enforcement mechanisms that are used for the spectrum sharing regime rely heavily on prevention-only measures as ex-ante enforcement types, such as exclusion zones and protection zones. Further, the dependency on the prevention-only measures such as the exclusion and protection zones would lead policymakers to use maximal sanctions as the ex-post enforcement.

Determining the role of ex-post enforcement in a spectrum sharing scheme is significant since spectrum sharing will, without doubt, result in interference events. This dissertation will explore the relationship between different enforcement mechanisms in the spectrum-sharing domain and their effects on enforcement costs. There are a number of factors to consider, including the cost and time of adjudication as well as how well the penalty is calibrated to the value of the communication. Further, this dissertation will discuss the use of a database system as an additional ex-ante enforcement measure by adding functionalities to the spectrum sharing regime to balance the use between the ex-ante and ex-post enforcement.

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First of all, I thank God for giving me faith, trust, and strength in myself to successfully complete this PhD journey.

I dedicate this dissertation to my family: to my mother Enayah Alaidarous who left this life before I finish this phase, she always said that her investment in this life was on her children; my father Professor Sulaiman Malki and my brothers (Mohammed, Dr. Zohair, Aasem, Abdulghani, and Bandar) , for their support, prayers, and being there for me when I needed it most which helped me to overcome many obstacles.

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1.0 INTRODUCTION

The inefficiency of spectrum utilization and spectrum limitation has led to the new approach to the communication policy of spectrum sharing. Spectrum sharing is a quite recent technique to overcome the issue of spectrum limitation and utilize the spectrum efficiently. Spectrum sharing policy is a reorganization of rights among spectrum sharing parties- the Primary User (PU) and Secondary User(s) (SU). PU is the license holder or the spectrum incumbent, while the SU is using the spectrum temporarily.

In its simplest form, spectrum can be shared in three dimensions (Space, Frequency, and Time), but these dimensions can be expanded to seven (Frequency, Time, Space (Longitude, Latitude, and Altitude), and Direction (Angel, and Azimuth)) [6]. Weiss and Lehr categorized the ways of sharing the spectrum into four general scenarios [7].

Spectrum Governing Organizations (SGO) (such as the Federal Communication Commission (FCC) and the National Telecommunication and Information Administration (NTIA) in the U.S., or the European Conference of Postal and Telecommunications Administration (CEPT) and European Telecommunications Standard Institute (ETSI) in Europe) took a series of steps toward developing spectrum sharing policies. The first step began with making available some previously allocated spectrum bands. In the US, NTIA offered government bands to be shared with commercial wireless service providers[8]. The next step towards implementing spectrum sharing policies was the design of the architecture needed for the

PU and SU to access the newly allocated shared bands. SGOs developed spectrum sharing access system architecture specifications to be used for one of the offered bands[1] [2]. The specification for the spectrum sharing access system architecture will rely on a database to manage, monitor, and enforce the rights of the shared spectrum.

A set of strategies and technologies are needed in any telecommunication management system to enforce the rights of stakeholders and use [11]. In these management systems, the timing of enforcement actions plays an important role [12] since they are designed to prevent, detect, and respond to any violation between the sharing parties.

Ex-ante and ex-post enforcement actions are the timing of the enforcement actions [12]. Generally, ex-ante enforcement mechanisms are the prevention techniques for stakeholders' rights from being violated, while ex-post enforcement mechanisms deal with addressing the consequences of violating the usage rights policy. The consequences of violating the usage rights policy may include penalties (such as economic penalties, recalling of the product, or licenses suspension) or modifications of rights between parties or other kinds of sanctions (e.g., power penalties, transmission moratoriums, etc.) such as in [13, 14]. The consequential measures that we intend to use in this dissertation are economic penalties (fines) as ex-post enforcement mechanisms.

In the literature, the timing of the enforcement actions is identified and classified differently by three parties based on each party specialty. These parties are Policy, Regulatory Economic, and Technical parties[3]. The Regulatory Economic party divided the ex-ante enforcement measures into two types based on how frequent the violations are. The ex-ante enforcement measures based on the Regulatory Economic party are: 1) prevention-only

[1] In the US, the Federal Communication Commission (FCC) provided Report and Order (R&O) that specify the tasks of Spectrum Access System (SAS) [9].

[2] In Europe, CEPT and ETSI provided the specification of the system architecture and operation of Licensed Shared Access (LSA) [10].

[3] These identifications and classifications will be explained on the Background chapter.

measures, 2) and prevention-and-detection measures. It has been hypothesized that using prevention-only measures such as ex-ante enforcement is more economically efficient than using prevention-and-detection measures [12, 15, 16].

The spectrum sharing approaches that have been introduced in the US that rely heavily on prevention-only measures as ex-ante enforcement types. These ex-ante measures are designed to prevent a PU's signal from harmful interference that could occur by the SU [17, 8]. The dependency on the prevention-only measures such as the exclusion and protection zones would lead policymakers to use maximal sanctions as the ex-post enforcement. Further, the dependency on the prevention-only measures, such as the exclusion/protection zones that cover heavily populated areas will reduce the incentive for the SU to share the spectrum which make them inefficient[4] ex-ante enforcement measures. A comprehensive enforcement framework would include protecting the rights of the SU as well, in addition to having an ex-post component that can efficiently and effectively adjudicate claims of interference.

Additionally, sharing the spectrum will inevitably result in interference events, so it is of significant importance to determine the role of ex-post enforcement in spectrum sharing scheme. On the other side, it has been posited that a system built on efficient ex-post enforcement would reduce the opportunity cost of the ex-ante enforcement mechanisms. This dissertation intends to evaluate the role of the ex-post enforcement in the spectrum sharing regime by modeling trade-off between ex-ante and ex-post enforcement, how an ex-post enforcement scheme might work, and to identify the limits of its effectiveness.

To do that, we have to consider number of elements. These elements are the cost and time of adjudication as well as how well the economic penalty is calibrated to the value of the communication. **Further, this dissertation will discuss the use of adding**

[4] Look at table (4) for the definition of Inefficient Measures.

functionalities to the database of the Spectrum Access System that had been suggested for spectrum sharing as an additional ex-ante enforcement measure to balance the use between the ex-ante and ex-post enforcement.

Ex-post enforcement must play a role in practical spectrum sharing systems. Despite this, it is not a topic that has attracted much attention in the research literature. Several approaches had been introduced to ease the process of ex-post enforcement and make it a more practical and acceptable approach for policymakers to adopt. Chapin and Lehr proposed an additional ex-ante enforcement measure- Time Limited Lease (TLL) that will ease the process of ex-post enforcement and make it an acceptable approach for policymakers to adopt [18]. Another proposed idea suggests the adoption of ex-post enforcement measures in the spectrum sharing regime, such as Spectrum jail [13, 14]. Both the TLL and Spectrum Jail ideas need the support of a database to enforce the spectrum sharing rights. In addition, these approaches require a costly supporting infrastructure, which is the main reason policymakers have temporarily put these approaches on hold.

2.0 BACKGROUND

In the Telecommunication industry, 'spectrum' indicates the spectrum of electromagnetic radio frequencies. Spectrum has a limited frequency range which is (9 KHz - 275 GHz) [19]. Spectrum is also counted as a renewable natural wealth of any nation (such as water or minerals). A management system is used for spectrum to increase its economic and technical efficiency[20]. In terms of economic efficiency, the spectrum is like any national-natural resource that provides economic incentives out of its usage. In terms of technical efficiency, when two or more devices are transmitting their signals on the same frequency, they will interfere with each other. To guarantee the technical efficiency, a spectrum management system must rely on efficient enforcement measures that guarantee spectrum usage rights [21].

Further, static spectrum allocation policy is used widely by the governments of the world to prevent interference among spectrum users. Figure (1) shows continuous intensive growth for the range of services of spectrum in the last decade. This growth with static spectrum allocation policy led to spectrum limitations. Spectrum sharing policy was introduced to overcome the spectrum limitations.

This chapter will provide a background on the enforcement tools that have been used by the spectrum management system in the United States. Then it will provide a background on the spectrum sharing and its regulations in the U.S..

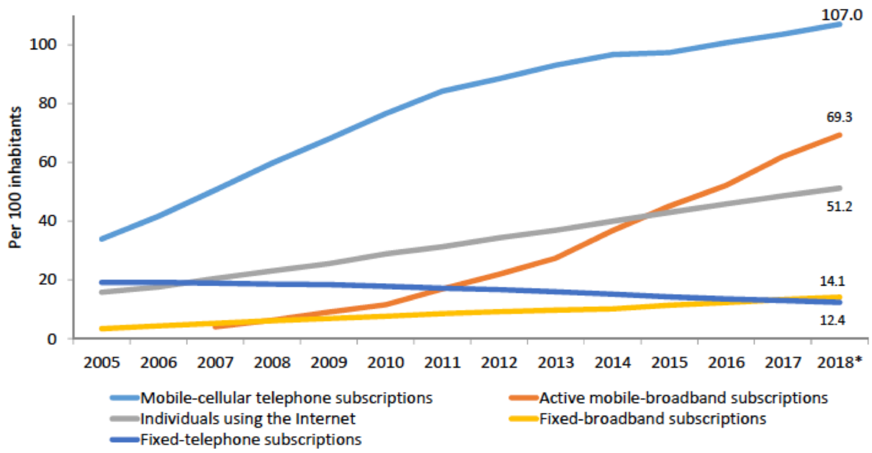

Figure 1: Information and Communication Technology report on global technology development adopted from [2]

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2.1 ENFORCEMENT

The main reason of using enforcement tools in the spectrum management systems is to provide optimal social manner [22]. Weiss et al. also indicated that optimal individual manners might be excluded because of the uncertainties, or failures in the system. The social manner implicates protection from harmful-interference.

In general, any management system requires a set of strategies and technologies to enforce the rights [11], and the timing of the enforcement action (ex-ante and ex-post) plays a significant role [12]. The general characteristics of the enforcement are [11, 17]: 1) timing of the enforcement actions (ex-ante or ex-post); 2) form of the sanctions; and 3) party (ies) carrying out the enforcement.

Shavell argues that the timing of the enforcement action plays an important role in any enforcement regime [12]. Enforcement actions can take place before (potential) interference events (ex-ante enforcement), or afterward (ex-post enforcement). Policymakers could design and use different measures as ex-ante and ex-post enforcement to enforce the rights. However, the choice of certain measures as ex-ante and ex-post enforcement depends on the frequency of the violation acts as we will explain in the following section.

2.1.1 Timing of enforcement actions

As mentioned, the timing of the enforcement actions are generally divided into two types, which are before (ex-ante) and after (ex-post) enforcement actions. However, the timing of the enforcement actions identification and the classifications may differ based on the speciality. Regulatory and Economic party, Policymakers, and Technical party are three parties who are responsible identifying, classifying, and designing the timing of enforcement actions as shown on Figure (2). Each party has its own perspectives on identifying the timing of the enforcement actions. The most important and relevant identification and design to this dissertation is the one that is classified by the regulatory and economic party. In this section we will identify the timing of the enforcement actions from each party's perspective.

- **Policy Identification:** Ex-ante enforcement is a general vocabulary in the economic party and it is equivalent to another general expression in the Law vocabulary of a priori [23]. Ex-ante enforcement can be identified as the measures that are used to prevent stakeholders' rights from being violated.

  On the other hand, ex-post enforcement is a general vocabulary in the economic party and it is equivalent to another general expression in the Law vocabulary of a posterior [23]. Ex-post enforcement is identified as any mechanism that is used as a reaction to recover the effect of the incident, or by other meaning, corrective measures after a violation event has occurred.

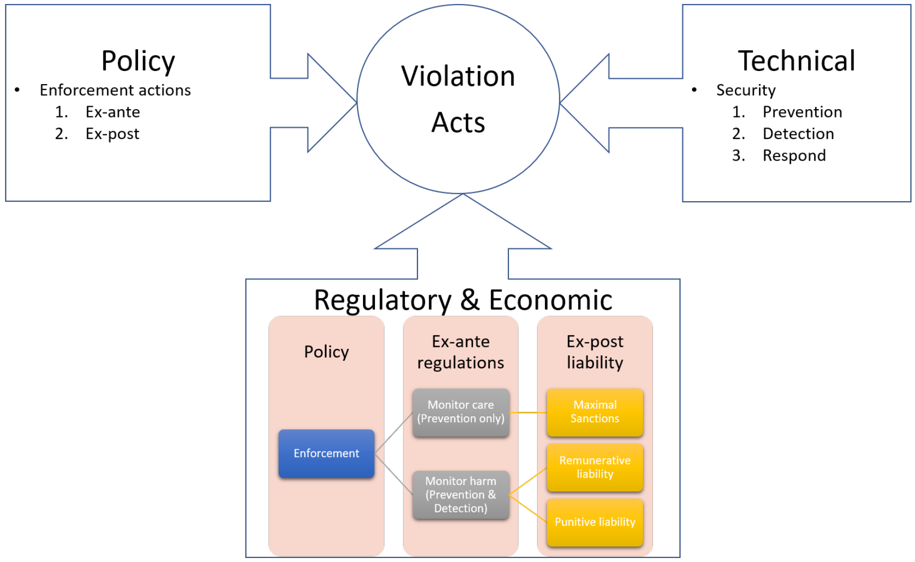


Figure 2: Explanation of enforcement timing actions from different domains

- **Technical Identification:** Any violation, such as signal interference, is counted as a risk and any organization should have a proper policy to prevent it from occurring. In the US, National Institute of Standard and Technology (NIST) and Emergency Response Team (US-CERT) provided frameworks to be used by the institutes, such as FCC, to evaluate and develop their capability to react to any violations [24, 25, 26]. The main three functions of these frameworks are guidelines for the prevention, detection, and responses to any violation act. These three functions are defined as [27, 28]:

  1. Prevention methods are used to assist the institutions to lower the risk of incorrect, bad, or prohibited behavior.
  2. Detection methods are used to discover any violation acts.
  3. Response methods are used to follow proper actions as reaction to claimed misbehavior, lawsuit or governing agreement issues.

  From the technical definitions we can categorize the ex-ante enforcement measures as the prevention technique that can be used before the violation acts; while the ex-post enforcement measures can be used for the detectionand the response methods to the violation acts of spectrum sharing policy.

- **Regulatory and Economic Identification:** Figure (2) shows that the ex-ante measures are divided into two parts depending on the frequency of occurrence of violations . The ex-ante enforcement types are: 1) prevention-only measures (monitor-care), and 2) prevention-and-detection measures (monitor-harm) [16]. When the violations are infrequent and difficult to sense, policymakers favor the use of prevention-only measures as an ex-ante enforcement mechanism and maximal sanctions as the ex-post enforcement mechanism [16]. The reason for using of maximal sanctions when the prevention-only methods as ex-ante measures because the detection techniques are not in place and the responsibility of detecting any violation act is transferred to third party. The cost (time and economics) of hiring a third party to detect, collect evidence, and prove the violation acts reflects on the sanction cost (time, and economic).

  Also, Figure 2 shows that the ex-post enforcement measures are divided into two groups based on which ex-ante enforcement measures are in place. The first group consists of the maximal sanctions only as consequence to any violation and the second ex-post enforcement consists of two measures that the policymakers could follow as a consequence of any violation: remunerative and punitive penalties (economic sanctions). A remunerative penalty is proportional to the lost value of the violation act, while the punitive penalty fine is much more the lost value of the violation act and it relies on the probability of detection[29].

The regulatory and economic categorized the detection methods as part of the ex-ante enforcement techniques. Whereas, Weiss et al. categorized the detection methods as ex-post enforcement measures [17]. The discussion of categorizing the detection methods as ex-ante or ex-post enforcement is beyond the scope of this dissertation. **This dissertation will follow Weiss et al. categorizations where the detection methods is part of of ex-post enforcement measures**.

2.2 CHARACTERISTICS OF THE ENFORCEMENT

Efficient enforcement measures will provide the capability for the spectrum manager to enforce appropriate spectrum rules, and assure spectrum management system efficiency [21]. To guarantee the spectrum management system efficiency a practical enforcement characteristic must be in place. The practical enforcement characteristics would consist of: 1) ex-ante enforcement; 2) ex-post enforcement; 3) enforcer. The following subsections will identify those three components of the enforcement system.

2.2.1 Ex-ante enforcement

Ex-ante enforcement procedures consist of prevention mechanisms that shape the activity before the interference occurs. Examples of ex-ante enforcement measures are the exclusion zones, protection zones, the SINR limitations, database system, standardization, and policy language.

The choice of Ex-ante measure affect on the choice of ex-post enforcement measures, this means that they function side by side. As mentioned, prevention-only ex-ante led to aggressive ex-post. Altamimi et al explained the relationship between the ex-ante and ex-post enforcment from the economic point of view [17]. They argued that the cost of providing desired manner to evade unacceptable one must be in correct proportions with different cases positive outcomes and the social costs.

2.2.2 Ex-post enforcement

Ex-post enforcement consists of corrective measures after a violation event has occurred. The corrective measures may include sensor network, database system, and penalties (such as fines, product recall, or revocation of licenses) or modifications of rights between parties or other kinds of sanctions (e.g., power penalties, transmission moratoriums, etc.) such as in [13, 14]. **This dissertation proposes to use the following ex-post measures:**

1. **Sensor network.**
2. **Database system.**
3. **Economic penalties (fines) as corrective measure.**

The following subsections will explain this dissertation proposal ex-post enforcement mechanisms. The use of sensor network and database system measures will provide prevention-detection technique to the enforcement. Additionally, these two measures will provide the opportunity to use relaxed ex-post enforcement measures, such remunerative and punitive economic penalties.

2.2.2.1 Sensor Network

In the past there was no practical reason to have sensor networks because the interference events were infrequent. However, senor network is very important tool for the spectrum management system especially with the new spectrum sharing policy because with more dynamic access to the spectrum will inevitably result in interference events.

The sensor network duty is to discover the received unwanted signals and locate them. The sensor antennas will have a range to detect the interference events. In this dissertation, this range is called the penalty zone. Although, the sensor antenna will detect the interference event with probability of detection. The probability of detection rate depends on the quality of the sensor antenna that the enforcer deployed around the designated area.

However, the use of the sensor network for the suggested 3550-3650 MHz band for spectrum sharing is the opposite to what this dissertation is suggesting. The Sensor Network for the 3550-3650 MHz band wil be deployed around the coastlines to sense the presence of the PU not to sense the interfered signals.

2.2.2.2 Database System

A database is a systematized information usually stored electronically in a computer system [30]. Database management system is used to store and control information about a particular entity. Database system includes Database, database management system, and the application linked to them [30]. The database system could take many forms: 1) centralized, 2) distributed, 3) decentralized, 4) and cloud data. In the database system [31]:

1. The information is indexed and contained in tables for the ease of use.
2. Information is modified and removed as new data is added.

In this dissertation, the database system is used: 1) to collect information about the PU spectrum utilization, 2) to coordinate with the regulator to update the policy, 3) and to gather the needed information of the SU's for any interference events settlement.

2.2.2.3 Economic Penalty

The definition of penalty according to The Law Dictionary[1] is: "A punishment; a punishment imposed by statute as a consequence of the commission of a certain specified offense". So,

[1] What is Penalty?(accessed: 11/23/2017) http://thelawdictionary.org/penalty/

penalties are important because (1) they encourage the violator not to impose harmful interference, (2) encourage the violator to look for alternatives to decrease the probability of a violation [32].

Generally, there are two approaches to determining economic penalties: remunerative and punitive. The punitive penalty means that if a breach event (such as harmful interference) occurs, the violator will pay much more than the real value of the breach (value of the lost data from harmful interference event). By contrast, a remunerative penalty seeks to compensate the injured for the value of the loss due the breach event.

Penalties could include fines only or fines and forfeiture. Imposing fines upon offenders stems from the ancient Anglo-Saxon tradition of extracting payment from families and sometimes whole communities for the commission of criminal acts [33]. The term "fine" is defined as a financial penalty enforced in illegal matters [34]. In the United States (US), fines are usually designated for particular offenses; because of existing statues they are restricted to minimum and maximum amounts. As an example, a fine for speeding in an automobile must fall between $30 and $300.

The Communications Act of 1934[2] regulates harmful interference in the telecommunications industry and this Act's rules have been applied to the present day practice of spectrum sharing. The Act imposes a base value for fines depending on the violation; it also sets maximum limits depending on the nature of the offense according to section five of the Act. Section five dictates the penalties when conducting harmful interference by any individuals [33]. The penalty levels vary depending on the degree of the violation or level of harm. If it causes harm to another entity the general penalty is a fine of no more than $10,000 (section 501). In the case of violating the rules or the regulations of the Communications Act of

[2] Communications Act of 1934 [35]

1934, the violator will be punished with a fine of no more than $500 for each and every day of the breach (section 502).

In the case of repeated harmful interference, the penalty is upgraded to a forfeiture penalty in the Communication Act of 1934. The FCC uses Forfeiture[3] Proceedings guidelines to issue additional penalties according to the Communications Act of 1934.

2.2.3 Enforcer

The role of the enforcer would be to monitor, detect, adjudicate, and control parties' behaviors. The enforcer must be trusted by all the entities of the system and must have authority to resolve enforcement violation events [37]. The parties could elect the enforcer to resolve both the acceptability of a hypothetical violation event and its costs [37].

In the US, there are two agencies that are responsible on enforcing the Telecommunication policies which are the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). NTIA has authority over federal spectrum users but has no authority over non-federal users. Conversely, the FCC governs non-federal spectrum users but has no authority over federal spectrum users [33].

Further, FCC and NTIA are using different ex-post enforcement approaches to govern the spectrum policy [33]. The FCC is using vehicles such as Notice of Apparent Liability and penalties (fines, forfeitures, cease and desist orders, equipment seizures, and in the most extreme cases criminal penalties) as ex-post enforcement measures in case of any violation acts. In contrast, the NTIA is using modification procedure or revoking Federal licenses as ex-post enforcement measures in case of any violation acts.

[3] Forfeiture Proceedings guidelines [36]

2.3 COSTS OF THE EX-ANTE AND EX-POST ENFORCEMENT

There are different aspects when a research is representing costs of the ex-ante and ex-post enforcement depending on the speciality of the party who is representing the enforcement cost. As mentioned there are three parties who concern about identifying, classifying, and designing the timing of enforcement actions which are Regulatory and Economic party, Policymakers, and Technical party. So, the cost of the enforcement measures can be divided into economical, procedural (temporal), and technical costs.

Altamimi and Weiss did unique contribution in calculating the economic cost of the detection method when is used in the cooperative spectrum sharing [38]. Specifically, they explored the total system cost and the practiced cost by the PU and SU. Since this dissertation intends to examine the role of the ex-post-only enforcement by providing alternative ex-post enforcement measures (remunerative and punitive economic penalties) that rely on prevention-detection technique. It will provide the economical costs of the ex-ante and ex-post enforcement measures. The ex-ante enforcement cost is linked to the cost of the excluded SUs from sharing the spectrum in a geographical location. Where the cost of the ex-post enforcement will be linked to the cost of the PUs' lost data resulted from SUs' signals when exceeding the suggested interference limit by the FCC/NTIA.

2.4 SPECTRUM SHARING AND ITS REGULATION

Spectrum can be shared in three dimensions: space, frequency, and time. Spectrum can also be shared in any combination of those dimensions. Static spectrum allocation means a spectrum user will have exclusive rights to the spectrum when the spectrum is not being

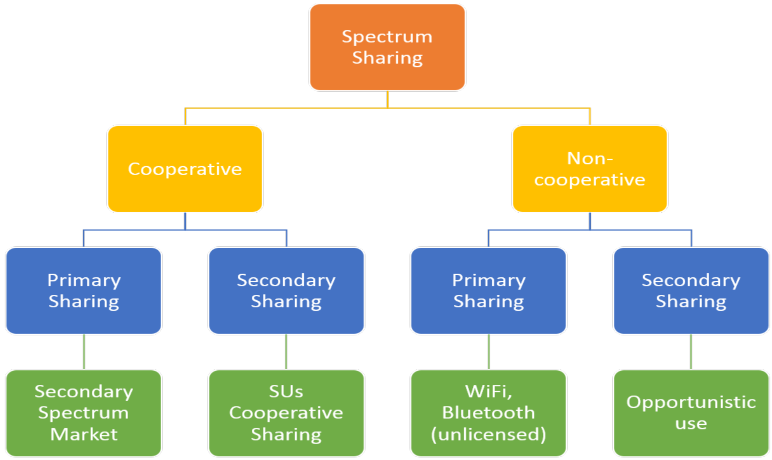


Figure 3: Spectrum Sharing Methods

shared in at least one of those dimensions.

There are a variety of methods to manage spectrum sharing between entities. The sharing entities are the license holder (or the spectrum incumbent) who is referred to as the Primary User (PU) and the Secondary User (SU) who is using the spectrum temporarily. Weiss and Lehr in [7] presented a taxonomy of spectrum sharing methods that depend on the presence of explicit coordination of usage (Figure 3). The Cooperative sharing depends on the coordination between users. The sharing coordination could be between PU and SU users or between SU users themselves. Non-Cooperative sharing, applies when there is no coordination between users. Cooperative and Non-Cooperative parties have two types of sharing: Primary and Secondary. Primary sharing means all users have equal rights whether they are sharing the spectrum (i.e. using WiFi) or using it for the secondary spectrum market. Secondary Sharing means there is no coordination between PU and SU but there could be coordination between SUs via Medium Access Control (MAC) protocol.

2.4.1 Spectrum Sharing Regulations

In the US, currently, the Wireless telecommunication system relies on a central authority to manage spectrum policy. The central authority is dependent on a closed-database that is used to register and approve any end-user. Spectrum sharing policy is a relatively new concept that has been proposed to solve the issue of spectrum limits in accessing the radio spectrum and to use the spectrum properly.

The Federal Communication Commission (FCC) has begun gradually adapting its policies to include spectrum sharing. In 2002, the Spectrum Policy Task Force (SPTF) supported the idea of using the market method to utilize spectrum dynamically and efficiently [39]. In 2003, the FCC allowed the spectrum license holder to apply spectrum leasing options for wireless services [40]. In 2010, the President of the United States signed a presidential memorandum calling for 500MHz of additional spectrum for mobile broadband [41]. The National Telecommunication and Information Administration (NTIA) and the FCC offered several bands to support this effort through spectrum sharing as shown in table (1) [42].

Table (1) shows the total offered Bands by the NTIA and the FCC for spectrum sharing amounted to 245 MegaHertz (MHz) [1]. The 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz bands are communally known as Advanced Wireless Services-3 ($AWS-3$). The 3550-3650 MHz is known as the Citizen Broadband Radio Service (CBRS) band [1]. In 2015, the $AWS-3$ bands were auctioned by the FCC for more than \$ 41 Billion US dollars. This dissertation will discuss two of the offered bands for sharing which are the 1695-1710 MHz (meteorological-satellite earth station's receiver), and the 3550-3650 MHz (3.5 GHz or Radar band).

Table 1: The 245 MHz Bands offered by the NTIA and the FCC [1].

	Frequency Range in Mega Hertz (MHz)	**Offered Bands for sharing in Mega Hertz (MHz)**
Federal Bands	1695- 1710	15
	1755- 1780	25
	3550- 3650	100
Non-Federal Bands	2305- 2320	15
	2345- 2360	15
	1915- 1920	5
	1995- 2000	5
	2000- 2020	20
	2180- 2200	20
	2155- 2180	15
Total		**245**

2.4.1.1 Spectrum Access System Design

In 2016, the FCC provided Report and Order (R&O) that specify the tasks of Spectrum Access System (SAS) in the Citizens Broadband Radio Service (CBRS) to be used for the 3.5 GHz band (3550-3650 MHz as on Table (1))[43]. SAS would play a role in implementing the enforcement mechanisms for spectrum sharing. Figure (4) shows the architecture of the CBRS. The R&O summarized the SAS duties as follow: [3]:

1. It would need to access PU's database to collect information about the PU spectrum utilization.
2. It would need to coordinate with the regulator to update the policy.
3. It also would need to access SU's database to get:
   a. devices geolocation,

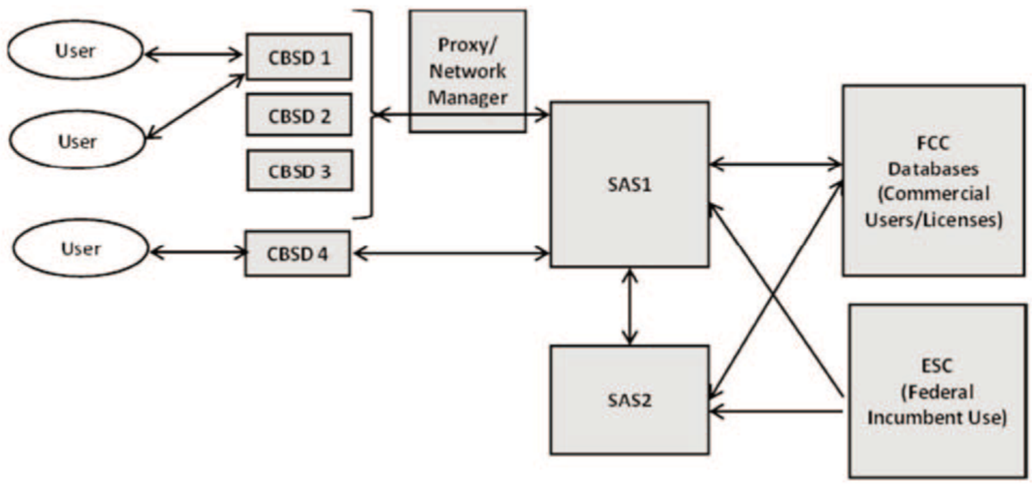


Figure 4: Prototype of Citizens Broadband Radio Service (CBRS) from [3, 4]

b. interference environment,

c. radio constraint,

d. and spectrum request.

4. It should have the ability to:

   a. allocate spectrum on a dynamic basis,

   b. detect and resolve any unwanted interference event.

The FCC divided the sharing parties into three access levels (including the PU). The FCC requires protection mechanisms for the PU which are the military radar and Fixed Satellite Service (FSS). The priority accesses are: 1) PU as tier-1, 2) Priority Access (PA) as tier-2, 3) and General Authorized Access (GAA) as tier-3.

3.0 LITERATURE REVIEW

This chapter will be divided into three parts. The first part will define the concepts of the signal interference, harmful interference level, and why it's important in any regulatory wireless system to prevent signal interference. Then we will show the previous Harmful-interference cases and the corrective ex-post enforcement measure that had been used to resolve them in the recent years. We will not consider the interference cases that were caused by "rogue" or "pirate" radios. Then we will provide an outline on the researches that had been done regarding the use of ex-post enforcement as prevention-only methods to avoid the Harmful interference instead of the prevention-detection methods as enforcement mechanisms from the economic perspective.

The second part of this chapter will review the research related to ex-post enforcement measures linked to the spectrum sharing regime, and the ideas of using alternative ex-post enforcement measures. This chapter will also provide an outline of the regulations that have been promulgated regarding the enforcement mechanisms in spectrum sharing.

The last part of this chapter will discuss three approaches that had been proposed to use/ease Ex-post Enforcement.

3.1 INTERFERENCE AND IT'S HARMFUL LIMIT

The performance of any wireless system is affected by a major limiting cause which is signal interference [44]. **Interference** is identified as "The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radio communication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy"[1] [45].

As mentioned, spectrum can be shared in Frequency, Time, and Space. The interference occurs when two or more wireless systems are sharing the spectrum, and one party is receiving unwanted signals from the other party/ies. The interference sources could be a wireless device/s, base station/s, or even a wired device which accidentally leaks energy into the shared spectrum.

The indication of the expression interference and its types differ based on the specialty of party [46]:

1. **Technical party**: The interference indicates the energy level of an unwanted interfering signal. There are many types of interference (e.g, Co-Channel Interference (CCI), Adjacent-Channel Interference (ACI), Inter-Symbol Interference (ISI), and Multiple-Access Interference (MAI)). We will explain two of them for the purpose of this research:

   a. *Co-Channel Interference (CCI)* [44]: In wireless mobile systems, the cellular network and the frequency reuse concepts were introduced due to the frequency limitations and to increase the system capacity. The cellular network consists of a number of cells; where a cell is a small geographical space that has a cellular base station with an allocated set of frequency channels. On the other side, frequency reuse means

[1] Code of Federal Regulations (CFR) - Title 47. Telecommunication- Section 2.1. Terms and definitions

there are some cells that use a similar set of frequency bands in a given coverage region. These cells that are using the similar set of frequency bands are called co-channel-cells. The CCI is the received interfering signals from co-channel-cells. The co-channel-cells should be geographically separated with a minimum physical distance to deliver adequate separation due to signal propagation and to overcome the issue of the CCI.

b. *Adjacent-Channel Interference (ACI)* [44]: This type of interference occurs with the usage of inadequate receiver filters that permits adjacent (neighboring) frequencies to leak into and get added to the desired signal. Appropriate filtering and channel assignment techniques could be used to decrease the ACI.

2. **Policy, Legal, and Economic parties**: For these parties the interference indicates the effect of signal energy on the wireless system performance. These parties divided the interference into two types which are No-Harm-Interference and Harmful-interference. Further, they divided the sources of the interference into two categories:

   a. Intra-interference: This type of interference occurs within the system and it can be handled by the system operative. This type of interference occurs from configuration error or failure of the equipment.

   b. Inter-interference: The source of the interference is out of the system. Additionally, they divided this type of interference into two types based on the number of the affected users or locations:

      i. adjacent interference (one user/location)

      ii. extensive interference (multiple users/locations)

3.1.1 Harmful-Interference

The term **Harmful interference** is identified as "Interference that endangers the functioning of radio-navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio-communication service operating in accordance with Radio Regulations" [45].

The Harmful interference occurs when two or more wireless devices are transmitting their signals using the same spectrum (Frequency, Time, Space) of another wireless system/s and the signal transmission "affects the performance, blocks, or frequently disturbs" the other wireless system/s [46]. Therefore, the level of interruption of the affected wireless system relies on two factors which are [47, 46]: 1) the power of the of the received unwanted signal that is a result of the transmitter emissions, 2) and the capability of the receiver to filter out all the unwanted received signal. So, the liability of conducting the Harmful interference is divided between the transmitter that transmits unwanted signal, and the receiver that is receiving the unwanted signal. In the past, several techniques were used by the regulators and technical parties to overcome the occurrence of Harmful-interference [46]:

1. Exclusion zones: licenses are assigned to certain Geographic allocations.
2. Transmit power limitation.
3. Allowed signal power limitation outside the assigned Geographic locations.
4. Static frequency allocation: licenses are assigned to certain frequency range.
5. Assigned frequencies are spread out broadly among the services.

In the mean time, the prolonged use of some of these techniques are debatable with the emergence of new technologies, frequency limitations, and spectrum sharing policy. There were other techniques that were proposed to overcome the Harmful interference occurrence but the regulators preferred not to follow them for different reasons because the implementation of these techniques is expensive to deploy such as the filtering technique on the receiver, or is hard to impose the rights of such negotiations among interfered parties.

3.1.2 Harm Claim Threshold

The definition of the interference and Harmful-interference that are stated by the statutes are very general and will not help with the current emerging wireless technologies and policies [48, 46]. In 2002, FCC Spectrum Policy Task Force (SPTF) declared that on their report [48]. They recommended the need to calculate acceptable limits of definite interference. In 2013, the FCC Technological Advisory Council (TAC) introduced Interference limits policy. The interference limits policy considered the use of minimal requirements for receiver performance. It is based on Harm claim threshold [47]. The wireless systems would use the Harm claim threshold limits to claim that they are receiving Harmful-interference.

The rule of thumb for pursuing enforcement when using the Harm claim threshold demands that the offended wireless provider presents to the FCC a proper received interference signal power level that exceeds their interference limits [47, 46]. Then, the Enforcement Bureau will determine if the offender is transmitting their signals outside its permitted transmission limits or not. If the Enforcement Bureau approves that the offender's wireless system exceeded its transmission limits, the FCC will conduct an enforcement proceeding.

3.1.3 Previous Harmful-interference Cases and its resolutions

As mentioned above, the only ex-post enforcement measure that is used by the FCC is the Forfeiture guidelines in case of the occurrence of any interference events. On the other hand, the NTIA is using different ex-post enforcement measures, such as modification procedure or revoking Federal licenses as ex-post enforcement measures in case of any violations.

Table (2) [2] shows the previous NALs issued by FCC Enforcement Bureau (EB) that followed the Forfeiture guidelines and apply economic penalties cases by the in the past from 2011 to 2018. We stopped at 2011 because the FCC EB database did not list NAL in order before that year. Table (2) did not consider the interference cases that were caused by "rogue" or "pirate" radios.

3.1.3.1 Ravi's Inc. and Mr. Buckley Interference Cases

The FCC issued a Notice of Apparent Liability (NAL) and assigned Forfeiture fines against Ravi's Inc. and Mr. Buckley [51, 53]. Ravi's and Buckley operated radio transmitters without authorization and caused harmful interference against the license holders.

- **Ravi's Import Warehouse Inc.:** Ravi's Inc. operated a cell phone jammer within the organization property in Dallas, TX. Cellphone jammers operate by transmitting powerful radio signals that override, block, or interfere with the cellphone signal that can stop cellphone holders from conducting any call. The case started when an agent filed a complaint from one of the authorized cell phone operators (AT&T) claims that one of its base stations was receiving (signal jammer) interference signal on 4-10-2017. The AT&T personnel helped the EB agent to locate the source of the signal jammer as coming from Ravi's organization. The company owner admitted to the EB agent that she had been using a signal jammer to prevent her employees from using their cell phones during their working hours.

  The EB in Ravi's case followed the Forfeiture procedure that is stated in section 503(b) of the Communication Act of 1934[3]. EB found that Ravi's Inc. actually violated section

[2] The description of each case is provided in Table (13) on Appendix A.

[3] Section 503(b) shapes that "any person who willfully or repeatedly fails to comply substantially with

Table 2: The FCC Enforcement Bureau (EB) Notice of Apparent Liability (NAL) from 2018 to 2011 for the conducted harmful interference cases.

Year	Case name	Complaint date	Monitoring date	Document date	Fine
2018	JJerry W., Materne, Lake Charles, Louisiana [49]	3- 6- 2017	8- 23- 2018	7- 25- 2018	$18,000
	Full Spectrum, Inc [50]	4- 4- 2017	4- 5- 2017	3- 30- 2018	$22,000
2017	Ravi's Import Warehouse, Inc. [51]	4- 10- 2017	February 2017 By AT&T agent	7- 26- 2017	$22,000
2014	CMARR, Inc., San Juan, PR [52]	11- 13- 2013	11- 13- 2013 And 11- 18- 2013	6- 24- 2014	$25,000
	Drew Buckley [53]	10- 31- 2013	From 11- 2- 2013 to 11- 6- 2013	6- 26- 2014	$25,000
	Jason R. Humphreys [54]	4- 29- 2013	From 5- 7- 2013 to 5- 9- 2013	4- 29- 2014	$48,000
	R&N, Manufacturing, Ltd (RNM) [55]	3- 29- 2013	4- 1- 2013	3- 26- 2014	$29,250
	Orloff Haines [56]		5- 14- 2013	3- 21- 2014	$12,000
	James R.,Winstead [57]		01-21-2014	02-19-2014	$7,000
2013	Acumen, Communications [58]		1-17-2013 And 1-18-2013	12-11-2013	$17,000
	Gary P. Bojczak[59]	8-3-2012	8- 4- 2012	8-2-2013	$31,875
2011	Estevan J., Gutierrez [60]		2- 15- 2011 And 2- 16- 2011	9-1-2011	$25,000

301[4], 302(b)[5], and 333[6] of the Communication Act of 1934, and section 2.805(a)[7] and 15.1(c)[8] of the Commission rules.

The EB assigned the base forfeiture fine for activating a device without authorization is $10,000 for violating section 301, the base interference forfeiture fine for is $7,000 for violating section 333 of the Communication Act of 1934. EB also added $5,000 as an upward adjustment to the combined base forfeiture fines and the total fine become $22,000.

- **Mr. Drew Buckley case:** Buckley operated a device that uses unauthorized transmission on a radio communication system belonging to the Melville Fire District of New York. Melville Fire District radio communication system licensed to activate its devices on an assigned pair of frequencies (474.2875 and 471.2875 MHz) that is used for public safety. Melville Fire District filed a complaint of interference to the EB on 10-31-2013. EB assigned an agent to conduct an investigation to monitor the repeater of Melville Fire District radio communication system. The investigating agent used a direction-finding device and located the cause of the interference signal to Mr. Buckley's house in Bay Shore, New York. Further, Melville Fire District requested assistance from the

the terms and conditions of any license, or willfully or repeatedly fails to comply with any of the provisions of the Act or of any rule, regulation, or order issued by the Commission there under, shall be liable for a forfeiture fine" [35]

[4]Section 301 states "No person shall use or operate any apparatus for the transmission of energy or communications or signals by radio within the United States, except under and in accordance with the Act and with a license granted under the provisions of the Act." [35]

[5]Section 302(b) states that "No person shall manufacture, import, sell, offer for sale, or ship devices or home electronic equipment and systems, or use devices, which fail to comply with regulations promulgated pursuant to this section" [35]

[6]Section 333 states "No person shall willfully or maliciously interfere with or cause interference to any radio communications of any station licensed or authorized by or under this Act or operated by the United States Government." [35]

[7]Section 2.805(a) states that "No person shall willfully or maliciously interfere with or cause interference to any radio communications of any station licensed or authorized by or under this Act or operated by the United States Government." [61]

[8]Section 15.1(c) states that "Intentional radiator (any device that generate radio frequency energy) cannot be operated in the United States or its territories unless they have first been authorized in accordance with the Commission's certification procedures" [61]

Police department. The police department sent an officer with the Melville Fire Chief to interview Mr. Buckley and they confirmed that Mr. Buckley had in his home pair of moveable radio devices that could transmit on the assigned frequency to the Melville Fire District. They also confirmed that one of the radios was used to transmit a unique identifying code that Melville Fire District detected during the interference.

EB in Mr. Buckley's case followed the Forfeiture procedure that is stated by section 503(b) of the Communication Act of 1934. EB found evidence that Mr. Buckley had violated Sections 301 and 333 of the Communications Act of 1934 [35]. EB assigned the base forfeiture fine for activating a device without authorization is $10,000 for violating section 301, the base interference forfeiture fine is $7,000 for violating section 333 of the Communication Act of 1934. EB also added $8,000 as an upward adjustment to the combined base forfeiture fines and the total fine became $25,000.

From the fine descriptions of these two cases and the other cases on Table (13) (see Appendix A), the economic forfeiture penalty consists of three factors which are:

1. The base amount forfeiture expense for transmitting close to PU-base station and exceeding the power limits.
2. The base forfeiture expense for interference.
3. The upward or downward adjustment factor

The following subsection will explain more how those three factors are employed on the Forfeiture penalty function. Further, those three factors are important for our model because:

- We will use them as base when we apply economic-penalties against the violators in our model.

- Similar technique will be used when we apply the economic-penalty equation in our model.

3.2 PREVENTION-ONLY VS PREVENTION-DETECTION METHODS

As mentioned, the researchers divided the ex-ante enforcement types into prevention-only methods (monitor-care) and prevention-and-detection methods (monitor-harm) approaches [16]. The prevention-only methods rely on ex-ante regulations, while the prevention-detection methods rely on ex-post liability.

When violations are infrequent and difficult to sense, policymakers favor the use of prevention-only measures as ex-ante enforcement and utmost sanctions as ex-post enforcement [16]. The detection techniques are transferred to a third party. The third party will be responsible for detecting any violation act. The cost (time, economic) of hiring a third party to detect, collect evidence, and prove the violation acts reflects on the sanction cost (time, economic).

The literature shows that researchers prefer to choose prevention-only methods as ex-ante enforcement instead of prevention-detection methods as ex-post liability [12, 15, 16]. Other researchers mentioned that when the regulatory uses prevention-only as ex-ante regulations instead of ex-post responsibility, it will discourage the violator from conducting the violation act and even lower the number of the incidents [62].

3.3 ENFORCEMENT MECHANISMS IN THE SPECTRUM SHARING REGIME IN THE U.S.

3.3.1 Enforcer in the Spectrum Sharing Regime

The enforcer would have different duties depending on the band that it is responsible for. The enforcer would act to manage the spectrum sharing regime by assuring the compliance of PU and SU with the spectrum sharing policy. The enforcer would have the ability to monitor the behaviors of the spectrum sharing parties, detect their misbehavior's, and provide response to complaints of the sharing parties (PU or SU) in the sense of feedback in the closed-control-loop system[9]).

One of the major complaints that might affect the spectrum sharing regime is the interference events that may occur when sharing the spectrum. The enforcer would need the ability to detect the interference events and provide response to the plaintiff and the defendant. The enforcer might need to build a sensor network in the case of the spectrum sharing to detect the aggregate signal energy of PU or SU. For example, for the 3.5GHz band, the sensor network will be built along the US coastal areas to detect the presence of the PU [64].

The enforcer would have different duties depending on the band that it is responsible for. For the 1695-1710 MHz, if the signal energy is below noise level, it would not be detectable. If the signal energy reaches the noise level, interference would be detected and the enforcer will apply the ex-post enforcement measures recommended by the central MOU, such as penalizing the SU. Details about the enforcer's role and sensing its mechanisms, are matters for future work and are beyond the scope of this thesis.

[9]Closed-control-loop is a system used in the electronic system where the objective of this system is "to measure, monitor, and control a process" [63].

3.3.2 Ex-ante Enforcement in the Spectrum Sharing Regime

The CSMAC-enforcement subcommittee recommended that the NTIA along with the FCC identify the ex-ante measures of the operational and technical guidelines governing the spectrum sharing of federal government bands. These guidelines include interference mitigation and enforcement procedures to provide ample precision for PUs and prospective SUs [33].

The ex-ante enforcement measures that would be applied to the spectrum sharing regime are [33, 43]:

- For the 1695-1710 MHz band (metrological-satellite earth station's receiver)
  - Protection Zones
  - SINR limitation of -10 dB to establish the interference threshold for the receivers of the PU's receiver
- For the 3550-3650 MHz (3.5 GHz or Radar Band) band
  - Dynamic Exclusion Zones when ever the PU is available
  - The maximum transmit power limit 24dBm and maximum Effective Isotropic Radiated Power (EIRP) 30dBm/10MHz of the CBSD.

3.3.3 Ex-post Enforcement in the Spectrum Sharing Regime

The ex-post enforcement consists of corrective measures after harmful interference has occurred. The corrective measures may include penalties (such as fines, product recall, or revocation of spectrum sharing licenses) or modifications to spectrum sharing rights between PUs and SUs.

However, the ex-post enforcement measures in spectrum sharing methods are different because the spectrum is going to be shared between Federal/non-federal and commercial usage. Each of these agencies has a different entity to govern spectrum usage. Those entities each have different ex-post measures. The entity that governs the Federal spectrum users is the NTIA but it has no authority over non-federal users. Conversely, the FCC governs non-federal uses but has no authority over federal spectrum users [33]. That is why we see differences in ex-post enforcement measures between NTIA and the FCC.

The FCC has different ex-post enforcement measures such as Notice of Apparent Liability and penalties. As previously mentioned, penalties may play an important role in spectrum sharing because they deter the violator from conducting harmful interference and encourage the violator to look for alternatives thereby decreasing the probability of repeated harmful interference [32]. The FCC penalties such as fines, forfeitures, cease and desist orders, equipment seizures and in the most extreme cases criminal penalties. In addition, the FCC governmental procedure consists of technical rights, as well as trials, in advance penalties are confirmed [33]. NTIA ex-post enforcement measures are different than the FCC because it is dealing with federal agencies. NTIA has the authority to modify and revoke Federal licenses.

The CSMAC-enforcement subcommittee report recognized the differences and difficulty of relying on one entity (NTIA or FCC) to govern if a harmful interference event occurred between PU and SUs [33]. It recommended that NTIA and the FCC enter into a new central Memorandum of Understanding (MOU) to govern spectrum sharing rights between federal and non-federal users. By central-MOU, federal and non-federal entities would rely on both the FCC and NTIA to take necessary actions in the event there is a breach of a sharing agreement.

The central-MOU would combine both (FCC and NTIA) agencies' ex-post enforcement measures and apply them when SU is transmitting within the protection zones. By using the central-MOU:

1. SUs will depend on NTIA authority to take action against the PU in the event there is a breach of spectrum sharing arrangement.
2. PU will rely on the FCC's authority to enforce spectrum sharing rights over SUs.

CSMAC-enforcement subcommittee report also recommended that both PU and SUs enter into specific-MOU to cover all specific interference concerns regarding spectrum sharing rights.

3.4 APPROACHES TO USE/EASE EX-POST ENFORCEMENT

3.4.1 Spectrum-Jail as alternative Ex-post Enforcement Measure

Woyach et al. introduced a technical framework of spectrum-jail as a consequence for radios that violate spectrum sharing rights [65, 66, 14]. The idea was to build a system that is able to ban any SU's radio from using the spectrum sharing band for a certain period of time when it violates the spectrum sharing rights and causes harmful interference to other users who are using the shared spectrum.

In the model of the spectrum-jail, they used the game theory and made several assumptions: 1) the spectrum holes exist in time to model the PU presence in two states of Markov-Chain., 2) the PU and SU transmissions are located and harmonized, 3) the sensing time is ignored, 4) and If the PU is transmitting and the SU decided to transmit at the same time, it is considered to be harmful interference and SU might be sent to spectrum-jail [14]. They modeled the sanction as a spectrum-jail where the SU loses the privilege to use the band/bands if it is caught conducting harmful interference.

Woyach preferred the idea of a spectrum-jail because it is simple and can be measured in QoS terms; and it is a feasible approach to be used in real life [14]. Woyach gave similar real-life examples to spectrum-jail, such as the kill-switch technologies in the telecommunication systems. The spectrum-jail was projected to be employed through a database. Woyach suggested to instrument the spectrum-jail on the same database for the TV whitespaces because it has the abilities: 1) of geographically locating the SUs (GPS), 2) and allocate spectrum holes [14]. Woyach also proposed in her work to switch the operation of the TV whitespace database from operation-manager to spectrum-manager. The operation of the TV whitespace database in her proposal is to issue and distribute free-transmission-tokens among the SU users instead. The token duty is used to allow SU to look for a spectrum hole to jump in it. The importance of the spectrum-jail comes when there is high insecurity and when the PU's signal is very significant.

3.4.2 Time Limited Lease (TLL)

Chapin and Lehr proposed time limited leases (TLLs) to be implemented among the SU devices [18]. The idea of the TLL is the use of the leasing contract in the spectrum sharing regime. They described it as a tool that can behave as a time-out coded in a software. When the timer is completed and no extension response is expected, the device stops the transmission. The TLL is a form of ex-ante technical mechanism that might be advantageous to decrease monitoring and ex-post enforcement costs (economic, and time).

The TLL applications were divided into four applications. The first application, device certification, is a process where a radio must be shown to comply with interference and safety regulations before sale. The second application, secondary spectrum markets, enable trading or sharing of spectrum access rights between primary and secondary users. Chapin and Lehr argue tht TLL can be used to reduce the risk of some types of violations because the devices are configured to accept certificates only if signed by PU. Thus, lessors (i.e., PUs) can be assure that the SU ceases operating in the listed band at the agreed end of the lease, never transmit beyond power level limits, and only transmits at approved time of the day. The SU can be limited to specified geographic areas if the lease mechanism includes GPS or some other location sensing mechanism.

The third application, novel business models, are the direct effects due to joint management risks, and indirect effects. The two main direct effects are when using cooperative radio meshes to reward or penalize a node; and using self-enforcing distributed contracts when the one of the lease table entries expire, the lease subsystem shuts off access to that band.

The final application is lease duration and other properties of the system design. Chapin and Lehr discussed in their proposal lease length issue and as the duration decreases, the cost of the lease increases due to the overhead associated with the repeated distribution of new certificates. Although, they mentioned that short leases are proper when the PU observes high risk in the transaction or relationship.

3.4.3 Wireless Network Virtualization (WNV) Approach

Gomez and Weiss introduced the Wireless Network Virtualization (WNV) concept to be used with SAS to enrich accessing the spectrum and the opportunities of sharing it [5, 67]. The idea is to use the concept of the virtualization from the perspective of resource pooling (where a couple of wireless service providers share their resources in a pool).

They introduced an external entity called Virtual Network Builder (VNB). The VNB would provide part of the spectrum pool management as an outsourcing party for SAS. SAS would deal with VNB as one of the major spectrum operators. The VNB's duty is: 1) to

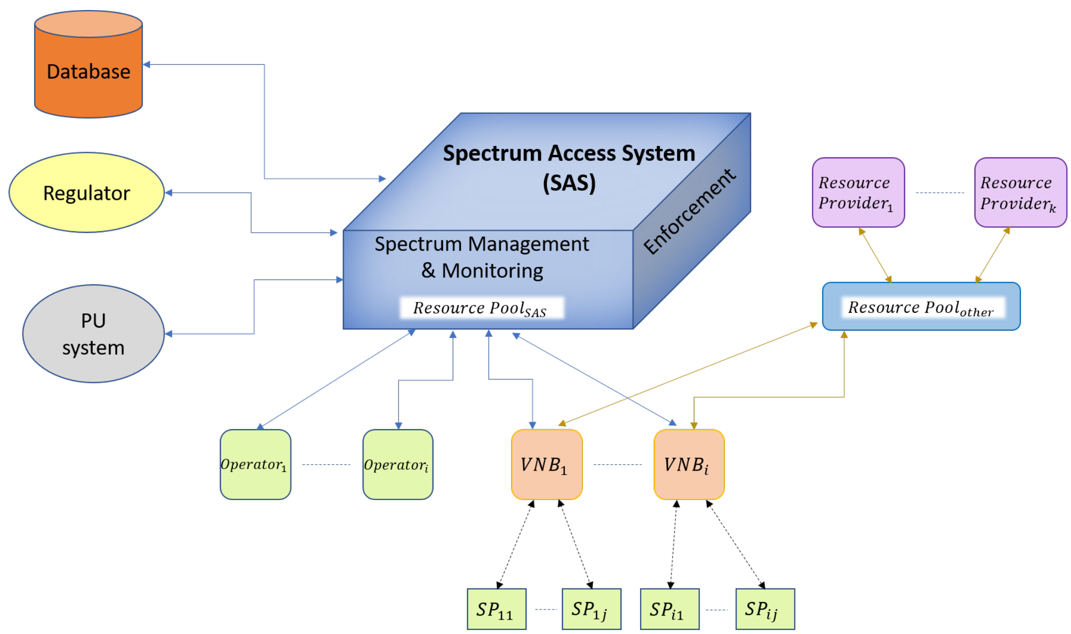


Figure 5: Prototype of the integrated Virtual Network Builder within SAS duties adopted from [5]

aggregate spectrum by negotiating access with SAS and estimated demand of the Service Providers (SP); 2) and to offer the spectrum for the SPs. When offering the spectrum to the SPs, WNV would need to auction for PALs from the SAS, and compete against other PAs and GAA users.

Figure (5) shows the VNB proposal as an integrated party within SAS architecture. As shown in the figure, the VNBs could be connected to different resource pools to add more flexibility to the network. The resource pools would be connected to Resource Providers (RP) where SAS is counted as one of the RPs.

4.0 MOTIVATION

This chapter will explain the motivation of this dissertation by discussing the enforcement mechanisms in general, spectrum sharing enforcement measures that are proposed by the regulators, a case study on the economic impact of one ex-ante measures that is in place, and the trade-off between ex-ante and ex-post enforcement measures.

4.1 ENFORCEMENT MECHANISMS

As mentioned, the timing actions of the enforcement can be explained differently from one person to another depending on his/her viewpoint. Figure (2) explains enforcement timing actions from the policy, regulatory and economic, and technical standpoints. Policymakers identified ex-ante enforcement as any measure that is used before the incidents or violation occurs. On the other hand, ex-post enforcement measures can be identified as any mechanisms that are used by the policymakers to recover the effect of the incident, or by other meaning, any corrective measure/s after a violation event has occurred. From the technical point of view, ex-ante enforcement measures can be identified as the prevention and detection mechanisms, while ex-post enforcement can be defined as the response measures to the violation of the policy or a spectrum sharing sharing policy.

Figure (2) shows that ex-ante enforcement measures are divided into two types from the regulatory and economic perspectives: prevention-only measures (monitor-care) and prevention and detection measures (monitor-harm) [16]. Policymakers selection of one of the two the ex-ante types will affect on the choice of the ex-post measures. When the incidents of violating the policy rights are infrequent and difficult to sense, policymakers favor the use of prevention-only measures as ex-ante enforcement, and extreme sanctions as ex-post enforcement [16].

4.2 SPECTRUM SHARING ENFORCEMENT MECHANISMS

Current spectrum sharing policy enforcement mechanisms rely heavily on the prevention-only techniques as ex-ante measures. For example, most of the recommended enforcement measures for the suggested 1695-1710 MHz band are ex-ante measures which are: 1) Signal Interference to Noise Ratio (SINR) limitation of $-10dB$, 2) Protection Zones (the radii of these zones vary between 16 - 98 km, depending on the specific site), 3) General Memorandum Of Understanding (General-MOU) between FCC and NTIA, 4) Coordination between PU and SU, 5) Specific Memorandum Of Understanding (Specific-MOU) between the PU and SU [68], while the only ex-post measure is found in the FCC forfeiture guidelines. For the suggested 3550-3650 MHz band, the recommended ex-ante measures are: 1) Power and SINR limitations, 2) Dynamic/Static Exclusion Zones, 3) Sensor Network around the coastlines to sense the presence of the PU, 4) Spectrum Access System (SAS) [69]. SAS is a special ex-ante measure that might play a role on lowering the cost (economic, time) of the ex-post enforcement as we will explain in the following subsection and in the tradeoff between ex-ante and ex-post enforcement measures subsection.

In case of the harmful interference, the only ex-post enforcement measure for the FCC to follow is the forfeiture guidelines. The cost of hiring a third party to detect, collect evidence, and prove the interference event when applying the forfeiture guidelines is very high (time, economic); in comparison to other proposed techniques that uses additional ex-ante measures, such SAS with a database system that has capability to collect proper information to ease such a process. The policymakers keep applying such enforcement measures because the use of prevention-only measures as ex-ante regulations are favorable especially if the violation incidents are infrequent, difficult to sense, or hard to allocate accountability because ex-post enforcement measures are complicated and costly (time, economic) [16, 12, 70].

4.2.1 Spectrum Access System

The Commerce Spectrum Management Advisory Committee (CSMAC) counsels the National Telecommunications and Information Administration (NTIA) on any matter related to spectrum policy. CSMAC's enforcement subcommittee report suggested Spectrum Access System (SAS) be responsible as an ex-ante enforcement mechanism on the spectrum sharing policy for the 3550-3650 MHz band [71].

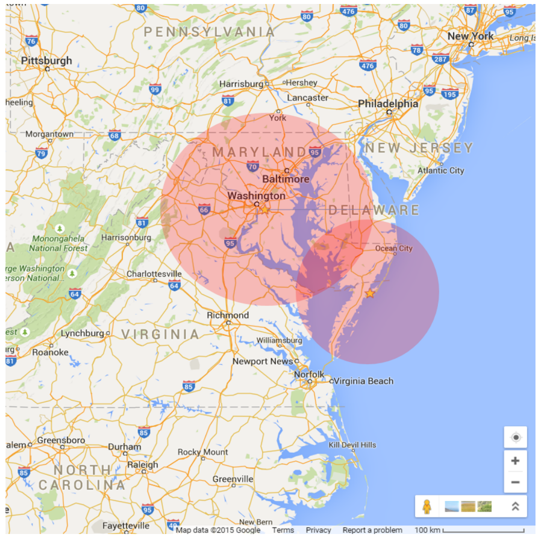
SAS will have the ability to [3]: 1) allocate the spectrum dynamically, and 2) detect and resolve any spectrum sharing policy violation. One of the SAS functionalities is warning the SU with the appearance of the PU to evacuate the band. SAS system will provide functionalities to help ease the process of ex-post enforcement mechanisms by detecting violation events which will reflect on lowering the ex-post enforcement cost.

4.2.2 A Case Study on the Impact of the Exclusion and Protection Zones

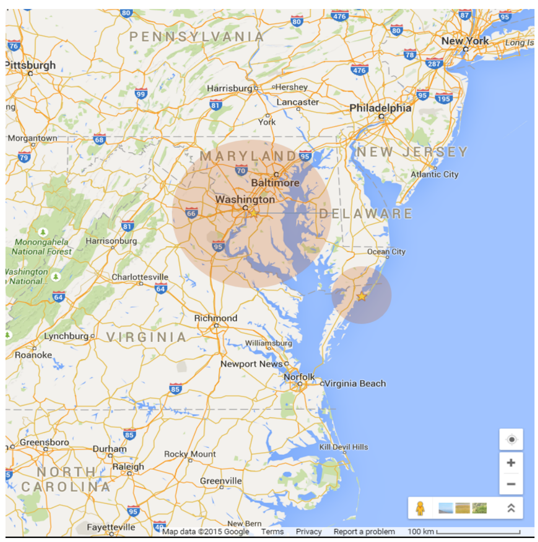
In 2010, the NTIA fast track report suggested that the bands can be available for spectrum sharing with two main restrictions [8]. First, power limitation that cannot be exceeded by the Secondary Users (SUs) depending on the band that is used for sharing. For the 1696-1710 MHz band, the Signal Interference to Noise Ratio (SINR) limitation of $-10dB$ that cannot be exceeded by the Secondary Users (SUs). And for the 3.5 GHz band, the maximum transmit power limit was 24 dBm and maximum Effective Isotropic Radiated Power (EIRP) 30dBm/10MHz of the CBSD. Second, geographic limitations (called exclusion zones) were defined within which spectrum is not shared.

For the 1695-1710 MHz band, the radii of these exclusion zones vary between 72-121 km, depending on the specific site. The lengths of the radii were given based on particular wireless systems used in their report. For the 3550-3650 MHz band, the NTIA fast track report recommended large radii of the exclusion zones around selected ground radar locations that vary between 40-60 km and large exclusion zones along the US (east, west, and south) coastlines [8]. These radii were reduced in the revised technical report for the 3.5 GHz band [69]. The length of the radii was established to prevent the Primary Users (PUs) from harmful interference. The exclusion zones will cover heavily populated areas that may reduce the incentives of the SUs to share. These two restrictions are examples of ex-ante enforcement and do not consider any ex-post measures that might be implemented.

In 2013, CSMAC- WG1 recommended another geographical limitation to be used instead of exclusion zones which was called "protection zones" to be used for the 1695-1710 MHz band [68]. The SU could freely use the band outside the protection zone. SU need to coordinate with the PU (Federal organization) for using the band within the protection zone.



(a) The exclusion zones



(b) The protection zones

Figure 6: Ex-ante enforcement

The protection zones are another example of ex-ante enforcement measures that will allow the use of spectrum after effective coordination between the Federal and the non-Federal organizations. The main reason for using the protection zones is because the exclusion zones were impacting nearly 13% of the United States (US) population. The radii of these protection zones vary between $16-98km$, depending on the specific site. The FCC adopted the protection zones in their Amendment rules with regard to commercial operation [68]. The protection zones reduced that impact on the US population to ten percent but the dedicated protection zones will still cover heavily populated areas that may reduce the incentive of the SUs to share.

Figure (6) shows an approximation when implementing the recommended ex-ante measures which are the exclusion and protection zones. Figure (6a) shows two of the exclusion zones denoted by the red circles (ex-ante enforcement only) which are Suitland, MD and Wallops Island, VA. These exclusion zones cover the Washington, D.C. metropolitan area which is the seventh largest metropolitan area, and the Baltimore, MD metropolitan area. It can be seen that the PU will not share the band $(1695-1710MHz)$ within these two exclusion zones and the SUs can transmit only if they are outside these zones.

Additionally, Figure (6b) shows an approximation of the adopted protection zone and the radii for Suitland, MD is 98 km that will impact 3.1% of the US population. This protection zone still cover major populated areas such the Washington, DC metropolitan area and the Baltimore MD metropolitan area.

4.2.3 Tradeoff Between Ex-ante and Ex-post Enforcement Measures

The dependency on prevention-only ex-ante measures and transferring the detection technique to a third party for the spectrum sharing regime would lead to dramatic increase on the ex-post enforcement. That was explained clearly in the two cases of Buckley and Acumen[1] when they operated radio transmitters without authorization and caused harmful interference against the license holders. The FCC applied very aggressive ex-post enforcement measures and followed the Forfeiture guidelines orders against Mr. Buckley and Ravi's Import Warehouse Inc. [53, 51].

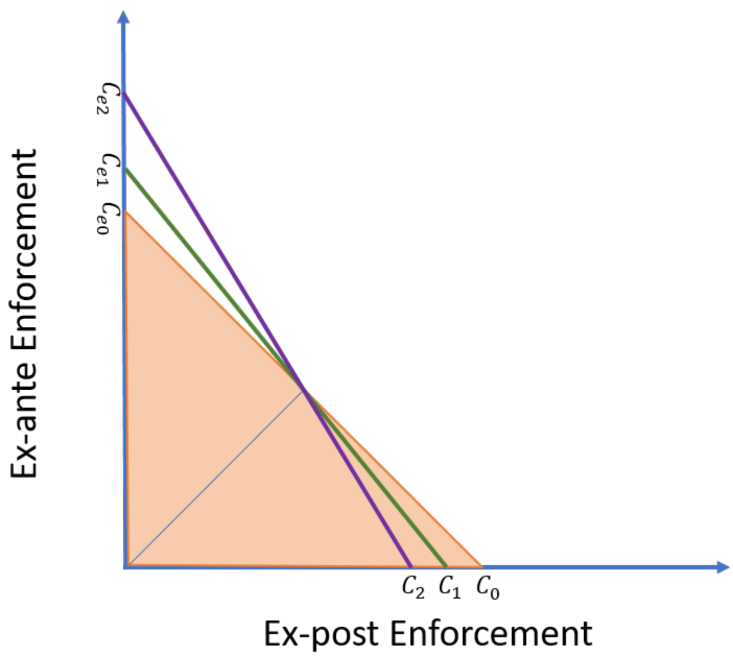


Figure 7: Tradeoff between ex-ante and ex-post enforcement

Altamimi et al explained the relationship between the ex-ante and ex-post from the economic point of view [17]. Since the adaptation is from the economic perspective, we have to put inconsideration the economic and regulatory categorization[2] where the detection methods is part of the ex-ante enforcement. Figure (7) is an adaptation of that relationship between the ex-ante and ex-post enforcement from [17] and it shows the trade-off between

[1]The two cases were explained in Previous Harmful-interference cases and resolution in Chapter 2.
[2]The background chapter explained the categorization of the ex-ante and ex-post enforcement from different specialties.

the ex-ante and the ex-post enforcement mechanisms. Figure (7) shows the economic relation between the cost of the ex-ante enforcement and the cost of the ex-post enforcement that are in place. C_e represents the cost of the ex-ante enforcement on the *y-axis*, and C represents the cost of the ex-post enforcement on the *x-axis* on Figure (7). Figure (7) shows that if we want to relax or lower the economic cost of the ex-post enforcement mechanisms (e.g. from C_0 to C_1), additional measures (such a Database to manage SUs and their locations, and sensor networks) need to be considered the ex-ante enforcement (e.g. the ex-ante cost will shift from C_{e0} to C_{e1}) which will be reflected on the cost of the ex-post enforcement.

4.3 SUMMARY

The use of the prevention-only measures as ex-ante enforcement, such as the exclusion/protection zones, are inefficient ex-ante enforcement measures to be used for spectrum sharing regime because these measures cover heavily populated areas which will reduce the incentive for the SU to share the spectrum. For example, the population density only for Washington metropolitan area is 5.9 million people. The value for these covered areas is approximately $ 119 million US Dollars [17] which is a good incentive for the SU to pay for sharing the spectrum within these areas. This value was calculated using the spectrum value opportunity that is used by the wireless operator to calculate spectrum value.

Although, policymakers cannot rely heavily on the ex-ante enforcement that provides prevention-only methods while ignoring detection methods and expect to have ex-post enforcement with lower costs. On the other hand, we cannot rely completely on ex-post-only enforcement because the ex-post enforcement measures are dependent on the ex-ante enforcement measures. For example, if we want to relax the ex-post enforcement cost and provide alternative corrective measures, policymakers have to consider prevention-detection methods to monitor harmful interference. The prevention-detection methods could provide more reliable and proper knowledge of the violation acts, such as violator-ID, violator's location etc. This dependency is what makes the ex-post enforcement measures costly (economic, time) when they are not in place.

Further, if the policymakers rely on complete ex-ante enforcement that provides prevention-detection techniques to help control the harmful interference, it is hypothesized that this will lead to significant cost savings. This can be measured by simulating a system with x number of PUs and y number of SUs and comparing them with existing data about enforcement costs (time, money) to quantify the change when applying different methodologies.

5.0 PROPOSAL AND RESEARCH GUIDELINES

For static spectrum allocation policy, policymakers relied on prevention-only measures as ex-ante enforcement which led to the use of maximal ex-post enforcement measures and to prevent the license incumbent from any Harmful-interference events. The reliance on the maximal ex-post enforcement measures proved its efficiency during the years because the interference events occurred rarely as per mentioned in the literature review chapter. However, the frequency of the interference events will increase with a more dynamic way to access the spectrum.

The policymakers should but in consideration the prevention-and-detection techniques to resolve and protect the sharing entities rights. Therefore, diversified ex-post enforcement measures (economic remunerative penalty, economic punitive penalty, forfeiture guideline) could play a role in the policy of the spectrum sharing regime to guarantee the rights of each party. This study will help researchers to develop feasible approaches to adjudication and will help policymakers balance the use of ex-ante and ex-post enforcement techniques in spectrum sharing regimes.

Our proposal is to evaluate the role of the ex-post enforcement (based on economic penalties) in the spectrum sharing regime by modeling trade off between ex-ante and ex-post enforcement, how an ex-post enforcement scheme might work, and to identify the limits of its effectiveness. There are a number of factors to consider, including the cost and time of adjudication as well as how the penalty will be calibrated to the value of the communication. Further, this dissertation will discuss the use of a database system (SAS that had been introduced to be used for the 3550-3650 MHz band) to be used for the 1695- 1710 MHz band as an additional ex-ante enforcement measure by adding functionalities to the spectrum sharing regime to balance the use between the ex-ante and ex-post enforcement.

5.1 RESEARCH QUESTIONS

This section will provide a questions list that will be addressed in this dissertation. The dissertation will answer the following questions qualitatively and quantitatively. Q1 through Q3 will be explained qualitatively. Q4 through Q7 will be quantitatively studied through three stages and tested by two hypothesis except Q5.c that is out of the scope of this dissertation and will be considered in future work. This dissertation will have one recommendation and will be explained quantitatively.

The dissertation will answer the following questions in detail:

Q 1. Which of the spectrum sharing types is feasible in the current sharing environment?

Q 2. What is the cost of the ex-ante enforcement?

Q 3. What is the cost of the ex-post enforcement?

  a. What are the cost elements of the ex-post enforcement?

  b. What are the impact of these factors on the cost of the ex-post enforcement?

Q 4. What is the SU risk of getting penalized when transmitting closer to PU's antenna?

  a. What is the value of SU's transmission?

  b. What is the interference penalty?

i. What are the influencing factors? (cost of the interference, number of the interferer, probability of detection, duration of the interference)

c. What is the risk of getting interference penalty? (Risk is defined as the probability of getting penalized by the enforcer and follows from the probability of detection)

d. How will the interference penalty prevent the SU's from transmitting closer to the PU's antenna?

i. How will the influencing factors affect the SU's transmission decision?

e. How does the increase of the SU's transmission value increase the risk of getting penalized?

Q 5. What are SU decision criteria to transmit within the penalty zone?

a. What are the decision criteria?

b. How can these criteria affect an SU's decision to transmit within the penalty zone? How can they be quantified?

c. What are the different choices the SU can make? The impact of the (Urban vs Suburb) it's not the focus of this dissertation because the research focus on the heavy populated areas.

d. How can we quantify the risk, if SU decides to transmit within the penalty zone?

e. What is the tradeoff between the transmission value and the penalty level?

Q 6. What is the impact of ex-post enforcement cost on the PU?

a. How will this cost affect the PU's decision to share their spectrum or not?

Q 7. What is the SU's ex-post enforcement cost?

a. How will this cost affect the SU's decision to share the available spectrum?

Q 8. What role could Spectrum Access System (SAS) as database like system play in the enforcement system for the 1695-1710 MHz?

a. Will an SAS-like database system be able to dynamically analyze and subsequently implement a balance of ex-ante and ex-post enforcement based on predefined rules and thresholds?

5.2 HYPOTHESES

As mentioned, couple of bands were offered for spectrum sharing. This dissertation will consider only the following selections:

- Two of the proposed bands for sharing, the 1695- 1710 MHz and 3550- 3650 MHz.
- These spectrum bands were introduced by the NTIA for spectrum sharing between Federal/non-federal and commercial usage.
- 1695- 1710 MHz
  - It will be limited to commercial systems operations which are LTE mobile uplink use only.
  - The Primary Users (PU) are the Federal agencies
  - The Secondary Users (SU) are the commercial mobile operators.
- 3550- 3650 MHz
  - The Primary Users (PU) are the ground-based radar.
  - The Secondary Users (SU) are The new Citizens Broadband Radio Service (CBRS) Access Point (AP).

This dissertation will examine two hypotheses and evaluate one recommendation. This section will link between the research questions and these hypotheses.

H1: If there is dynamic response system[1] **(i.e, graduated response sanctions), most SU will not risk a higher interference penalty by transmitting closer to the PU's antenna as the value of the SU transmissions increase.** [H1: *Pr (A|B)*]

$H1 \rightarrow Pr\{Penalty\} = Value_{Trans} \rightarrow y = x(t) + adj.$

Where $Value_{Trans} = y$

And $Penalty = x(t) + adj.$

Where $adj. = adjustmentfactor = Linearorexponentialfunction$

For example, a dynamic response system could impose graduated penalties based on factors like time of interference, number of times that violation had occurred etc.

H2: Including detection as part of ex-ante enforcement, will lead to better quality of service for PU, lower the probability of SU violations, and lower the cost of the ex-post enforcement. [H2$\rightarrow \frac{Cost_{ex-post}}{Cost_{ex-ante}} \leq 1$]

$WhereCost_{ex-post} = Penalty = x(t) + adj.$

And $Cost_{ex-ante}$ = *opportunity cost* = the cost for the number of users that will not be able to share the spectrum when using exclusion/protection zones as ex-ante enforcement measures.

[1] As mentioned in proposal section, we will evaluate the role of the ex-post (based on economic penalties) in the spectrum sharing regime by examining how an ex-post enforcement scheme might work, and to identify the limits of its effectiveness. To do that, we will study the role of the ex-post-only enforcement by applying the two types of the economic penalties (remunerative and punitive economic penalties). Also, we are going to study the role of the ex-post-only enforcement to find out if the policymakers used these two measures only, remunerative/punitive economic penalty will stop the SU from transmitting closer to the PU's antenna. On the other hand, a purely remunerative nor punitive economic penalties as ex-post-only enforcement may not be the best strategy because they might not significant enough to to stop the SU from interfering with PU's signals. Graduated Response is a broader framework that we will introduce to evaluate the role of the ex-post-only enforcement and we hypothesis that it would be a better approach to be used by the policymakers for the spectrum sharing regime to stop the SU from interfering with PU's signals.

5.3 RESEARCH FRAMEWORK

This work intends to evaluate the role of ex-post enforcement in the spectrum sharing regime by modeling how an ex-post-only enforcement scheme might work, and what the limits are on its effectiveness. In particular, there are a number of factors to consider, including the cost and time of adjudication as well as how well the penalty is calibrated to the value of the communication.

To determine whether (and when) the ex-post-only enforcement approach is superior to an ex-ante approach, we build a model of a geographic region with geographically distributed Secondary Users (SU) and a single Primary User (PU). Aggregate signal power of the Secondary Users (SUs) were computed at the PU's antenna to calculate the interference level. We hypothesized an adjudication system would penalize the SU when the interference level reaches certain limit received at the PU's antenna in the model.

Figure (8) shows three different model sittings of cooperative spectrum sharing. We will examine the first two scenarios in this dissertation. The third scenario will be as a future work. These scenarios are extracted from the spectrum sharing methods that are explained on Figure 3. Each scenario will be examined in certain stage/s. In the the first scenario, we will simulate a geographic region with one Service Providers (SP) as a single Secondary User (SU) that has geographically distributed customers and a single Primary User (PU). This scenario will be examined in stages 3 and 5 of this work. Each stage will discuss how the SU will react to different economic penalty approach as ex-post-only enforcement measure.

In the second scenario, we will simulate a model of a geographic region with two SPs as SUs that each have geographically distributed customers and a single Primary User (PU). In this part, we will discuss how each SP will react to the applied (remunerative, punitive, and

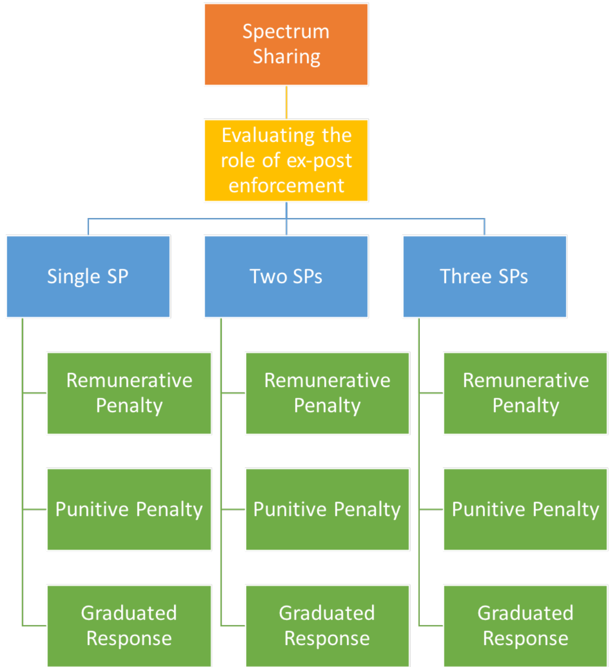


Figure 8: Model Settings

graduated response) economic penalties as ex-post-only enforcement measures differently. In this part, we hypothesize one of the service provider does not care about the applied ex-post-only enforcement, while the other one will try to optimizes their transmissions so that the net value of a sequence of transmissions is positive. This scenario will be examined in stage 6.

To examine the hypothesis, a list of research sittings need to be measured. The list of these research settings is shown as follows in stages :

Stage 1: We will study the enforcement measures for the suggestd 1695-1710 MHz band. We will identify the methods of spectrum sharing in general, and we will explain the most feasible method that can be used for this band. Then, we will identify the enforcement measures that will be used in our spectrum sharing model.

Stage 2: We will identify the cost elements of the ex-post enforcement that we will use in our model.

Stage 3: We will build a model of a geographic region with a single Service Provider (SP) that provide service to geographically distributed Secondary Users (SU) and a single Primary User (PU) to determine whether (and when) this approach is superior to an ex-ante approach. Aggregate signal power of the secondary users will be calculated at the Primary User's (PU's) antenna. The number of excluded secondary users will be determined based on an ex-ante approach that uses exclusion zones. We will plot the opportunity cost of the exclusion zones for varying values of Secondary User communications.

Then, we hypothesize an adjudication system would apply remunerative penalty against the SU. The remunerative penalty would be proportional to the lost value of the lost data by the PU plus the expected increase in enforcement costs occasioned by it. The SU then optimizes their transmissions so that the net value of a sequence of transmissions is positive.

Stage 4: We will hypothesize an adjudication system would use a broader framework by applying more aggressive ex-post measure. We do that to conduct broader evaluation the role of the ex-post enforcement through modeling how an ex-post-only enforcement scheme might work, and what the limits are on its effectiveness. This setting will extend the work in remunerative penalty by applying punitive economic penalty in the cooperative spectrum sharing regime when SUs cause interference. There are a number of aspects to consider, including what the sanctions are and how they should be applied to enforce the PU's rights.

Stage 5: Then we will present a graduated response approach. In the graduated response approach, the interference levels will be divided into three different interference event levels received at the PU's antenna.

In the first interference level, the penalty would be a fine proportional to the lost data by the PU plus the expected increase in enforcement costs occasioned by it. In the second interference level, when the SU does not optimize its transmission and decides to continue transmitting closer to the PU's antenna, more punitive penalties would be applied. The SU then optimizes their transmissions so that the net value of a sequence of transmissions is positive. In the third interference level, if the penalty value exceeds the maximum limit or the SU's interference duration exceeds a hypothesized maximum duration, other ex-post enforcement sanctions would be suggested like conditionally suspending SU license.

Stage 6: We will build a model of a geographic region with two Service Providers (SPs) and a single Primary User (PU). Each SP will have a geographically distributed Secondary Users (SU). We will hypothesize an adjudication system would use (remunerative, punitive, and graduated response) economic penalties as ex-post-only enforcement measures.

5.4 RESEARCH GUIDELINE

Table (3) summarizes the connections between research stages, hypotheses, and research questions.

Chapter (6 and 7) will address **Stages (1 and 2)** and associates the basics that were explained in **chapter (2)** to the end of this dissertation. It will explain the feasible spectrum sharing methods and the enforcement measures that will be used for the 1695-1710 MHz band. It will describe the recommended enforcement measures (ex-ante and ex-post) and analyzes them qualitatively. Then, it will describe the costs of the enforcement measures that we will use in this work. Furthermore, it will introduce the graduated response penalty

Table 3: Research settings, hypothesis, and the comprehensive research questions list.

Proposed research	Research questions
Stage 1, 2	Q1- Q3
H1, H2	Q4 -Q7
Recomm.1	Q8

approach as an alternative ex-post enforcement mechanism.

Chapter (8) will demonstrate our hypothetical model and the methodology that we will use on the experiments. It will set the needed experiments to accomplish the goal of this dissertation. Moreover, it will demonstrate **Stages (3 - 7)**.

Chapter (9) will show the results of the experiments for **Stages (3 - 7)**. These results will be generated from the hypothetical model based on each stage. It will also examine the proposed hypotheses.

5.5 DEFINITION OF RESEARCH VARIABLES

Table (4) is defining research variables that are used through this research.

Table 4: Operational definitions to the variables.

Terms	Operational definition
Inefficient measure	A mechanism that is used for for the static spectrum allocation may not be appropriate one for the spectrum sharing policy and that will effect on its efficiency on providing incentives to the PU and SU to share the spectrum. The incentives were calculated per the model set out in [72]
Inefficiency	The inefficiencies can be identified as the percentage of the populations or the number of users that will not be able to share the spectrum when using exclusion/protection zones as ex-ante enforcement measures.
Primary User (PU)	The Federal agencies which are license holders that use the band for fixed communication services. In the model, the federal agencies are Meteorological-Satellite (MetSat) and Meteorological Aids (MetAids) for space-to-earth and radiosondes links.
Secondary User (SU)	The commercial mobile operators and their customers. In the model, commercial systems operations (LTE mobile) that use the shared spectrum for uplink use only.
Spectrum Sharing	”Simultaneous usage of a specific radio frequency band in a specific geographic area by a number of independent entities leverage through mechanisms other than traditional multiple and random access techniques” [73]

6.0 STAGE 1: ENFORCEMENT MEASURES FOR SPECTRUM SHARING: A CASE STUDY OF THE 1695-1710 MHZ BAND

We will explain what the feasible types of spectrum sharing are that can be deployed in the current sharing environment. We will build our argument on one of the 1695- 1710MHz frequency band. This spectrum band was introduced by the NTIA for spectrum sharing between Federal/non-federal and commercial usage. This chapter will analyze the recomended ex-ante and ex-post enforcement measures that are recommended by the SGO in the US. Further, this chapter will identify the cost of the ex-ante and ex-post enforcement's that will be used in this dissertation.

6.1 SPECTRUM SHARING METHODS

As mentioned, there are a variety of methods to manage spectrum sharing between entities. Cooperative sharing depends on the coordination between users. The sharing coordination could be between PU and SU users or between SU users themselves. Non-Cooperative sharing, applies when there is no coordination between users. Cooperative and Non-Cooperative parties have two types of sharing: Primary and Secondary. Primary sharing means all users have equal rights whether they are sharing the spectrum (i.e. using WiFi) or using it for the secondary spectrum market. Secondary Sharing means there is no coordination between PU and SU but there could be coordination between SUs via medium access control (MAC) protocol.

When the spectrum sharing idea was proposed, Non-cooperative Opportunistic spectrum sharing (i.e., cognitive radio) was most heavily researched. The Opportunistic spectrum sharing method does not require any type of coordination. It turns out that Cooperative spectrum sharing is more commercially feasible at present, with the exception of the non-cooperative primary sharing (exemplified by unlicensed technologies such as WiFi).

Federal agencies, who are the primary users (PUs) on this band, generally do not accept any sort of interference to their signals. To avoid the interference events from occurrence, coordination between PU and SUs must be in-place to protect PU from interference.

6.2 ANALYSIS OF RECOMENDED EX-ANTE AND EX-POST ENFORCEMENT

The main reason to use the enforcement measures is to provide social welfare. Generally, the enforcement is the mechanisms that protects the rights of the sharing entities. The timing of the enforcement actions are used to prevent the occurrence of the interference events and to apply efficient corrective measures against the violator.

6.2.1 Ex-ante Enforcement

Ex-ante enforcement procedures as mentioned in the background chapter consist of prevention mechanisms that shape the activity before the interference occurs. Examples of ex-ante enforcement measures are the exclusion zones, protection zones, the SINR limitations, standardization, and policy language.

As mentioned, the two ex-ante measures that have been recommended for the 1695-1710 MHz band are 1) protection zones, 2) and the Signal Interference to Noise Ratio (SINR) limitation of -10 dB that cannot be exceeded by SUs.

SU users might be allowed to use the spectrum within the protection zones with the following conditions [74]:

1. Coordination between PU and SU to prevent interference.
2. Coordination among the SGOs (FCC and NTIA) and PU to ascertain: 1) prediction model for interference, 2) procedures to measure Interference level, 3) and monitoring the interference level.
3. Clear identification for the enforcement measures that are going to be used.
4. Protection from both Intra-interference and Inter-interference[1].
5. For any Harmful-interference incident, the SU must be notified and halt their signal till the event is resolved through the SGO's ex-post measures.

6.2.1.1 Analysis

The main reason for using the protection zones instead of exclusion zones was the population impact in the US.The protection zones allow the use of spectrum within the zone after effective coordination between the PU and SUs. The radii of these protection zones vary between 16-98 km, depending on the specific site.

However, the impact on the US population was not completely eliminated with the use of the protection zones;the dedicated protection zones will still cover heavily populated areas

[1] See section (3.1) for the definitions of these two terms

that may reduce the incentives of the SUs to participate. As an example, one of the protection zones is Suitland, MD and the recommended radius is 98 km. It covers the Washington, DC metropolitan area (which is the seventh largest metropolitan area in the US) as well as the Baltimore, MD metropolitan area. This protection zone impacts 3.1% of the US population, which is significant because it will affect the methods of spectrum sharing within protection zones. Moreover, the only method that is allowed to be used within the protection zones is the Cooperative Primary Spectrum Sharing.

6.2.2 Ex-post Enforcement

Polinsky and Shavell argue that there are two types of enforcement costs: unchanging enforcement costs and changeable enforcement costs [75]. Unchanging enforcement costs are costs that do not depend on the number of SUs that exceed the interference limits. These costs would include, for example, the expenses of detecting the interference in the shared spectrum. Changeable enforcement costs depend on the number of SUs involved in the interference events; these costs range from attributing interference to the appropriate party and penalizing the interferer, to collecting the penalties.

Polinsky and Shavell studied these two types of costs and how they directly and indirectly affect the penalty value and the probability of detection [75]. The unchanging enforcement costs do not directly affect the penalty value because these costs do not vary as the number of SUs who interfered with the PU increase. When an SU interferes, the expense of measuring the interference level is not affected. However, unchanging enforcement costs do control the optimal probability of detection; they therefore indirectly affect penalty values since the factor by which the interference is increased is a function of the probability of detection.

Polinsky and Shavell argued that the probability of detection depends on both types of enforcement costs [75]. For example, if the changeable enforcement costs are high, the probability will be low because enforcement will be expensive; for adequately high changeable costs, the probability will be zero. Likewise, if it is costly to invest in a new sensor network to improve the probability of detection, then the probability of detection will be low; in the extreme cases, it will be zero. Further, it may not be necessary to improve the probability of detection because increase the changeable enforcement cost even if the improvement of the probability of detection improved with no additional cost. The ideal economical cost of ex-post enforcement sanction should be equal to the lost value from the violation act, adjusted for the probability of not being detected, in addition to the changeable enforcement cost [75].

6.2.3 In Case of Violating Spectrum Sharing Rights

If the SU violates the spectrum sharing agreement by causing interference, the PU will rely on the FCC's ex-post enforcement measures to stop the SU from continuing or repeating this violation. The FCC has a variety of ex-post enforcement measures such as Notice of Apparent Liability and penalties. FCC relies on the Communications Act of 1934 to regulate harmful interference event by using a Forfeiture Proceedings guidelines [36]. The Forfeiture Proceedings guidelines are used to issue no forfeiture at all, a higher or lower forfeiture than provided in the Communications Act of 1934, or to apply alternative or additional sanctions as permitted by the statute depending on other factors.

$$Forfeiture = Op + I \pm Adj \tag{6.1}$$

Equation (6.1) is the forfeiture penalty which consists of three factors: 1) Op is the base amount forfeiture expense for transmitting near to PU base station and exceeding the power limits; 2) I is base forfeiture expense for interference; 3) and Adj is upward or downward adjustment factor. The base amount forfeiture expense for transmitting near PU base station and exceeding the power limits is $4,000. The base forfeiture expense amount for interference is $7,000. The downward or upward adjustment factor depends on the violation act and it rely on section 503 (b)(2)(E) of the Communications Act of 1934 to consider the nature, circumstances, extent and gravity of the violations and with respect to the violator, the degree of liability, any history of prior violations, capability to pay, and such other measures as justice require [36].

Therefore, the adjustment factors regarding the severity of the violation that may increase or decrease the forfeiture such as substantial harm, repeated or continuous violation, or substantial or economic gain derived from the violation, and the minor nature of the violation. Based on the Communications Act of 1934, the forfeiture penalty can be upgraded until it reaches the maximum limit. The maximum forfeiture amount per harmful interference or per day for a continuing interference is $160,000. If the harmful interference continued by the SU involving single act or failure to act, the statute limits thef forfeiture penalty for the SU to $1,575,000.

6.2.3.1 Analysis

The ex-post enforcement measures that had been used by the NTIA and FCC are based on the Communications Act of 1934, which were designed for a static spectrum allocation policy. Thus, these measures may not be suitable for a more dynamic spectrum sharing policy, and they might unduly reduce the incentives for the SU to share the spectrum because of the following:

1. Regulation

a. They are based on the Communications Act of 1934 Section 302(1) (transfer the authority to the FCC to govern the likely interference of devices but it did gave the authority for FCC or NTIA to give this authority to a trusted third party).

b. They are more generic.

c. They are more punitive than corrective measures for individual cases.

d. There is no alternative to the Forfeiture Proceeding guidelines when harmful interference event occurs that the enforcer can follow.

2. Technically: The band is dedicated for the uplink communication from SU-mobile devices to SU-base station. SU is a mobile operator and cannot control the mobility of the SU-mobile devices. If an SU-mobile device moves close to the PU's base station and tried to communicate with SU-base station, it might affect receipt of the satellite signal for the PU which may result in interference. The consequence for that would be implemented by the enforcer, who would follow the FCC Forfeiture guidelines by forfeiting the mobile devices and applying the forfeiture penalty to the SU.

   a. If this happened once, the enforcer might go with no forfeiture at all or have the authority upgrade the forfeiture penalty until it reach the maximum amount of $160,000 but that is not explained well in the CSMAC-enforcement subcommittee recommendation.

   b. If it occurred a second time in the same day, the enforcer would have the authority to upgrade the forfeiture penalty to the maximum amount of $160,000.

   c. If the violation occurred for the second time in another day, the enforcer would have the authority to upgrade the forfeiture penalty up to the maximum amount of $1,575,000.

d. Sometimes the SU-mobile devices transmit a signal with high power to communicate with the SU-base station until it receives a signal from the SU-base station to lower its power. If the SU-mobile device is transmitting near PU's base station interference may occur and the enforcer might follow the procedure that has been outlined above.

The CSMAC-enforcement subcommittee recommended that PU and SU enter into specific MOU or individual agreement to cover all specific interference enforcement issues [33]. The specific MOU would framework enforcement rights and penalties of the sharing parties. This recommendation will not be an ideal solution because it will be under the umbrella of the Communications Act of 1934 and the Forfeiture Proceedings guidelines. In addition, the Forfeiture Proceeding guidelines did not take into consideration the time period of the interference. The time period of the interference is needed to impose the proper penalty to cover the value of lost data. The Forfeiture Proceeding did not take into consideration the number of interferers because it was based on the static spectrum policy under which interference cases were rare.

Alternatively, CSMAC-enforcement subcommittee could be more specific and recommends that the PU and SU enter into specific MOU to cover other ex-post enforcement (interference remedies) that are related to spectrum sharing. Ex-post enforcement that are not included in the Communication Act of 1934 such as other types of penalties (fines) against the interferer such as remunerative or punitive penalties depending on the level and time of the interference. The following sections will evaluate the scenarios of using those two approaches in the spectrum sharing regime to find which is better approach that could be used.

7.0 STAGE 2

7.1 EX-ANTE AND EX-POST ENFORCEMENT COSTS

As mentioned there are economical, procedural (temporal), and technical costs that are used to calculate enforcement measures. This dissertation is focussed on the **economic cost** associated with the ex-ante and ex-post enforcement measures that will be used in spectrum sharing for the 1695-1710 MHz band. This work intends to study the ex-post-only enforcement and to do that, we will explicitly explain the costs of the ex-post enforcement measures.

7.1.1 Ex-ante Enforcement Cost

The cost of the ex-ante enforcement that we are going to use in this dissertation is represented as C_{ex}. The ex-ante enforcement cost will be equivalent to the number of SU who will be able to transmit outside the suggested exclusion/protection zones. For example, the population density only for Washington metropolitan area is 5.9 million people. The value for these covered areas approximately is worth \$119 million [17]. Therefore, if only 10 % of the population are allowed to share the spectrum outside the exclusion/protection zone of Washington metropolitan area, the C_{ex} is equivalent to \$11.9 million U.S. Dollars. Equation

(7.1) represents the ex-ante enforcement cost that we will use in this dissertation.

$$C_{ex} = n_{ex} \times V = n_{ex} \times C_{trans}(POP/MHz) \times 15MHz \tag{7.1}$$

Where n_{ex} is the fraction of SUs who are outside of the exclusion zone and V is the value of the transmissions per SU. C_{trans} cost will be calculated using the spectrum value opportunity that is used by the wireless operator to calculate spectrum value. The spectrum value opportunity is calculated by the population that each MHz of spectrum reaches ($MHz - POP$). The LTE required bandwidth by the ITU is 20 MHz, but we will use the available bandwidth for the band 1695-1710 MHz which is 15 MHz.

7.1.2 Ex-post Enforcement Cost

The ex-post enforcement measures that this dissertation proposes to use are: 1) Sensor network, 2)Database system, 3) and economic penalties (fines) as corrective measure. However, Altamimi and Weiss explored the economic cost for the sensing, sensor network, and Database system [38].

This dissertation contribution is to explore two types of economic penalties as ex-post enforcement measures. These two measures can be used as corrective measures in case SUs violate the spectrum sharing rights since the policymakers are obligated to use prevention-detection technique in [74]. Further, these two ex-post enforcement measures can be used in addition to the current ex-post enforcement measures that are in place.

The economic cost of the ex-post enforcement will be represented as C_{ep}. The ex-post enforcement cost will be equivalent to economic penalties that imposed against SUs when they violate the terms of spectrum sharing. Equation (7.2) represents the cost of the ex-post enforcement.

$$C_{ep} = N_{SU} \times P \tag{7.2}$$

Where N_{SU} is the number of detected SUs whose their signals power level exceed the the SINR limit of -10 dB. P is a function that represents the economic penalty. The value of P will be equivalent to the PUs' lost data. P function is extracted from:

1. Polinsky and Shavell argument that ex-post enforcement costs has two types which are unchangeable and changeable enforcement costs. Unchangeable enforcement costs are the costs that do not depend on the number of interferer which is the value of the transmission loss due to interference. Changeable enforcement costs depends on the number of SUs that go beyond the interference limits, such as costs of penalizing the interferer and collecting penalties.
2. The Forfeiture penalty function.

There are two approaches to determine economic penalties: remunerative and punitive penalties. The punitive penalty means that if interference events occur, the SU will pay much more than the real value of the lost data during reception by the PU. By contrast, a remunerative penalty seeks to compensate the PU for the value of the loss due the interference event. The following sub-sections will explain remunerative and punitive penalties cost functions.

7.1.2.1 Remunerative Penalty

Equation (7.3) represents the remunerative penalty function that will be imposed by the enforcer to each SU-mobile device exceeds the SINR limits. The remunerative penalty P_{Rem}

function will be as follows:

$$P_{Rem} = \alpha \times (\$I \times t + \$C) \tag{7.3}$$

The enforcer charges P_{Rem} to the SU that recovers PU's (1) transmission loss due to interference ($\$I$) for the time t and (2) the changeable enforcement costs ($\$C$) which represents the costs of imposing and collecting the penalties (3) all multiplied by a probability of detection (α) because the number of interference events depend on this probability. Undetected interference should not increase the penalty. The PU cannot know for certain what α is, so it is a private estimate. It could adjust the Penalty ($\$I$) by α, but not the changeable cost ($\$C$).

7.1.2.2 Punitive Penalty

As mentioned, a punitive penalty approach means that the value of the fine is much higher than the value of PU's lost data. Polinsky and Shavell argued that punitive damages ordinarily should be awarded **if, and only if,** a person who cause harm has a chance of escaping responsibility for the harm caused [29]. In the spectrum sharing regime, the enforcer will detect the interference events by using a sensor. These sensors will have a sufficient range to detect the interference events with probability of detection (α).

Additionally, Polinsky and Shavell argued that if the SU has a chance of not being detected, the suitable level of total loss to impose on them (if SU-mobile device is detected) is the value of the lost data multiplied by the equivalent of the probability of detection [29]. For example, if the value of the lost data is $\$1,000$ and the probability of detection is 50% (which means that there is a 50% chance that interferer SU-mobile device will found responsible) then the penalty fine should be damage/0.5, or twice the damage. In this example that would be $\$2,000$. Similarly, if the probability of detection is 25%, the punitive penalty should be \$4,000 (the value of the lost data multiplied by 4). The ideal level of punitive costs should be equal to the value of the lost data multiplied by a punitive factor. The punitive factor can be represented as the ratio of the probability of detection and the probability of escaping.

Thus, the punitive penalty P_{Pun} function will consist of two values: the value of the lost data and the value of the punitive costs.

$$P_{Pun} = (\$I \times t + \$C) + Adj \tag{7.4}$$

Equation (7.4) represents the punitive penalty P_{Pun} function that is imposed by the enforcer when SU-mobile signal exceeds the SINR limits. The P_{Pun} consists of two fields added together. The first field represents the value of the unchangeable enforcement cost ($\$I$) multiplied by the time (t) and changeable enforcement costs ($\$C$). The second field represents the adjustment factor (Adj).

$$Adj = \begin{cases} \frac{(100-\alpha)}{\alpha} \times (\$I \times t + \$C) & \text{Linear Adjustment} \\ (\$I \times t + \$C)^{\frac{(100-\alpha)}{\alpha}} & \text{Exponential} \\ e^{\frac{(100-\alpha)}{\alpha} \times (\$I \times t + \$C)} & \text{Natural Exponential} \end{cases} \tag{7.5}$$

Equation (7.5) represents Adj functions which could be calculated either linearly, or exponentially. There are two variables within the adjustment factor that might play a role when calculating the punitive penalties which are the value of the probability of detection and the changeable enforcement costs.

7.2 GRADUATED RESPONSE PENALTY APPROACH

Graduated response idea is used in the Internet for Internet Service Provider (ISP) to check, conditionally suspend, or disconnect internet access to a subscriber who had received three warning letters of alleged copyright infringement. The idea came from the baseball rule of "three strikes and you are out" and at the start it was known as "three strikes" [76]. The graduated response approach is used in UK, France and other countries.

In the graduated response approach for the spectrum sharing regime, the interference levels will be divided into three different interference event levels received at the PU's antenna. At the first interference level, the penalty would be a fine proportional to the lost data by the PU plus the expected increase in enforcement costs occasioned by it. At the second interference level, when the SU does not optimize its transmission and decides to continue transmitting closer to the PU's antenna, more punitive penalties would be applied. The SU then optimizes their transmissions so that the net value of a sequence of transmissions is positive. At the third interference level, if the penalty value exceeds the maximum limit or the SU's interference duration exceeds a hypothesized maximum duration, other ex-post enforcement sanctions would be suggested like conditionally suspending SU license.

There are many ways to implement the graduated response idea in spectrum sharing and it depends on the agreement between PU and SU. The agreement could require dividing the power limits into three levels, the call duration of the harmful interference, or it may combine both ways for more efficiency. Table (5) shows two examples of the graduated response implementation techniques which are the power level and the combination between power and call duration. The enforcement sanctions would be upgraded gradually in responding to the SU's interfering behavior (see Table (5)). The second column in Table (5) shows

Table 5: Ways of Implementing Graduated Response in Spectrum Sharing.

Response	Power Level (P) in dB		Call Duration (T) in minutes	
			$P > -10dB$	
1	$\rho_1 < P \leq \rho_0$	Warning	$P \leq \rho_0$	Warning
			$P \leq -10dB$	
2	$\rho_2 < P \leq \rho_1$	Penalty level-1	$\tau_0 \leq T < \tau_1$	Penalty level-1
3	$\rho_3 < P \leq \rho_2$	Penalty level-2	$\tau_1 \leq T < \tau_2$	Penalty level-2
4	$P \leq \rho_3$	Penalty level-3	$T \geq \tau_2$	Penalty level-3

when the agreement requires dividing the power limits into three levels; while the third column of Table (5) the agreement would require dividing both power and call duration. The agreement might include different punitive penalties instead of remunerative, or even the forefiture penalty in penalty level-3.

Table (5) column 2 and 3 show the graduated response procedures when using SUs' received signal power level (P) as shown on Table (5). Here, the agreement could require dividing the power limits into three levels. In the first response (warning response), there would be no penalty imposed to the SU instead the enforcer would send a warning message to the SU, so SU could have an opportunity to stop the interference. The warning response would give the opportunity for the SU not to interfere with the PU's signals.

In the second response (first interference level); e.g. the penalty level-1 could be proportional to the value of lost data by the PU plus the expected increase in enforcement costs occasioned by it. If penalty value reaches the forfeiture maximum limit, the enforcer would go to the third strike and bans SU from sharing the spectrum. In the third response (second interference level), when the SU do not optimize the transmission and decided to continue transmitting closer to the PU's antenna and the penalty value is less than the forfeiture limits, the enforcer would upgrade to the penalty level-2 ; e.g. punitive penalty approach. If the SU then optimized transmissions, the net value of a sequence of transmissions.

In the fourth response (third interference level), when the interference exceeds the threshold that had been suggested in [8, 77] or the penalty value (remunerative plus punitive) reaches the forfeiture limits, the enforcer would have the right to step up the response against the SU actions to the penalty level-3; e.g. temporarily suspending the spectrum sharing license from SU. On the other hand, same steps could be followed when using harmful interference time period as ex-post graduated response approach.

Further, the graduated response approach steps using both the power level and call duration mentioned on Table (5) can be explained as follows:

1. If the SU-mobile device transmitting (P) is greater than or equal ρ_0 where $\rho_0 > -10dB$, the PU will not lose any data because this power level is less than the harmful level. The enforcer will send a warning to the SU. When the SU receives the warning, SU would have the option to:
   a. Disconnect SU-mobile device.
   b. Send a message to maintain SUs power.
   c. Transfer SU-mobile device to an alternative band.
2. If SU-mobile device transmitting (P) reaches $-10dB$ or less, the call duration timer (T) would start from $\tau_0 \leq T < \tau_1$.

   The enforcer would start penalizing each SU-mobile device using penalty level-1; e.g. the remunerative penalty approach as long as the call duration T is less than τ_1 and the penalty value is less than the forfeiture maximum limit of $\$160,000$.

When the SU receives the first penalty level, SU would have the option to:

a. Disconnect SU-mobile device.

b. Send a message to SU-mobile devices to lower its power.

c. Transfer SU-mobile device to an alternative band.

3. If call duration timer (T) is greater than or equal τ_1 and less than τ_2, and the first response value is less than the forfeiture maximum limit of $\$160,000$.

   The enforcer would upgrade to penalty leve-2; e.g. from remunerative to punitive penalties. When the SU receives the penalties, it would have the option to:

   a. Disconnect SU-mobile device.

   b. Send a message to SU-mobile devices to lower its power.

   c. Transfer SU-mobile device to alternative band.

4. If SU-mobile device call duration exceeds τ_2 or the penalty value reaches the forfeiture maximum limit of $\$160,000$. The enforcer upgrade to penalty level-3 (go to the third strike); e.g. conditionally suspend the SU spectrum sharing license.

Following either technique of the graduated response procedures, the PU would guarantee that the SU would not exceed the threshold limits. If the SU's response to this penalty approach is decreasing the number of SU-mobile devices until it reaches profitable transmission values, then the SU must also consider that until the penalty values reach forfeiture limits, the response will continue to be graduated to the next level.

Also, the SU could not causing interference for more than a certain time period until the penalty values reaches the forfeiture limits and the response would be graduated. Unfortunately, these responses are not covered by the Communication Act of 1934. The ex-post enforcement only with graduated response penalty approach might not be applicable with the current Communication Act. To overcome this matter, the policymaker of the CSMAC-enforcement subcommittee propose an update to the Communications Act of 1934 or adjust the procedures of adjudication to overcome these concerns.

8.0 MODEL AND ASSUMPTIONS

8.1 MODEL

We will build our argument on one of the proposed bands for sharing, the 1695- 1710 MHz frequency bands. This spectrum band was introduced by the NTIA for spectrum sharing between Federal/non-federal and commercial usage. The sharing strategy on this band is limited to commercial systems operations which are uplink use only [77]. The PUs are Meteorological-Satellite (MetSat) and Meteorological Aids (MetAids) and this band is used for space-to-earth and radiosondes links (downlink). The reasons for choosing this band are:

1. This band is suitable for the LTE mobile network (which is the SU in this model).
2. The available bandwidth suggests that there will be a single SU which is a single mobile operator, simplifying the enforcement problem.
3. The PU of the spectrum uses fixed earth stations (which is the incumbent of the band for this model).
4. Two of the exclusion zones for this band are for Suitland, Maryland and Wallops Island, Virginia. These exclusion zones cover Richmond City of Virginia State, the Washington DC metropolitan area which is the seventh largest metropolitan area, and the Baltimore, Maryland metropolitan area.
5. The FCC suggested the use of protection zones in their Amendments instead of the

exclusion zones to reduce the impact on the population [74]. The suggested protection zones radii are 98 km for Suitland, Maryland and 30 km for Wallops Island, Virginia.

The PU will share the spectrum within the suggested protection zones if:

1. The SUs agree on the spectrum sharing rights that include the SINR limits of $-10dB$.
2. If any interference event occurrs, the SUs will be penalized by the enforcer.
3. The SU will not be penalized as long as its interfering signal does not exceed the interference limits ($-10dB$).

The protection zone in this model is built on $90km \times 90km$ which is the max-point among the proposed two protection zones by the NTIA and because it is almost equal to the radius that had been suggested by the NTIA for the Suitland, Maryland protection zone.

8.2 SPECTRUM SHARING SCENARIO

To examine the role of ex post enforcement in a spectrum sharing regime, we study an ex-post-only regime. To determine whether (and when) this approach is superior to an ex-ante approach, we build a simple model of a geographic region with geographically distributed secondary users and a single primary user. The aggregate signal power of the secondary users is computed at the primary user's antenna.

Figure (9) shows our hypothetical scenario using the protection zones and the involved entities which are PU, SU, and enforcer. This hypothetical scenario will be used throughout this work to evaluate the usage of ex-post-only enforcement measures. This hypothetical scenario demonstrates the potential consequences of an SU-mobile device transmitting a high power signal near the PU earth station within the protection zone. Ex-post-only enforcement

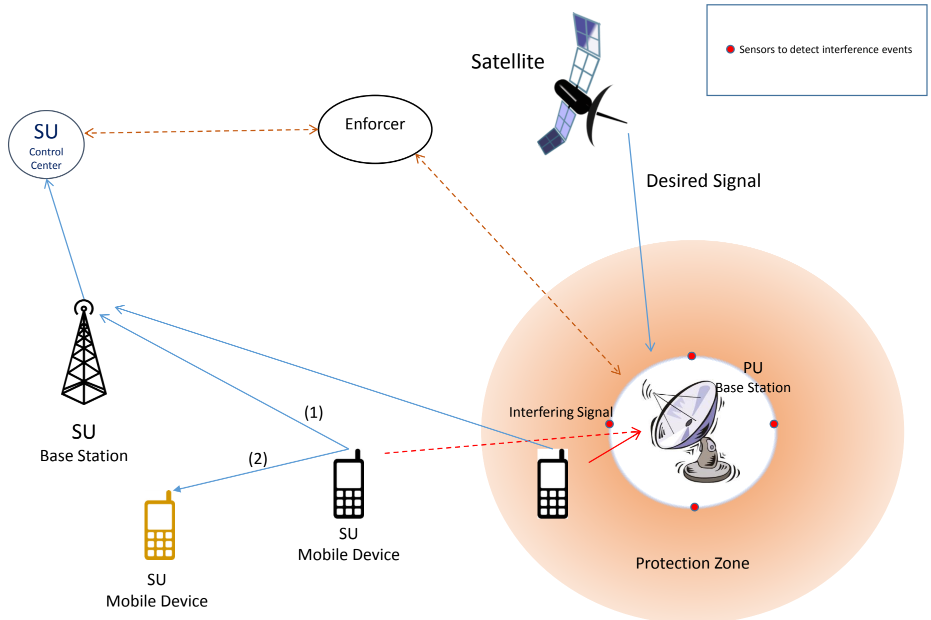


Figure 9: Spectrum sharing entities and sharing scenarios using protection zone

measures will be applied to this scenario and analyzed to evaluate how these measures might work, along with limitations on their effectiveness.

Figure (9) shows the three entities that will be involved in spectrum sharing: the PU, the SU, and an enforcer. The SU might be a single mobile operator, multiple mobile operators or individual SUs . The band will be shared between PU and SUs. The PU will be an earth base station and will be using this band for a downlink signal from the satellite. The Secondary User (SU) is a non-federal commercial agency that is assumed to be an LTE operator.

In Figure (9), we can see that an SU-mobile device outside the protection zone can use the band as an uplink to an SU-base station as link (1), or it can use the band to communicate with another SU's mobile devices as a link (2) to cooperate with other SUs. Within the protection zone we assume that only Cooperative Primary Spectrum sharing between PU and SU will be used.

8.3 ENFORCEMENT

An ex-post-only enforcement measures will be used in our hypothetical model. We will assume the following enforcement characteristics where the PU will share the spectrum: (1) if the SUs agree on the spectrum sharing rights that includes the SINR limits, (2) and if any interference event occurs the SUs will be penalized by the enforcer.

8.3.1 Enforcer

The enforcer role would be to govern PU and SU behaviors to 1) guarantee that spectrum sharing rights are enforced; 2) and assure that PU will not receive any harmful interference signals from the SU. The enforcer would need to detect the interference events that affect the PU's received signal and are caused by the SU's uplink signal. Details about the enforcer role and sensing mechanisms are matters for future work and will not be discussed here.

8.3.2 Ex-post-only enforcement

In our hypothetical model, we will assume the use of additional ex-post enforcement measures. These ex-post-only enforcement measures are:

1. Sensor network around PU-earth-station.
2. Database.
3. Economic penalties.

8.3.3 Detection of Interference event

To identify the interference events that affect the PU's received signal and are caused by the SU's uplink signal, a sensing system must be built around the PU (which is an Earth Base Station in our model). The sensor network will detect the aggregate signal energy attributable to the SU. If the signal energy reaches the noise level, interference is detected and the SU will be penalized. If the signal energy is below noise level, it is not detectable.

We hypothesise the use of a database system: 1) to collect information about the PU spectrum utilization, 2) to coordinate with the regulator to update the policy, 3) and to gather the needed information of the SU's for any interference events settlement.

8.4 OPPORTUNITY COST

The opportunity cost in the case of the spectrum is the value of the next highest alternative use of that spectrum when using ex-ante enforcement or ex-post enforcement. This value will be represented using the ratio between economic-cost of the ex-post enforcement over the economic-cost of the ex-ante enforcement. We will look at the opportunity cost of each option to find the most valuable opportunity. If we choose ex-ante enforcement only, we lose a number of SUs who will not transmit within the protection zone but we will gain no interrupted or lost data to the PU. If we choose the ex-post enforcement only within the penalty zone, we will allow transmission for SUs within the protection zone.

We can calculate the opportunity cost from the SU's perspective over the protection zone by counting the number of all the potential SUs' values. The SU could be Secondary-User-Service-Provider (SUSP)'s or individual SUs. For each one of these, we examine whether or not the SU shall provide service to its client?

1. In the ex-ante case, we can transmit if the SU is outside the protection zone. The value of the transmission realized by the SUs in the protection zone model will be:

$$C_{ex} = n_{ex} \times V = n_{ex} \times \$1\frac{POP}{MHz} \times 15MHz \tag{8.1}$$

Where C_{ex} is the economic cost of the ex-ante enforcement and n_{ex} is the number of SUs outside of the protection zone multiplied by the value of the transmissions per SU.

2. In the ex-post case, if the SUs entered the protection zone, to which one of them belongs shall the transmission continue on as SUSP? The following model demonstrates:

$$SU_{Tranmits} = \begin{cases} Yes & \text{if Outside exclusion/protection zone (ex-ante)} \\ Yes & \text{if } Penalty < TransmitValue \\ yes & \text{if } C_{ep} < C_{ex} \\ No & \text{else} \end{cases} \tag{8.2}$$

Further, the cost of the ex-post enforcement is C_{ep} will be equal

$$C_{ep} = N_{SU} \times P \tag{8.3}$$

Where N_{SU} is the number of detected SUs whose their signals power level exceed the the SINR limit (-10 dB) multiplied by the value of the assigned penalty P (Remunerative or Punitive economic penalty).

By getting the ratio between the two costs of ex-ante enforcement and ex-post enforcement, we can predict if the SU can transmit using the ex-post enforcement when the ratio is less than or equal to 1.

$$C_{ep} < C_{ex} \rightarrow \frac{N_{SU} \times Penalty}{n_{ex} \times V} < 1 \tag{8.4}$$

Where C_{ep} is the economic cost of the ex-post enforcement, C_{ex} is the economic cost of the ex-ante enforcement, N_{SU} is the number of detected SUs whose their signals power level exceed the the SINR limit (-10 dB) multiplied by the value of the assigned penalty P, and n_{ex} is the number of SUs outside of the protection zone multiplied by the value of the transmissions V.

8.5 ASSUMPTIONS AND METHODS

8.5.1 Assumptions

In our hypothetical model, there are a number of considerations:

1. We will assume the time of adjudication is immediate and cost-less.
2. The three entities will be involved in our hypothetical spectrum sharing model are the PU, a single/multiple SU mobile operator, and an enforcer.
3. PU will be an earth base station and it will be using this band for downlink signal from the satellite.
4. The Secondary User Service Provider (SUSP) is a non-federal commercial agency which is assumed to be an LTE operator.
5. The SUSP, as an LTE operator, will have $N_{SU} = 100,000$[1] potential SU users that are

[1]The N_{SU} could vary from one SU to millions of SU. And because we gave an example in chapter (4) about the impact of the exclusion/protection zones on the population in Washington DC metropolitan and Baltimore metropolitan areas (where the population density of Washington DC metropolitan is 3,977 $person/km^2$ [78] and Baltimore metropolitan areas population density is 2917 $person/km^2$ [79]). We build

uniformly distributed around the PU's station in an area of $90 \times 90km^2$[2].

6. We will consider the uplink from the handsets will transmit its signal using the shared frquency band to the SU's base station.

7. The enforcer's role is to govern the spectrum sharing rules between the PU and SUs to guarantee their behaviors.

8. We will assume that an additional ex-post enforcement measure is added by the enforcer which is a sensor network around the PU's base station. The sensor network will be used to detect the interference events that affect the PU's received signal and are caused by the SU's uplink signals.

9. The sensor's antenna will have a range to detect the interference events with probability of detection, called a penalty zone.

10. If the signal energy reaches the noise level (-10 dB), interference is detected and the SU will be penalized. If the signal energy is below noise level, it is not detectable. The following section will explain the equation of calculating Signal Interference-to-Noise Ratio (SINR) To calculate the energy level.

11. The noise level reaches -10 dB, the PU cannot receive the downlink signal which will result in losing the received data.

12. We will assume an adjudication system that penalizes the Secondary User (SU) for each interference event detected at the PU's antenna.

13. We will determine a hypothetical cost level of a region that is equivalent to an exclusion zone/protection zone in ex-ante enforcement to determine the bounds of adjudication

our hypothetical model on this assumption to make this study more feasible for the reader. Further, please see Appendix (C) where we simulated our hypothetical model for different number of SUs.

[2]As mentioned, the FCC suggested the use of protection zones in their Amendments instead of the exclusion zones to reduce the impact on the population [74]. The suggested protection zones radii are 98 *km* for Suitland, Maryland and 30 *km* for Wallops Island, Virginia. To make it more feasible for the reader, we assumed that SUSP will have uniformly distributed SU in an equivalent approximate maximum-area the exclusion/protection zones.

costs.

14. We will assume the economic penalty would be proportional to the value of the data lost by the PU plus the expected increase in enforcement costs occasioned by it.
15. We will assume the propagation is circular.
16. A model of a geographic region with geographically distributed SUs and a single PU will be simulated to determine whether (and when) the ex-post approach is superior to an ex-ante approach.
17. Aggregate signal power of the SUs' signal will be calculated at the Primary User's (PU's) antenna by using COST-231 path loss model.
18. By setting a threshold value for received power, we will be able to relate the model results to the hypotheses.
19. We will also measure the amount of time that the SU is interfering with PU and it will affect the penalty imposed on the SU.
20. The penalty would be a fine equal to the value of the lost data plus the enforcement costs when the interference level reaches certain limit received at the PU's antenna in the model.
21. We will assume that the value of this band is $1 per MHZ-POP which is the same value that has been used by Bazelon and McHenry [80].
22. The LTE required bandwidth by the ITU is 20 MHz, but we will use the available bandwidth for the band 1695-1710 MHz which is 15 MHz.
23. We do not consider interference caused by "rogue" or "pirate" radios.

8.5.2 Research Methods

1. We will assume that the enforcer will apply different Ex-post-only enforcement (economic-penalty) measures on the SU:

   a. Simulate when the enforcer applies remunerative penalty approach

      - SU stop transmit (Penalty $\geq$ Transmit value).

   b. Simulate when the enforcer applies the punitive penalty approach

      - SU stop transmit (Penalty $\geq$ Transmit value).

   c. Simulate when the enforcer applies the graduated response approach

      - SU stop transmit (Penalty $\geq$ Transmit value).

2. We will evaluate how these measures might work.
3. Show when ex-ante/ex-post mechanism is superior to the other, e.g., cost of the ex-ante measure (exclusion zone) is lower than the ex-post measure (forfeiture penalty).
4. We will reason about the effectiveness of an ex-post enforcement system and its technical requirements. An ex-ante/ex-post enforcement system will force the SU to stop violating the spectrum sharing rights.

8.5.3 Signal Interference-To-Noise Ratio (SINR)

To detect the interference event, Signal Interference-to-Noise Ratio (SINR) will be used . This section will address how we will calculate the noise level (-10 dB). SINR is used in wireless systems to measure the quality of the link or the connection. The equation for the SINR can be expressed as:

$$SINR_i = \frac{P_{r_{PU}} \times G_{ii}}{\sum_{j \neq i} P_{r_{SU}} G_{ij} + n_i} \tag{8.5}$$

SINR is equal to the desired received power by the PUs' antenna over the aggregate interference received power by the SUs plus the noise power. The signal to interference and noise ratio varies with the transmission parameters for SU. It depends on the distance between the PU and the SU, the desired received power $P_{r_{PU}}$ of the PU, the antenna parameters of the PU, the received unwanted signal power $P_{r_{SU}}$ of SU, the transmitter density, the antenna parameters of the SU and PU, and n_i is the noise.

To calculate the received power we will use the following equation:

$$P_r = P_t(dB) + G_R(dB) + G_T(dB) - Pathloss(dB) \tag{8.6}$$

Where P_r is the received power, P_t is the transmitted power, G_R is the maximum receive antenna gain, G_t is the maximum transmit antenna gain. To get the received power the path loss must be found first. And to get the path loss, two equations will be used:

1. Free Space Path Loss [81]:

$$FSPL = \frac{4\pi f_c d}{c} \tag{8.7}$$

   $FSPL$ will be used to calculate downlink signal received power from the satellite at the PUs' base station. Where f_c is the center frequency, c is the speed of light, and d is the distance. The Free Space Path Loss equation is used to get the desired received power by the earth station.

2. To get the Path Loss (PL) the COST-231 model will be used. This is a propagation model funded by the European COST-231 program. The COST-231 propagation model can be applied to the frequency range (1500- 2000 MHz) [81]:

$$PL = 46.3 + (33.9 \times log_{10}(f_c)) - (13.82 \times log_{10}(h_t)) - a \times (h_{re}) \\ + [44.9 - 6.55 \times log_{10}(h_t)] \times log_{10}(d) + C \quad (8.8)$$

PL will be used to calculate uplink signal power of the SUs, that is received power by the PUs' antenna. Where f_c is the center frequency, $a(h_{re})$ is the mobile antenna correction factor for the effective antenna height in dB [81]:

$$a(h_{re}) = \begin{cases} 8.29 \times (log_{10}(1.54 \times h_{re}))^2 - 1.1 & \text{if } f_c \leq 300MHz \\ 3.2 \times (log_{10}(11.75 \times h_{re}))^2 - 4.98 & \text{if } f_c > 300MHz \end{cases} \quad (8.9)$$

Where h_t is the effective transmitter antenna height ranging from 30 to 200 meter, h_{re} is the effective receiver antenna height ranging from 1 to 10 Meters, d is the distance between the transmitter and the receiver in kilometers, and the value of $C = 0dB$ for medium-size city and $C = 3\ dB$ for metropolitan areas.

Table (6) shows the values that we will use to build the hypothetical model. We will use these values to calculate the Path Loss (PL) of the satellite signal and SUs' signals PL. In doing so, we will be able to calculate the received signals power and the SINR.

8.5.4 Value of the Lost Data

The lost data can be expressed as:

$$C_{LD} = C_{Rec} \times T_{call} \quad (8.10)$$

Where C_{LD} is the economic cost of interfering with the PU's received signal measured in \$ US dollar. C_{Rec} represents the cost received data in \$ US dollar per second. And T_{call} is the

Table 6: Research settings.

Parameter	Value	Comments
FSPL		It will be used to get the desired received power by the earth station.
f_c	1702.5 MHz	
EIRP	8.1dBW [82]	Equivalent Isotropic Radiated Power (EIRP) value includes the effects of antenna gain, antenna efficiencies, transmitter power, coupling and wave guide losses. No additional information about the transmitter is required when the EIRP is known [82].
d	35785 km	The distance between the satellite and the earth station which is approximately 22,236 miles.
c	3×10^8	Speed of light
COST-231		COST-231 is used to calculate the path loss to get the interfered received power.
f_c	1702.5 MHz	
C	3	This value is used in the metropolitan area.
h_{re}	30m	Received antenna height.
h_t	1.5m	Transmitter height.
P_t	23 dBm	Transmitted power which is the highest transmission power for the LTE mobile phones.
n	0 W	We assume the antenna receiver is engineered to deal with and reject normal noise.

interfering time in seconds.

Since there is no published estimate of the value for data such as MetSat and MetAids data, we use the cost to receive $1MHz$ from a satellite link as a proxy. Our research has shown that building, launching, and operating a new satellite with 15 transponders for ten years will cost around \$300 million [83]. The cost of leasing a transponder costs approximately $\$2\frac{Million}{Year}$. The transponder bandwidth is $36MHz$, which means that this 1 MHz lease cost is approximately \$0.0018 per second. Therefore, the cost of the received data $C_{Rec} = \$0.0018\frac{USdollars}{second}$ that we will use in this work.

To estimate the duration of an interference event T_{call}, we assume that this would be the average length of an SU session. For a voice call, the average duration for a data session is *2 minutes* [3]. We will use this average time as a starting point.

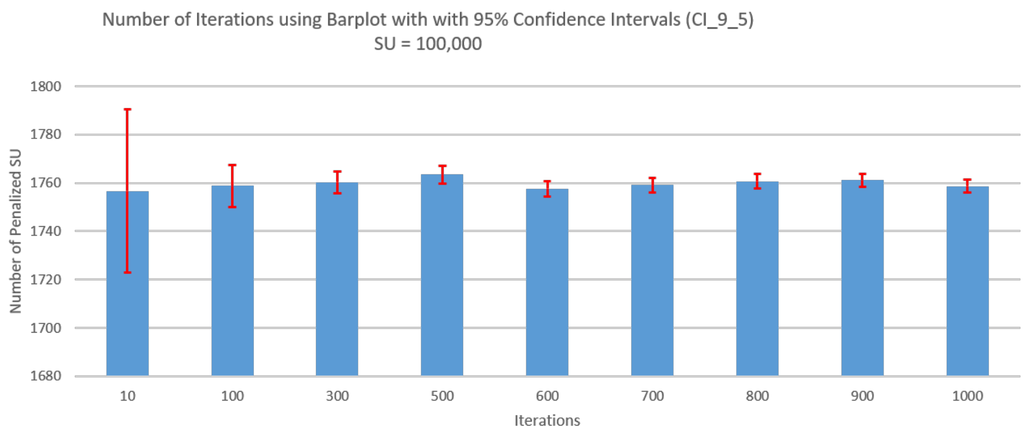
So by replacing the calculated values of C_{Rec} and T_{call} in equation (8.10), the value of the lost data will be ($\$0.0018 \times 2minutes \times 60\frac{seconds}{minutes}$). The SU will use the 15MHZ bandwidth which means that ($\$0.0018 \times 2minutes \times 60\frac{seconds}{minutes} \times 15MHz = \$3.24$). Thus, the value of the lost data for each interfering event will cost **\$3.24**.

Additionally, we will assume that the maximum changeable enforcement cost that can be reached in this study is **\$3.24** to make it more feasible for the reader.

8.5.5 Simulation

We will build our hypothetical model with the use of Matlab software to test the outcome via simulation. Figure (35) shows the number of penalized SU when we run the simulation for different number of iterations with Confidence Interval of 95% (CI_95). Figure (35) also contain a table that represents the mean, standard deviation and CI_95 for each number of iterations. We can see that after 100 iterations the CI_95 becomes almost steady ($\approx \pm 3$). So, we will run our experiment for 200 iterations for the rest of this work to get high significant results. Except for the sensitivity analysis in the Path loss model, we will run the simulation for 20 iterations only.

[3] The Statistics Portal (Last visited 12/2/2018): https://www.statista.com/statistics/185828/average-local-mobile-wireless-call-length-in-the-united-states-since-1987/



Matlab Results									
SU = 100000									
Iterations	10	100	300	500	600	700	800	900	1000
Avg	1756.7	1758.78	1760.31333	1763.488	1757.68833	1759.17429	1760.665	1761.19111	1758.682
std	47.2982264	43.8501995	39.081535	41.2788292	39.6892503	40.2856172	42.4620013	40.4600509	42.6502511
CI95	33.8351129	8.70083093	4.4403843	3.62697958	3.18217289	2.98952185	2.94687645	2.64690498	2.64664793

Figure 10: Number of iteration with Confidence Interval of 95%.

9.0 SIMULATION RESULTS

9.1 STAGE 3: EX-POST-ONLY ENFORCEMENT - REMUNERATIVE PENALTY APPROACH RESULTS

9.1.1 Description

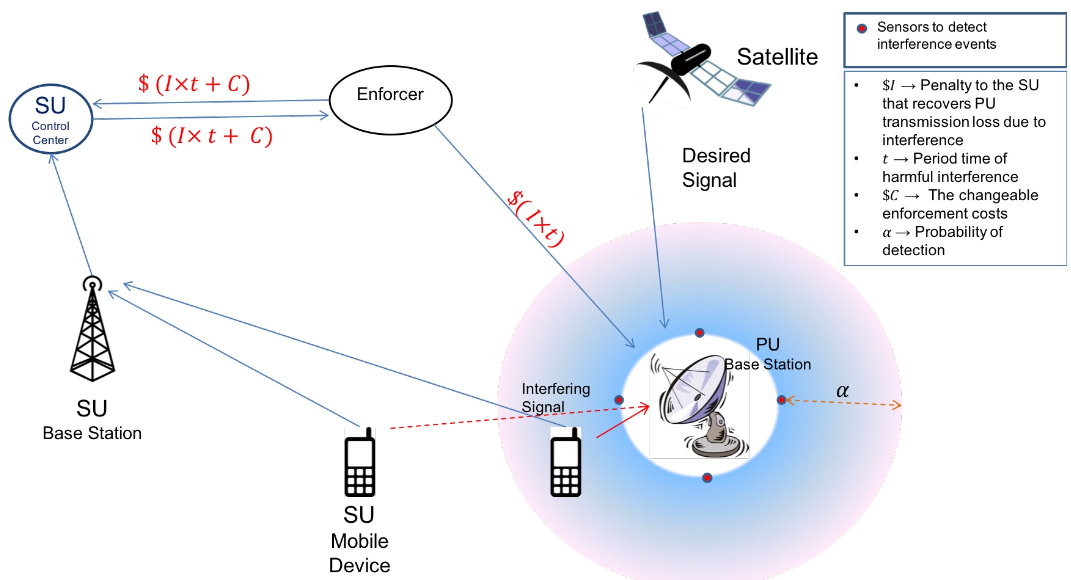
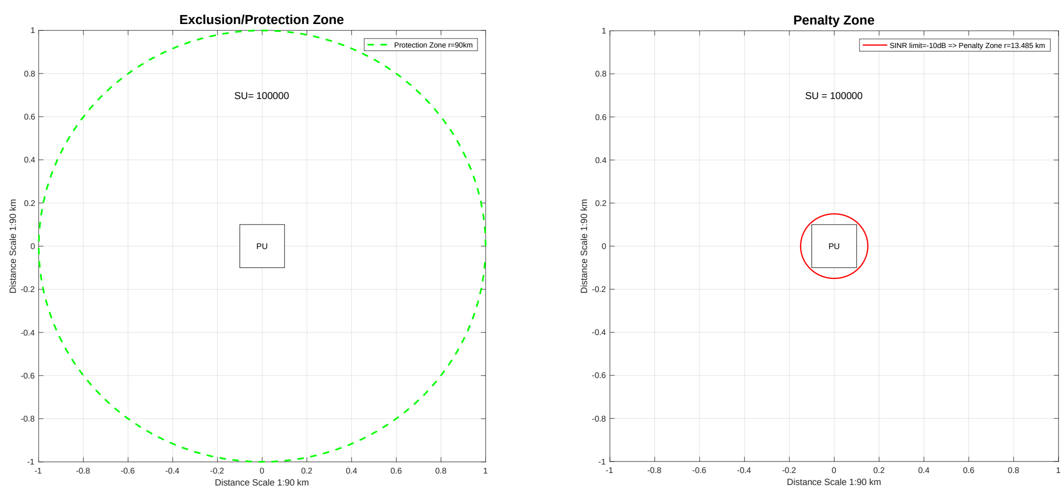


Figure 11: Spectrum sharing entities and sharing scenarios using ex-post enforcement- remunerative approach.

This work was introduced in [84] for evaluating ex-post-only enforcement. Figure (11) shows our hypothetical scenario where the SU is represented as a mobile device transmitting near the earth base station (PU). The PU is receiving two signals; the desired signal (the downlink signal by Federal Metrological-satellite) and the interfering signal by the mobile device (SU). The SU will not be penalized as long as its interfering signal does not exceed the interference limits (-10 dB).

When the SU moves closer to the PU base station and the interference event is detected; the enforcer will charge the SU with P_{Rem} of equation (7.3). Then the enforcer sends $\$I$ to the PU after receiving the penalties from the SU.

9.1.2 Ex-ante-only vs Ex-post-only



(a) SU are distributed in 90 kmx90 km, 21.583% will be allowed.

(b) SU are distributed in 90 kmx90 km, 1.726% of the SU will be penalized

Figure 12: Ex-ante vs Ex-post-only Enforcement Simulation results.

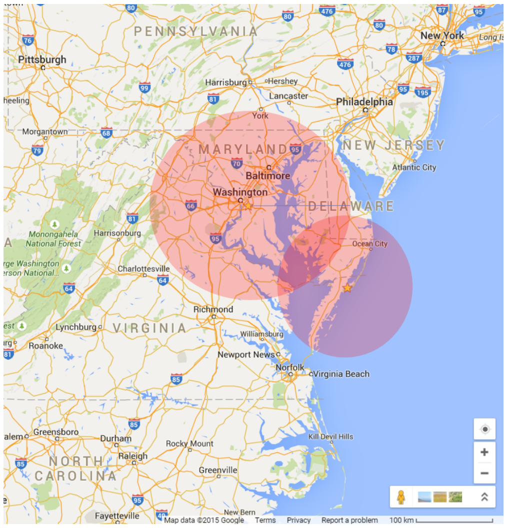
To determine whether (and when) this approach is superior to an ex-ante approach, we built a simple model of geographically distributed secondary users and a single primary user. Figure (12) shows the percentage of excluded SU devices from sharing the spectrum when using exclusion/protection zones versus the penalized SU when using ex-post-only enforcement.

Figure (12a) shows 100,000 SU transmitters uniformly distributed in an area of $90\times90km$. If we use the recommended two restrictions ex-ante enforcement measures which are: 1) -10dB, 2) and 90km exclusion/protection zone, approximately, 21% of SUs will be allowed outside the green circle.

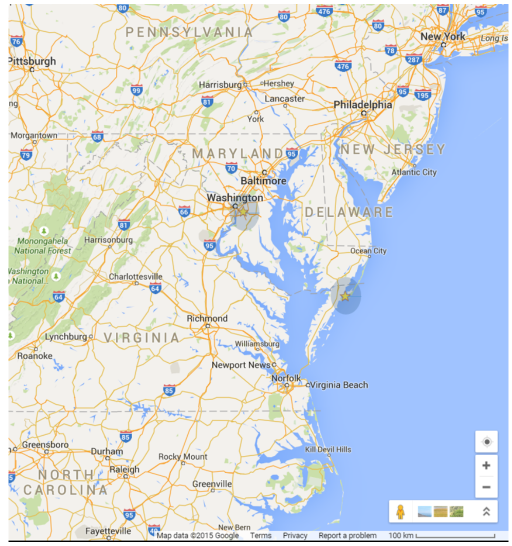
On the other hand, Figure (12b) shows ex-post-only enforcement. In this scenario, we have 100,000 SU devices uniformly distributed in the same area ($90\times90km$). We disregarded the use of the geographical limitation (exclusion/protection zone). The PU and SU agreed on an interference limitation of $-10dB$, and any SU exceeding that level will be penalized. Each run in the simulation takes time period, and the simulation is run for different times. The SU radios are given mobile characteristics and the following results are obtained. The simulation results show that all 100,000 SUs will be allowed to transmit in the assigned area. The penalty zone range is approximately 13 km and only 1.7% out of 100,000 SUs will be penalized.

Further, if the PU decides to make the penalty zone a no transmit zone, then the radius would be smaller for ex-post only enforcement than for ex-ante only enforcement. To make it clearer to the reader, Figure (13) shows an approximation when implementing the ex-ante only versus ex-post-only enforcement.

Figure (13a) shows two of the exclusion zones denoted by the red circles (ex-ante-only enforcement) which are Suitland, MD and Wallops Island, VA. These exclusion zones cover Richmond, VA, Washington metropolitan area (Washington DC is part of it) which is the



(a) Exclusion zones for Suitland, MD and Wallops Island, VA.



(b) Penalty zones for Suitland, MD and Wallops Island, VA.

Figure 13: Comparison between the radii of the exclusion zones and penalty zones

seventh-largest metropolitan area, and Baltimore, MD metropolitan area. We can see that the PU will not share the band (1695-1710MHz) within these two exclusion zones and the SUs can transmit only if they are outside these zones.

On the other hand, Figure (13b) shows when the ex-post only is used the penalty zones, which are denoted as blue circles, will be much smaller than the exclusion zone. Thus, the SUs will be able to transmit within these two zones but they will have the risk of being penalized if their signal power exceeds the SINR limits and is detected. In addition, the spectrum can be shared in some major cities that are within the exclusion zones.

9.1.3 Remunerative Penalty Function Variables

There are three factors that will have a direct impact on the SUs' decision either to share the spectrum or not. These factors are the penalty value, the probability of detection, and the penalty zone radii (Radius of $SINR$ Limit).

The remunerative penalty function has two variables that affect the radius of the penalty zone (Radius of $SINR$ Limit); the changeable enforcement cost and the probability of detection. The radius of the penalty zone will have a direct impact on the SU users decision. The smaller the radius of the penalty zone, the more geographic locations available to share the spectrum.

9.1.3.1 Changeable Enforcement Cost Effect

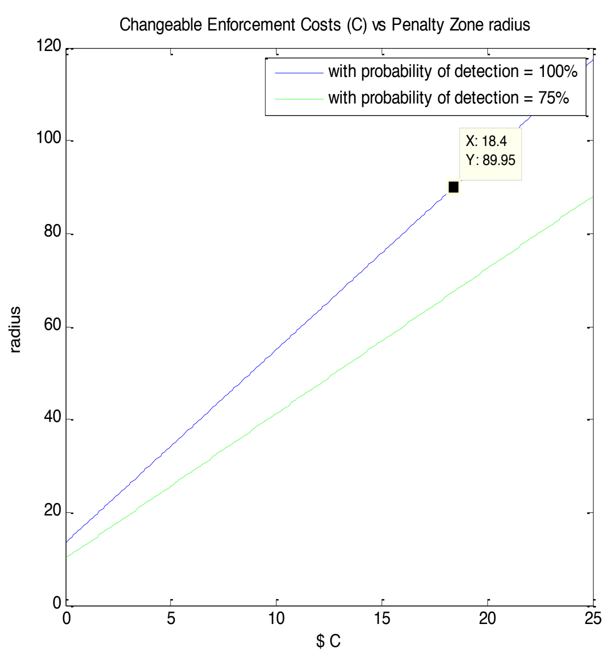


Figure 14: Effect of the changeable enforcement cost on the radius of the penalty zone.

Figure (14) shows that varying the changeable enforcement costs affect the penalty zone radius with two values of probability of detection ($\alpha = 100\%$ and 75%). The penalty zone radius increases as the changeable cost of enforcement increases.

The maximum feasible changeable enforcement cost occurs when the radius of ex-post-only matches the ex-ante-only radius when penalty zone radius equals 90km. This can be seen with $\alpha = 100\%$ the changeable enforcement cost C \$18.4, and with $\alpha = 75\%$ the changeable enforcement cost C > \$25 .

Figure (14) shows that when the changeable enforcement cost increases (from \$3.24 to \$18.4) with the same probability of detection, it will positively impact the radius of the penalty zone which may increase the income for the PU. Figure (14) shows that the effect of the changeable enforcement costs (\$$C$) on the increment of the penalty zone radius will be greater when the probability of detection is higher and vice versa.

9.1.3.2 Probability Of Detection Effect

Figure (15) shows that when the probability of detection is zero the radius of the penalty zone is zero and as the probability of detection goes up the radius of the penalty zone goes up. The two lines on Figure (14) each represent different changeable enforcement costs. The two values of the changeable enforcement costs, used to plot Figure (15), are \$1 to represent neutrality, and \$3.24 which is same value of the lost data. Figure (15) shows that increasing the quality of the sensor network to improve the probability of detection will increase the changeable enforcement cost \$$C$.

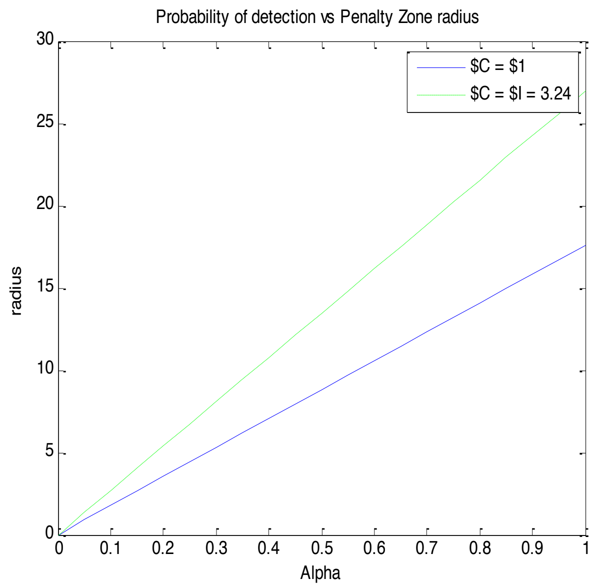


Figure 15: Probability of detection (α) effect on the radius of the penalty zone.

9.1.4 SU Transmission Options

Figure (16) shows the opportunity cost of the ex-post-only enforcement over the exclusion/protection zone. The decision of the SUs to either share the spectrum or not rely on equation (8.2) which was introduced in section (8.4). It can be predicted if the SU will share the spectrum and transmit by using the ratio equation (8.4) in section (8.4) which represents the ratio between the ex-ante enforcement and ex-post enforcement. It can be predicted when the SU can transmit using the ex-post enforcement if the ratio is less than or equal to one. The ex-post-only enforcement is superior to an ex-ante approach as long as the ratio is less than one.

Figure (16) shows the impact of the varying probability of detection and changeable enforcement cost on the radius of the penalty zone and ratio between the cost of ex-post-only enforcement over the cost of ex-ante-only enforcement. If the enforcer decided to use a

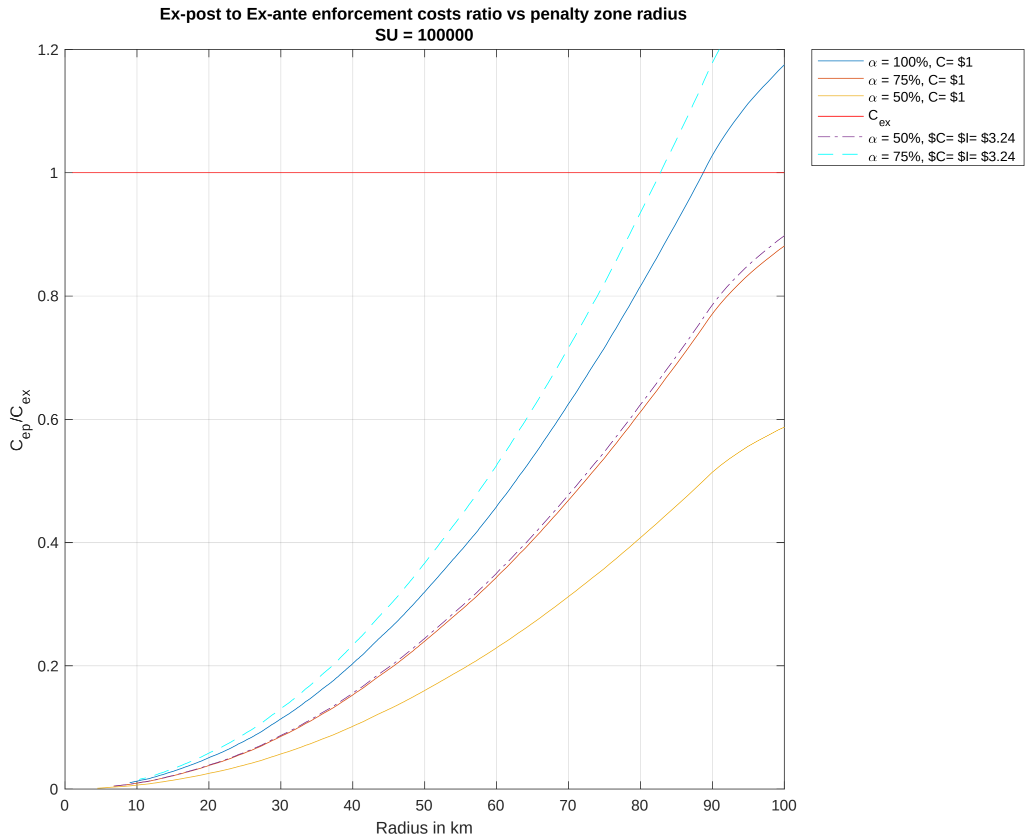


Figure 16: Probability of detection (α) effect on the radius of the penalty zone.

sensor network with low quality that provides probability of detection of (50%) with the low changeable enforcement cost of ($1), the SU will find it valuable to transmit without being caught and penalized. Or they may find it valuable to risk higher interference penalty by transmitting closer to the PU's antenna as long as the value for SU transmission increases and the radius of the penalty zone is less than 100km which is unrealistic.

Figure (16) shows that if the enforcer increases the quality of the sensor network, which will reflect as an increase in the probability of detection (75%) with the increase of the changeable enforcement cost to ($3.24), the SU will then need to optimize transmission so that the net value of a sequence of transmissions would be greater than one. That means the SU will transmit as long as the radius of the penalty zone is less than 80km, and if the radius of the penalty zone is set to more than 80km, the ex-post-only enforcement will be ineffective and SU will have no incentive to share the spectrum. This results in dynamic and self-determined "exclusion zones".

The SU also needs to predict the probability of detection and the changeable enforcement cost in order to calculate the maximum penalty zone radius that is used by the enforcer to decide whether the SU is transmitting or not. Additionally, Figure 16 shows that when the changeable enforcement costs rise ($3.24), the maximum range for the penalty zone radius decreases. For example, if the radius of the penalty zone is more than 80km, that may lead to inefficient ex-post-only enforcement.

9.1.5 Summary of Results

In this section, the results of our model shows that the penalty zone radius increases as the changeable cost of enforcement increases. The maximum feasible changeable enforcement cost occurs when the radius of ex-post-only matches the ex-ante-only radius. The main theme for this section is how these cost elements play together when the ex-post-only enforcement with the use of remunerative penalty approach is in place, We achieved the limit on the enforcement costs.

Additionally, the benefits of using ex-post-only with remunerative approach for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas, (3) the cost of building the sensors around the PU's base station to detect harmful interference is less than the one for protection zones because it would have a smaller range.

On the other hand, using this approach has several possible disadvantages for the PU: (1) if the lost data cannot be recovered; (2) this approach would not stop the SU from conducting harmful interference to PU because as the value for SU transmissions increase, SU may find it valuable to risk a higher interference penalty by transmitting closer to the PU's antenna; (3) if the SUs keep transmitting near the PU for an extended period of time it would lead to denial of service (DOS) for the PU; (4) and imposing the penalties depend on the probability of detection. If the probability of detection is 50%, the PU will only get paid once for every two events where it is losing data.

9.2 STAGE 4: EX-POST-ONLY ENFORCEMENT - PUNITIVE PENALTY APPROACH RESULTS

9.2.1 Description

This work was introduced in [85] to overcome the disadvantages when using the ex-post-only enforcement with a remunerative economic penalty, the enforcer could use punitive economic penalties. The same hypothetical scenario will be used on Figure (9) with the use of the punitive penalty approach. The punitive penalty function should guarantee that the SU will pay the value of the data lost due to interference when it is detected. It will be imposed for each SU-mobile device's harmful interference to the PU's received signal and will consider the time period for the interference. The main reason for using punitive penalty is to deter the SU from interfering with the PU's received signals, which could lead to the loss of data. When constructing the punitive penalty function, the enforcer and the sharing entities must

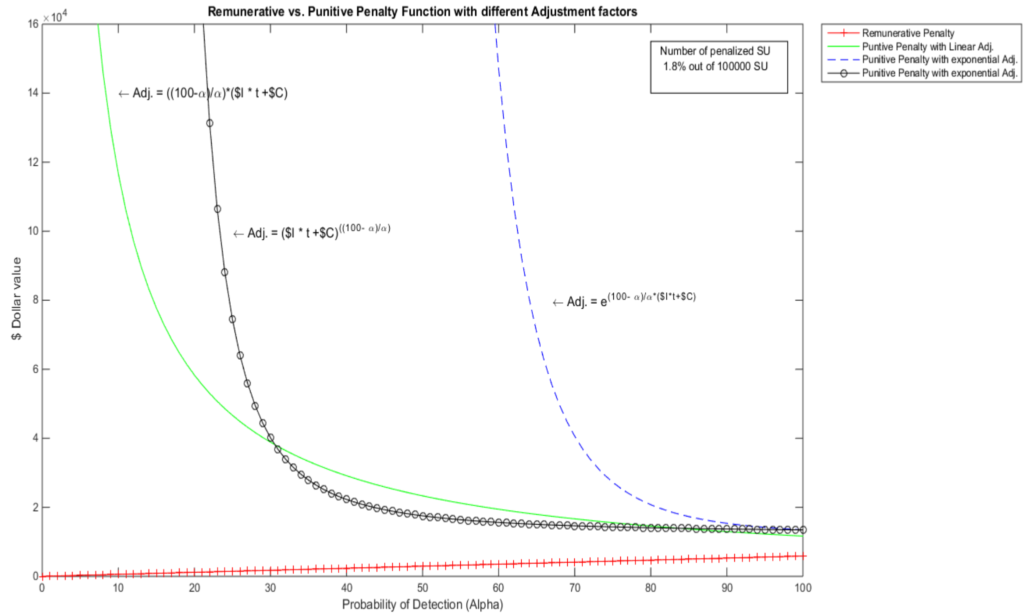


Figure 17: Remunerative Penalty vs. Punitive Penalties with different adjustment factors

take into consideration the under or over deterrence.

Equation (7.4) in section (7.1.2.2) represents the punitive penalty function that is imposed by the enforcer to each SU-mobile device exceeds the SINR limits. The punitive penalty function consists of two fields added together. The first field represents the value of the unchangeable enforcement cost ($\$I$) multiplied by time ($t$) plus changeable enforcement costs ($\$C$). The second field represents the adjustment factor (adj). The function of the adjustment factor could be calculated linearly, or exponentially.

9.2.2 Punitive vs Remunerative Penalties

Figure (17) shows a comparison between the remunerative penalty and punitive penalty with three different ways of calculating the adjustment factors. The hypothetical model of

Figure (12b) is used to calculate the penalized SU-mobile devices which is (1.8%) out of (100, 000 SUs). The result is calculated when the estimated SU-mobile devices signals power exceed the SINR limit for two minutes ($t = 2min$) which is the average call duration and causes a loss in the reception of PU's signal. The value of the lost data and the changeable enforcement costs were chosen to be ($3.24) to show the reader how the adjustment factor was calculated and how it varies with the variation of the probability of detection.

Figure (17) shows that the SU penalty will be much higher than the value of the lost data as the probability of detection decreases. Also when the probability of detection is less than (25%) with the punitive penalty function, it may be preferable to use a linear adjustment factor equal to the punitive factor multiplied by the value of the lost data. The other two approaches will be considered to be over-deterrents. And if the probability of detection is less than (55%), it will be preferable not to use the natural exponential function for the same reason. From that we can conclude that the preferred deterrence approach is the punitive penalty function with the linear adjustment factor.

9.2.3 Punitive Penalty Function Variables

A different approach will be used to show the importance of the changeable enforcement costs on the punitive penalty functions. From equation (7.3) and (7.4), we can see that the higher the value of the changeable enforcement cost, the higher the value of the penalty regardless of how one calculates the penalty function. We also know from section (9.1.3.1) that when we increase its value it will affect the radius of the penalty zone positively.

Figure (18) shows the effect of the changeable enforcement cost on the radius of the penalty zone. It shows a comparison between the remunerative penalty and punitive penalty with three different ways of calculating the adjustment factors. The same equations (7.5)

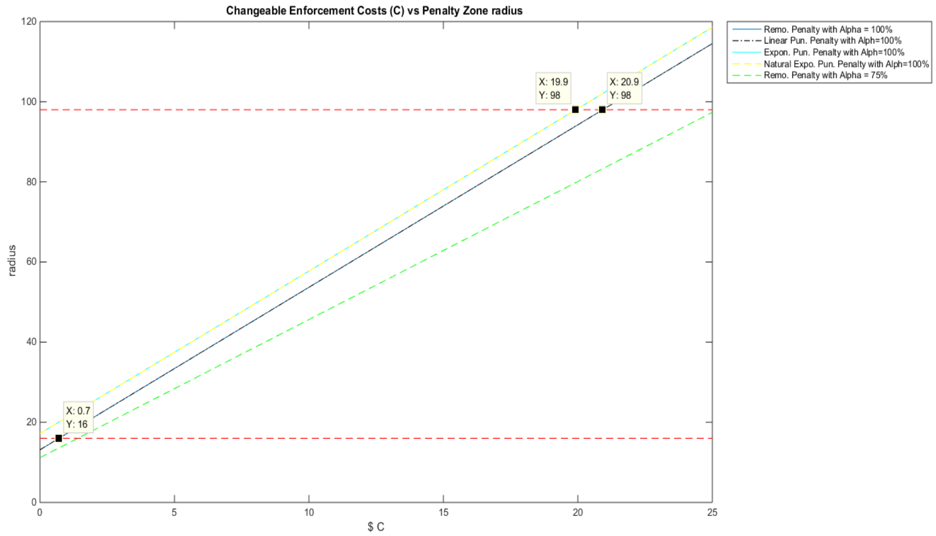


Figure 18: Changeable Enforcement Costs $\$C$ vs. Penalty Zone Radius

are used to calculate the adjustment factor of the punitive penalty function which are linear, exponential, and natural exponential equations. The hypothetical model of Figure 9 is used to calculate the radius of the penalty zone. The value of the lost data (\$3.24) is the same value as the model in Figure 6. Figure 7 also shows that, even with different values of the probability of detection ($\alpha = 100\%$ and 75%), the radius of the penalty zone will increase as the changeable enforcement cost increases. When the probability of detection is (100%), the remunerative penalty function line is equal to the linear punitive function. It also shows that the punitive penalty functions with exponential adjustment factor are equal.

Figure (18) shows that the maximum feasible changeable enforcement cost occurs when the radius of ex-post-only region matches the ex-ante-only radius because, at that point, ex-ante enforcement is the more attractive approach. This equivalent occurs when the penalty zone radius equals ($98km$) (the maximum range of the protection zone) or ($16km$) which is the minimum range of the protection zone. The maximum feasible value of the changeable enforcement cost will be ($0.70 – $20.40) if the remunerative penalty function or punitive penalty function are used with the linear adjustment factor. The maximum feasible value of the changeable enforcement cost will be ($0.00 – $19.40) if the punitive penalty function with exponential adjustment factor is used. As mentioned in section (9.2.2), the punitive penalty function that uses the exponential adjustment factor might not be preferable, if low probability of detection (less than 10%) is in place because they will be considered to be an over-deterrent.

9.2.4 SU Transmission Options

Figure (19) is similar to Figure (16), but with the punitive penalty approach added to it. It shows that if the enforcer decided to build a sensor network with quality less than (50%), the punitive penalty approaches are superior to the remunerative penalty approach from the PU and enforcer's perspective. It also shows that the maximum feasible penalty zone radius with the use of the punitive penalty approach is smaller than the remunerative penalty approach.

The decision of the SUs either to share the spectrum or not rely on the ratio of the ex-post-only enforcement over the ex-ante enforcement. It can be predicted from the figure when the enforcer is using the exponential penalty approach, the SUs will put in consideration the high cost of their violation action's consequences even if the enforcer is deploying sensor networks with quality of prediction less than (50%).

9.2.5 Opportunity cost of Ex-post-only over Ex-ante-only

In this section, we will not plot the Production Possibilities Curve (PPC), instead we will plot the ratio between the cost of ex-post-only enforcement over the cost of ex-ante en-

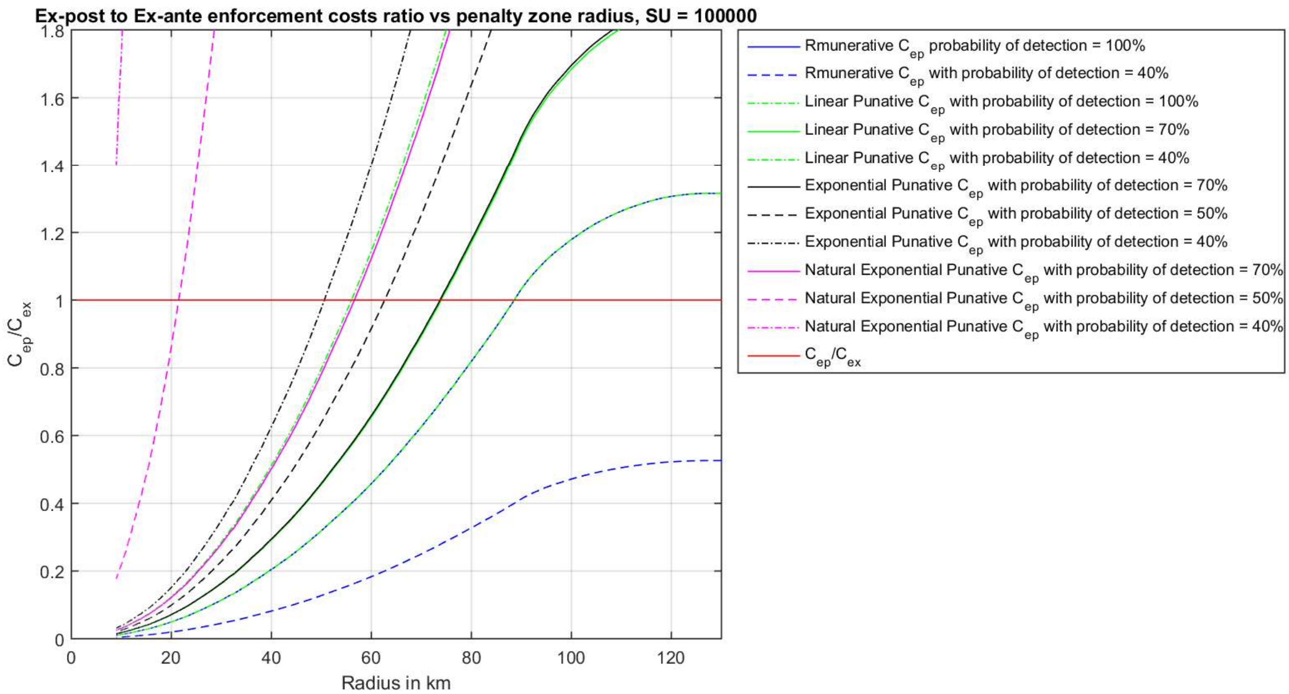


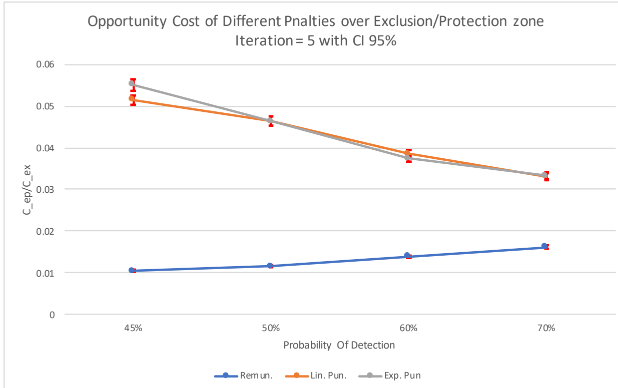
Figure 19: Probability of detection (α) effect on the radius of the penalty zone for different penalty approaches.

forcement using different probability of detection. Figure (20) is a plot of Table (7) that shows opportunity cost between ex-post-only and ex-ante enforcement. The ex-post-only enforcement measures are remunerative penalty and three different punitive penalties (Linear, exponential, and natural exponential). Each one of these measures is represented with four different probabilities of detection (45%, 50%, 60%, and 70%). We did not use probability of detection (α) lower than (45%) because the ratio will increase exponentially for the natural exponential punitive penalty. However, if we choose exclusion/protection zone with smaller radii, we could plot the ratio curve with α less than (45%). Representing the ratio between the ex-post-only over the ex-ante enforcement with different radius's of the exclusion/protection zone is beyond the scope of this work.

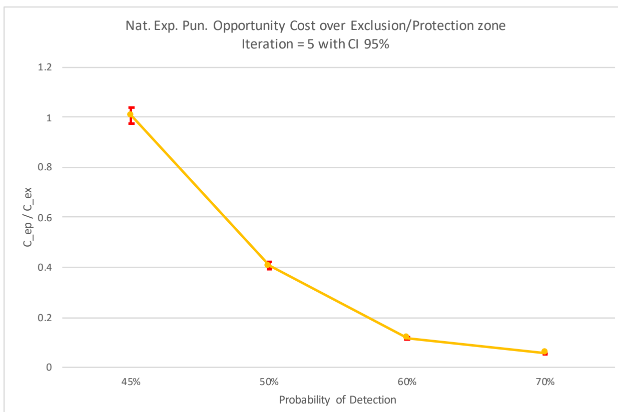
Figure (20a) shows that if α is less than (50%), the cost ratio of the ex-post-only enforcement of the punitive penalties is much higher than the remunerative penalty which is preferable for the policymakers. Figure (20b) shows that the ratio plot for the natural exponential punitive penalty cost over the cost of the exclusion/protection zone is increasing exponentially.

The curve shows a decreasing opportunity cost for all the punitive penalties because the opportunity cost curve is convex. The opportunity cost for the remunerative penalty is decreasing because the function that we used depends on the probability of detection itself, not its equivalent and that is why its curve looks the opposite of the punitive penalties' opportunity cost.

To explain the opportunity cost of ex-post-only enforcement, i.e., if the SGO decides to build a sensor network that detects (45%) of the violation acts with a database system to assign the penalties among the violators. The opportunity cost of 1 exclusion/protection zone is 0.01 of penalty zone using ex-post-only with the remunerative penalty measure with probability of detection of (45%). Put another way, the opportunity cost is 100 penalty zones with the use of ex-post-only as remunerative penalty measure (with the use of probability of detection of (45%)) when giving up 1 exclusion/protection zone.



(a) Punitive/remunerative penalties opportunity cost over the exclusion/protection zone with different probability of detection.



(b) Natural Exponential Punitive penalty opportunity cost over the exclusion/protection zone with different probability of detection

Figure 20: Opportunity Cost of ex-post-only enforcement over ex-ante-only with four different probability of detection.

Additionally, the results show that the opportunity cost of 1 exclusion/protection zone is approximately equal to 1 penalty zone of natural exponential punitive penalty as an ex-post enforcement measure(with the probability of detection becoming less than (45%)). The

Table 7: Opportunity Cost between ex-post-only and ex-ante enforcement with four different probability of detection for 5 iteration and Confidence Interval (CI) of 95%.

Cep/Cex	45%	50%	60%	70%
Remunerative	0.0104 $\pm 2.46 \times 10^{-4}$	0.0115 $\pm 4.63 \times 10^{-4}$	0.0138 $\pm 3.27 \times 10^{-4}$	0.0162 $\pm 3.82 \times 10^{-4}$
Linear Punitive	0.052 $\pm 1.21 \times 10^{-3}$	0.046 $\pm 1.09 \times 10^{-3}$	0.039 $\pm 9.1 \times 10^{-4}$	0.033 $\pm 7.8 \times 10^{-4}$
Exponential Punitive	0.055 $\pm 1.29 \times 10^{-3}$	0.046 $\pm 1.09 \times 10^{-3}$	0.037 $\pm 8.83 \times 10^{-4}$	0.033 $\pm 7.85 \times 10^{-4}$
Natural Exponential Punitive	1.008 $\pm 3.16 \times 10^{-2}$	0.407 $\pm 1.27 \times 10^{-2}$	0.116 $\pm 3.66 \times 10^{-3}$	0.057 $\pm 1.80 \times 10^{-3}$

penalty value will increase exponentially every time the SU violates the spectrum sharing agreement and the SU might not have the incentives to share the spectrum.

Figure (20) shows that if the SGO decides to use alternative ex-post enforcement rather than forfeiture guideline, it will be in sequence of natural-exponential-punitive penalty, exponential-punitive penalty, linear-punitive penalty, and the last choice would be the remunerative penalty. The SGO will choose the remunerative penalty approach, **if and only if** the probability of detection is (100%).

9.2.6 Summary of Results

Ex-post-only enforcement with punitive penalty approaches might not be sufficient to stop the SU from repeatedly imposing harmful interference on the PU because 1) the SU may react to these punitive penalty approaches by decreasing the number of SU-mobile devices that interfere with the PU's receiving signal until its transmission values are profitable, and 2) the SU can repeat the violating action as long as the penalty is not upgraded to more aggressive sanctions.

9.3 STAGE 5: EX-POST-ONLY ENFORCEMENT- GRADUATED RESPONSE (GR) PENALTY APPROACH RESULTS

9.3.1 Description

A purely remunerative penalty function nor punitive penalty as an ex-post-only enforcement may not be the best strategy because it might not be significant enough to stop the SU from interfering with the PU. A broader framework of using the Graduated Response (GR) penalty approach will be used in this section for evaluating the role of the ex-post-only enforcement to find out if it would be a better approach than punitive penalty approaches or not.

Table 8: The Graduated Response procedure.

Step	Call Duration	
$P = -9dB$		
1		Warning
$P \leq -10dB$		
	T (minutes)	Response
2	$0 < T \leq \tau_0$	Linear Punitive penalty
3	$\tau_0 < T \leq \tau_1$	Exponential Punitive penalty
4	$\tau_1 < T$	Natural Exponential Punitive penalty

As mentioned in section (7.2), the GR penalty approach could be implemented in many ways depending on the agreement among the sharing parties (PU and SU). Table (8) shows our implementation of the GR penalty approach that we will use. We hypothesize an adjudication system by an enforcer that applies different enforcement sanctions on the SU. The enforcement sanctions would be upgraded gradually in response to SU's behavior.

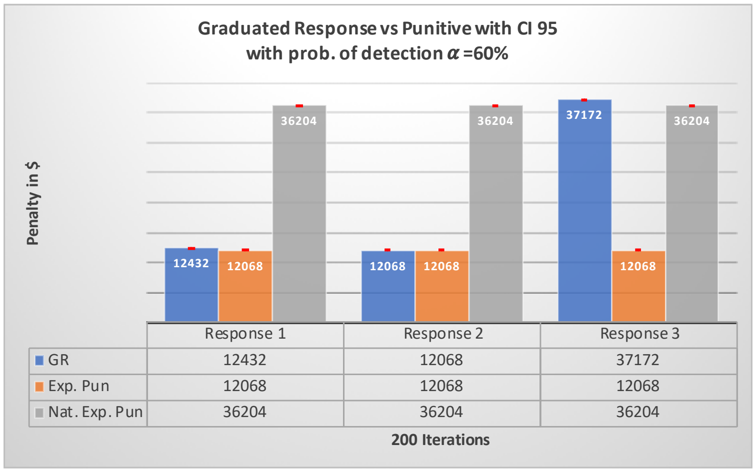
In the previous two sections, we learned that the remunerative penalty approach will not be an efficient mechanism to stop the SU from violating the spectrum sharing rights if the probability of detection is less than (100%). Therefore, we will exclude the use of the remunerative penalty from our GR penalty approach. Also, we will exclude the warning response and the condition of the maximum forfeiture limit $\$160,000$ from our results.

In our hypothetical scenario, we will use different punitive penalty approaches as GR penalty responses to the SU behaviors. If the power limit is exceeded by the SUs' in GR-1, the enforcer will impose the ex-post-only enforcement measures which are: 1) linear punitive penalty for the first response, 2) exponential punitive penalty for the third response, 3) and a natural exponential punitive penalty for the third response.

9.3.2 GR-1 vs Exponential Punitive Function

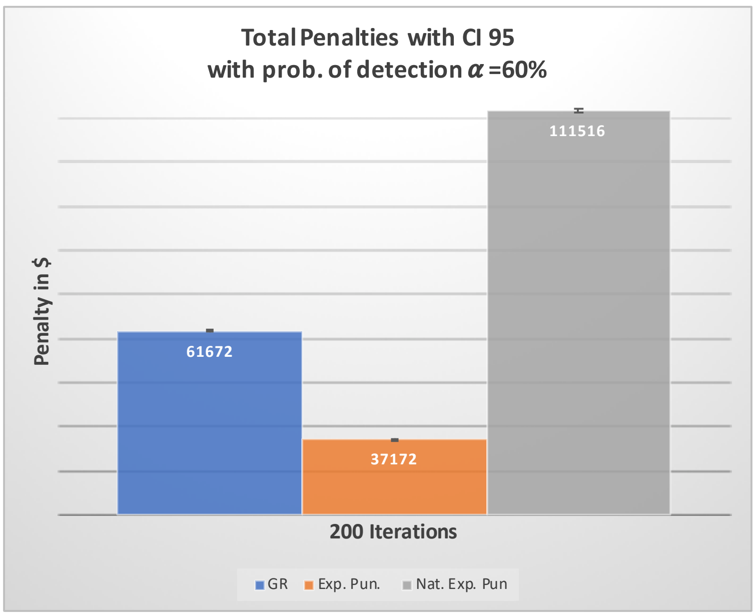
In this part of our simulation, we used one traffic intensity which is 6 minutes per call but the sanctions are graduated every 2 minutes, and the probability of detection for the sensor network that we used was (60%). We ran the simulation for 200 iterations. Figure (21) shows the results of this simulation and is a comparison between the GR-1 and the two exponential punitive penalty approaches.

Figure (21a) shows how the enforcer with the GR-1 penalty approach is gradually increasing the applied penalties every two minutes while it also shows how the other exponential



	Response 1	Response 2	Response 3
GR	12432	12068	37172
Exp. Pun	12068	12068	12068
Nat. Exp. Pun	36204	36204	36204

(a) Graduated Responses Penalty approach versus exponential punitive penalty approach.



(b) Total penalties for three different ex-post-only enforcement Graduated Responses Penalty approach versus two exponential punitive penalties.

Figure 21: Graduated Responses versus two different punitive penalties with one traffic intensity

penalties are not increasing with time. Figure (21b) shows the total penalty values applied to the SU by the enforcer. It also shows that the GR-1 penalty approach value is more than (50%) of the aggressive natural exponential punitive penalty approach.

9.3.3 GR Penalty Approach Variables

Table (8) shows that the GR penalty approach has two variables which are the time and the responses. These variables might have a major impact on the efficiency of the GR penalty approach. We also showed in the previous two sections that the probability of detection has a major impact on the penalty function efficiency. In this section, we will examine the impact when using different time limits and when using different probability of detection on the GR penalty approach efficiency. We will not include different sequences of the responses because the end result is the total applied penalties against the SU and that would be the sum of the responses which will not prove or deny an outcome.

In this section, we will test two Graduated Response (GR) penalty approaches on our model. We hypothesize an adjudication system by an enforcer that applies different enforcement sanctions on the SU. The enforcement sanctions would be upgraded gradually in response to SU's behavior. Then we will compare the outcome results of the two tests. Table (9) shows the two approaches which are GR-1 and GR-2. Both of them are hypothesizing the use of both power level and call duration.

9.3.3.1 Variable Time

In this section, we will test the impact of the penalties when the responses are linked to different time limits. Table (8) shows the both GR penalty (GR-1 and GR-2) procedures. When the power limit is exceeded by the SU in GR-1 and GR-2, the enforcer response will be the same - imposing ex-post-only enforcement measures. They are: 1) linear punitive penalty for the first response, 2) exponential punitive penalty for the second response, 3) and a natural exponential punitive penalty for the third response.

For the GR-1 penalty approach, the sanctions are graduated every 2 minutes, or every time the SUs' signal exceeds the power limits. On the other side, the GR-2 penalty approach in Table (8) is slightly different than the GR-1 penalty approach procedures. In the GR-2 penalty approach, the sanctions are graduated every (1, 2, and 3) minutes, or every time the SUs' signal exceeds the power limits. We used the same probability of detection for the sensor network for all the penalty approaches which is (60%), and we ran the simulation for 200 iterations.

Table 9: The Graduated Response procedure with one traffic intensity that we used in the simulation.

Step	GR-1		GR-2	
$P = -9dB$				
		Warning		Warning
$P \leq -10dB$				
	T (minutes)	Response	T (minutes)	Response
1	$0 < \tau_0 \leq 2$	Linear Punitive penalty	$0 < \tau_0 \leq 1$	Linear Punitive penalty
2	$2 < \tau_1 \leq 4$	Exponential Punitive penalty	$1 < \tau_1 \leq 3$	Exponential Punitive penalty
3	$4 < \tau_2 \leq 6$	Natural Exponential Punitive penalty	$3 < \tau_2 \leq 6$	Natural Exponential Punitive penalty

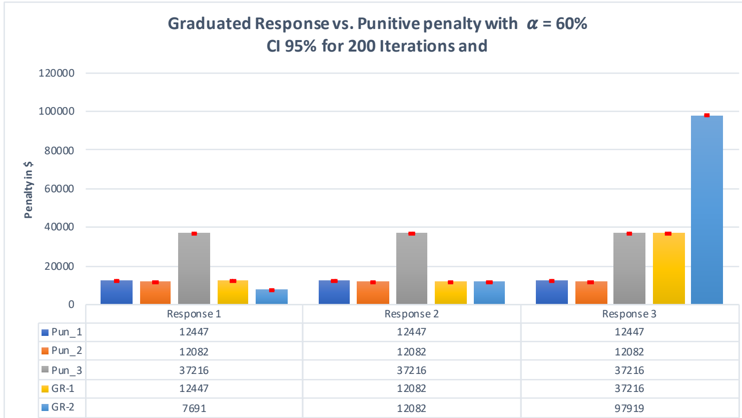
Figure (22) shows the results when the SUs generate one traffic intensity in which one call lasted for 6 minutes. Figure (22a) shows the responses that are applied against the SUs for five penalty approaches. It shows that the GR-2 penalty approach will apply a reasonable penalty on the first response compared to the other four penalty approaches. Then, GR-2 will increase to the most aggressive level on the third response. Figure (22a) also shows that GR-2 will provide the opportunity for the SU to stop transmitting closer to the PU with lower penalty values than the other penalty approaches in the first response.

Figure (22b) shows the total penalties applied by the enforcer against the SUs. The highest penalty value is for the GR-2 penalty approach. The results show that when the enforcer uses the GR penalty approach with responses that are based on different timestamps is a better approach than using the one-time stamp for each response. The GR-2 penalty approach results are even more aggressive than the natural exponential punitive penalty in total.

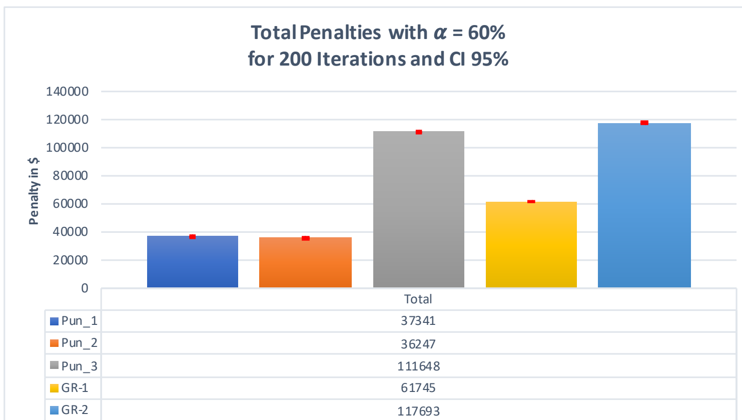
9.3.3.2 Different Probability of Detection

In this section, we will use the same scenario that was explained in the previous section on Table (9) but with the probability of detection ($\alpha = 45\%$). One traffic intensity of one call lasted for 6 minutes is generated by the SUs. We will test the two GR approaches, GR-1 and GR-2, against the natural exponential punitive penalty approach (Pun_3). As mentioned, the GR responses are linear punitive, exponential punitive, and natural exponential punitive penalty approaches. The reason that we nominated the natural exponential punitive penalty approach to compare it with the GR approach because 1) it is the most aggressive punitive penalty approach, 2) and the results of the previous section showed that the other two punitive penalty approaches in total are not aggressive enough to stop the SU from interfering with PUs' signal.

We run the experiment for 200 iterations with a Confidence Interval of (95%). Figure (23)



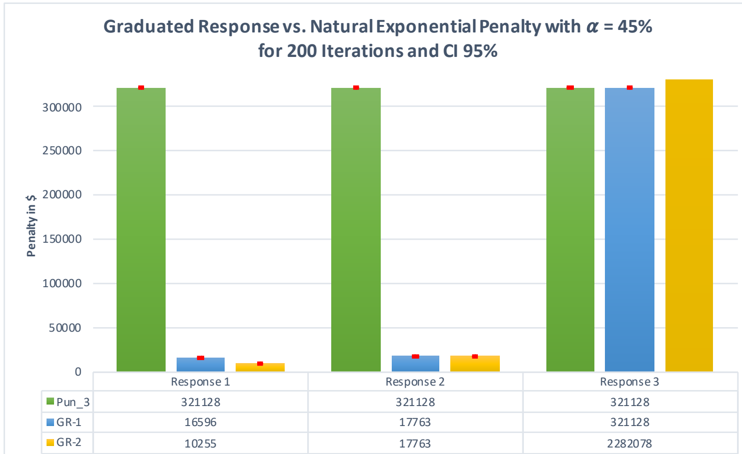
(a) Graduated Responses Penalty approach versus punitive penalty approaches.



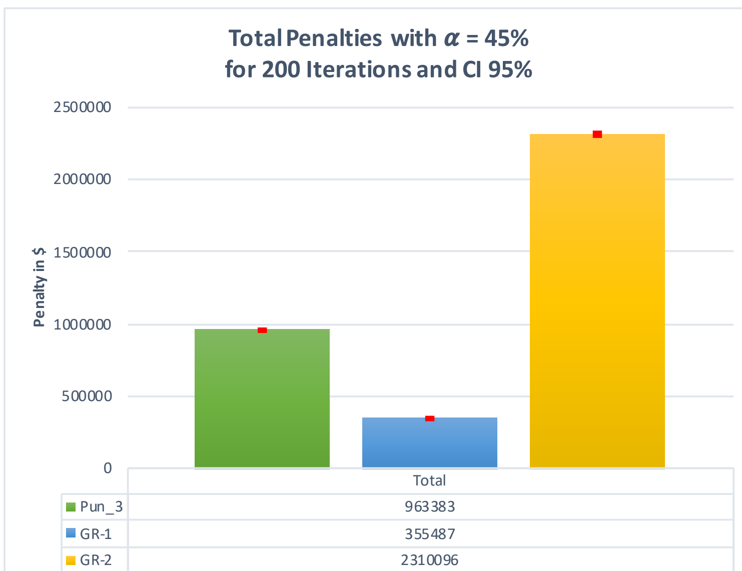
(b) Total penalties for three different ex-post-only enforcement Graduated Responses Penalty approach versus two exponential punitive penalties.

Figure 22: Two GR penalty approaches versus two different punitive penalties with one traffic intensity

shows the results of the three penalty approaches. Figure (23) shows the effects of applying the same/different time limits and when lowering the quality of the sensor networks on the penalty approaches. Figure (23a) shows that GR-2 first response value is the lowest among



(a) Responses of natural exponential punitive penalty and two Graduated Responses Penalty approaches



(b) Total penalties for Natural exponential punitive and two GR approaches showing the effect of probability of detection

Figure 23: Two GR penalty approaches versus natural exponential punitive penalty approach with one traffic intensity

the other two penalty approaches response (GR-1 and Pun_3) because the time limit is the lowest (1 minute) while the other two penalty approaches (GR-1 and Pun_3) response's time limit is (2 minutes). GR-2 will increase rapidly in the third response to be the highest among the other two penalty approaches (GR-1 and Pun_3).

Figure (23a) also shows that if the enforcer decided to use a low probability of detection, the penalty value will be increased due to the increase of the equivalent of the probability of detection. The equivalent of the probability of detection is used to guarantee that SUs will recompense the exact value of the lost data even when they have the risk of avoidance the accountability of conducting the Harmful interference.

Figure (23b) shows the total GR penalty values applied against the SUs when their signal power exceeds the power limits. The results also show that if the enforcer decided to use a sensor network with lower quality to detect the Harmful-interference, the enforcer will have to choose among these three penalty approaches. Figure (23b), GR-2 is the most aggressive penalty approach among the three tested penalties in total. As a result:

1. If the enforcer is applying GR-1 or GR-2, the SUSP will avoid providing the service for calls lasting longer than 4 minutes.
   a. SUSP will prefer GR-1 because the total penalty value would be the lowest among the three penalty approaches.
   b. PU might prefer GR-2 because it is a more aggressive penalty approach than GR-1.
2. If the enforcer is applying natural exponential penalty approach (Pun_3), the SUSP will have the options:
   a. To avoid as much as possible of not getting penalized.
   b. Or will not share the spectrum and provide the service outside the exclusion/protection zone.

3. All the three penalty approaches (GR-1, GR-2, and Pun_3) with a low probability of detection will stop the SUSP from interfering with PU signal at a certain level.

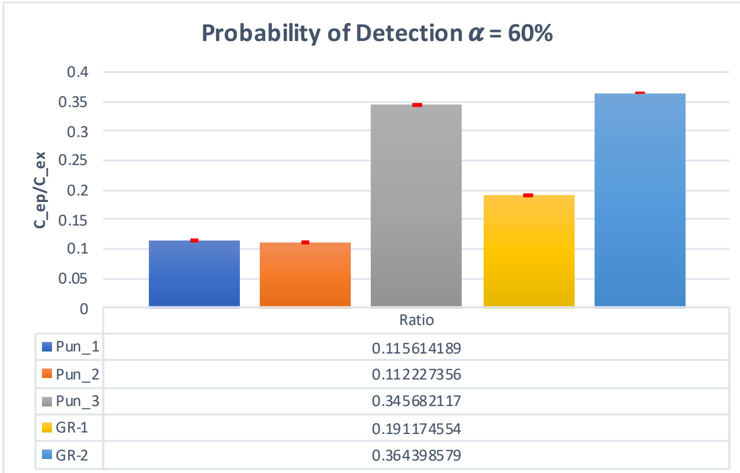
9.3.4 Opportunity Cost Using the Ratio of Ex-post-only over Ex-ante-only

As mentioned, the opportunity cost is usually represented by plotting the Production Possibilities Curve (PPC). In this work, the opportunity cost is represented by plotting plot the ratio between the cost of ex-post-only enforcement (C_{ep}) over the cost of ex-ante enforcement (C_{ex}). The PPC is used to explain how much a person will give up of goods-1 to get an extra of goods-2. The C_{ep}/C_{ex} ratio will provide the same concept as the PPC, where if we are using one exclusion/protection zone, the C_{ep}/C_{ex} ratio will let us know how many penalty zones we could use instead of or vies versa.

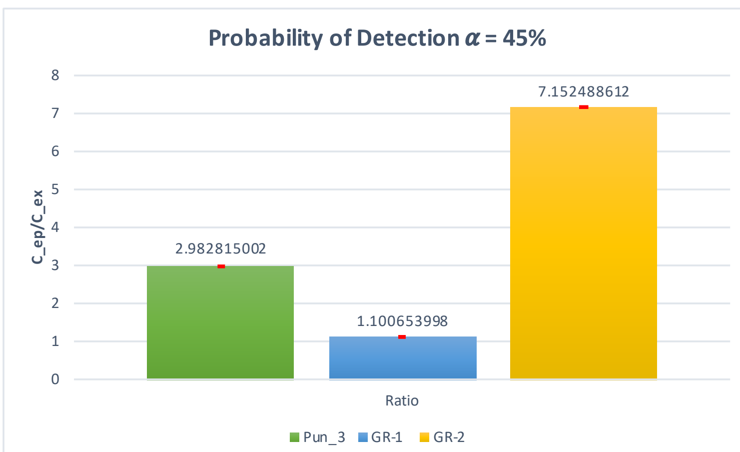
There are three punitive penalty approaches (Linear punitive penalty (Pun_1), exponential punitive (Pun_2), and natural exponential punitive penalty (Pun_3)) and two GR penalty approaches in Figure (24). We used the 2 minutes time limits for GR-1 and all the punitive penalty approaches. And for GR-2, we used 1, 2, and 3 minutes time limits.

Figure (24) shows the effect of the probability of detection on the ratio between ex-post-only enforcement cost and ex-ante enforcement cost. Figure (24a) shows the C_{ep}/C_{ex} ratio when the probability of detection is ($\alpha = 60\%$). Figure (24a) shows that GR-1 ratio is superior to the linear and exponential (Pun_1 and Pun_2) punitive penalty approaches ratio. It also shows that when we changed the behavior of the responses for GR-2 with the use of the same probability of detection, the GR-2 ratio still superior to (Pun_1 and Pun_2) and becomes approximately the same as the aggressive Natural exponential (Pun_3) punitive penalty ratio.

Also, Figure (24a) shows that with a high probability of detection, the five tested eco-



(a) Ex-post-only enforcement cost over Ex-ante enforcement cost ratio when using probability of detection 60% with 200 Iterations and CI 95%



(b) Ex-post-only enforcement cost over the ex-ante enforcement cost ratio when using probability of detection 45% with 200 iteratios and CI 95%

Figure 24: Probability of detection (α) effect on the ex-post-only enforcement cost over the ex-ante enforcement cost ratio .

nomic penalty approaches are not high enough to stop the SU from interfering with PU's signal. To overcome this matter, an additional sanction must be in place (e.g., Forfeiture penalty or license suspension).

Figure (24b) shows the (C_{ep}/C_{ex}) ratio when the probability of detection is $(\alpha = 60\%)$. It also shows that all the three tested economic penalties (C_{ep}/C_{ex}) ratio are above 1. That means, their costs exceeded the cost of the ex-ante enforcement which means all the three tested economic penalties have the ability to stop the SU from interfering with the PUs' signal. As mentioned in the previous section, the natural exponential punitive penalty (Pun_3) is not suggested to be used because the SU might prefer not to share the spectrum because the first response penalty is equivalent to one exclusion/protection zone.

Additionally, if the enforcer decides to use a sensor network that provides a low probability of detection, the GR approach results show its efficiency to stop the SU from interfering with the PU. The GR-2 ratio is 7 times higher than the ex-ante enforcement cost. In other words, one penalty zone that is using GR-2 as an ex-post-only enforcement measure is equivalent to 7 exclusion/protection zones. The results show that GR-2 is a more aggressive economic penalty approach.

9.4 STAGE 6 RESULTS

In this section, we will examine the role of the ex-post-only penalty approaches (Punitive (Pun) and Graduated Response (GR) when the SUs react to these approaches by decreasing the number of SU-mobile devices that interfere with the PU's receiving signal until its transmission values are profitable. We did not consider the remunerative penalty approach since the results of section (9.2.5) proved that this approach will not be efficient when the probability of detection is less than (100%).

9.4.1 Description

We will examine two ex-post-only enforcement approaches which are the Punitive (Pun) penalty approach and the Graduated Response (GR) penalty approach. For the Pun penalty approach, we will use the Natural Exponential adjustment function because of the reasons that we explained in section (9.3.3.2). We will use Table (10) for the GR approaches which have the same concept of Table (9). Table (10) provides an extra condition in the third response which is spectrum sharing license suspension to guarantee that SU will stop violating the spectrum sharing rights. We will use the probability of detection ($\alpha = 45\%$) with the GR and Pun_3 penalty approaches since this probability of detection approved its efficiency to stop the SU from violating the spectrum sharing rights. We will plot the opportunity cost as a ratio of ex-post-only enforcement cost over the ex-ante enforcement cost to compare between the outcome results.

In this part of our experiment, we will have two SU Service Providers (SUSP). The SUSP-1 does not care about the sanctions and will provide the service to any SU-device who asks for the service even if SU-device's signal interferes with the PU signal. The SUSP-2 dose cares about the sanctions and will try as possible to get the minimum sanctions.

One traffic intensity of one call lasted for 6 minutes is generated by the SUs. SUSP-1 will provide the service for all the users. SUSP-2 will have many scenarios to follow since SUSP-2 is trying to minimize the sanctions as possible (e.g., SUSP-2 could stop providing the service to any SUs transmitting close to the PU base station, or provide the service for 2 or 4 minutes at max to avoid getting aggressively penalized). We will explore two scenarios only to demonstrate the efficiency of the proposed GR and punitive penalty approaches. The two scenarios that we will explore are as follows:

1. Scenario-1: SUSP-2 will provide the service for the users for 6 minutes but divide them

Table 10: The Graduated Response procedures.

Step	GR-1		GR-2	
$P = -9dB$				
		Warning		Warning
$P \leq -10dB$				
	T (minutes)	Response	T (minutes)	Response
1	$0 < \tau_0 \leq 2$	Linear Punitive penalty	$0 < \tau_0 \leq 1$	Linear Punitive penalty
2	$2 < \tau_1 \leq 4$	Exponential Punitive penalty	$1 < \tau_1 \leq 3$	Exponential Punitive penalty
3	$4 < \tau_2 \leq 6$	Natural Exponential Punitive penalty	$3 < \tau_2 \leq 6$	Natural Exponential Punitive penalty and License suspension

randomly into three groups:

a. Group-1: will have the service for 2 minutes and then move them to a different band or disconnect the service.

b. Group-2: will have the service for 4 minutes and then move them to a different band or disconnect the service.

c. Group-3: will have the service for 6 minutes.

2. Scenario-2: SUSP-2 will provide the service for the users for 6 minutes but every time SUSP-2 gets sanctioned, SUSP-2 will divide them by half.

9.4.2 Results

Figure (25) and (26) shows the results of the three scenarios that were explained in the previous section where we have SUSP-1 who does not care about the consequences of getting penalized and provide the service to any SU-device, and SUSP-2 who cares with two scenarios. SUSP-1 has only one scenario and SUSP-2 has two scenarios.

9.4.2.1 SUSP-1: Scenario

Figure (25) and Figure (26) show the results for SUSP-1 where GR-2 is most likely the most aggressive economic penalty approach while the natural exponential punitive penalty approach (Pun_3) is the second aggressive approach. Figure (25) also shows that the responses for Pun_3 are equal.

9.4.2.2 SUSP-2: Scenario-1 and Scenario-2

Figure (25) and Figure (26) show the results for SUSP-2 where GR-2 for both scenarios is most likely the most aggressive economic penalty approach while the natural exponential punitive penalty approach (Pun_3) is the second aggressive approach. The two figures also show that the Pun_3 approach is degrading when the SUs are decreasing, while the GR approaches are graduating even when the number of SUs is decreasing.

9.4.3 Opportunity Cost Using the Ratio of Ex-post-only over Ex-ante enforcement

Figure (27) shows ex-post-only enforcement cost to ex-ante enforcement cost ratio for two SUSPs when using two Graduated Responses Penalty approaches (GR-1 and GR-2) and natural exponential punitive penalty approach (Pun_3) to stop the SUSP from violating the spectrum sharing rights. The results show GR-1 is the acceptable approach for PU and SU when the SUSP choose not to care about getting penalized where it guarantees that SUSP will not exceed the time limit and choose not to share the spectrum for the third response. Although, the results show that GR-1 becomes not acceptable approach and need an additional sanction to stop the SUSP from violating the spectrum sharing rights when the SUSP cares when getting penalized and try to reduce the SUs.

Further, Figure (27) shows that Pun_3 is the second alternative approach for the SUSP among the three scenarios. The results show that even when the SUSP is trying to avoid the consequences, it will stop the SUSP from violating the spectrum sharing rights at a certain point. On the other hand, the results on Figure (25) show that Pun_3 is most likely not the best approach when the SUSP is trying to avoid higher penalties by reducing the number of SU-devices who violated the spectrum sharing rights.

Additionally, Figure (27) shows that GR-2 proved its efficiency for all the scenarios and compared to GR-1 and Pun_3 penalty approaches, even when the SUSP-2 tried to avoid getting high penalties. GR-2 results show it would provide the highest penalty ratio for the three tested scenarios among the other two economic penalty approaches (GR-1 and Pun_3). The results show that even when the SUSP-2 tried to minimize the number of SU-devices by half every time it got penalized, the ratio of the ex-post-only enforcement cost to ex-ante enforcement cost was approximately 1.8 (more than one which is the limit when the SUSP decide either to stop violating the spectrum sharing rights or not sharing the spectrum).

However, the GR-2 approach might not be efficient enough to stop the SUSP from violating the spectrum sharing rights with the use of a high probability of detection (e.g., 60% and up). The results show, when using high probability of detection, all the penalty approaches need extra sanctions that have the capability to halt SUSP process.

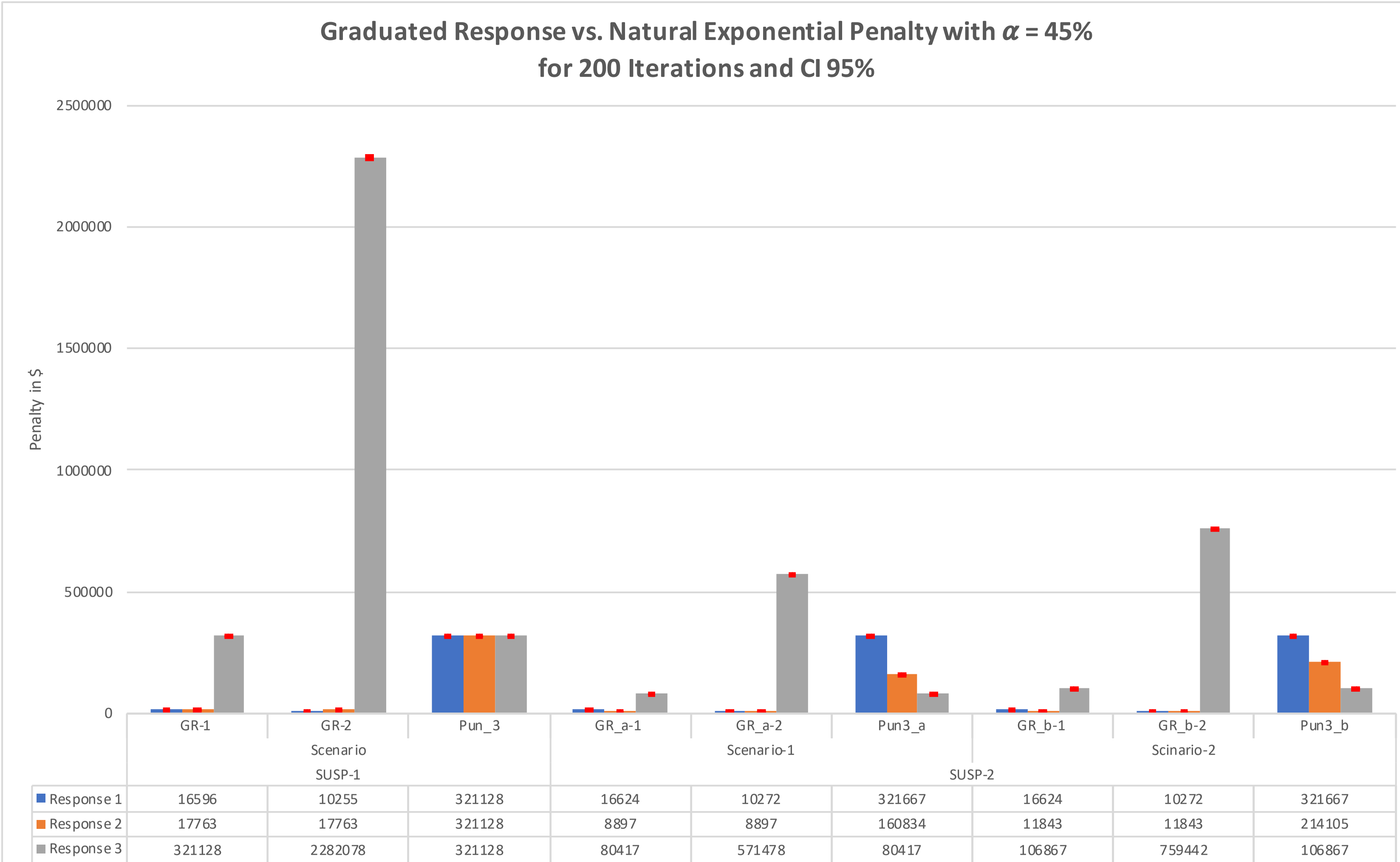


Figure 25: Two SUSPs behavior using two Graduated Responses Penalty approaches (GR-1 and GR-2) and natural exponential punitive penalty approach (Pun_3).

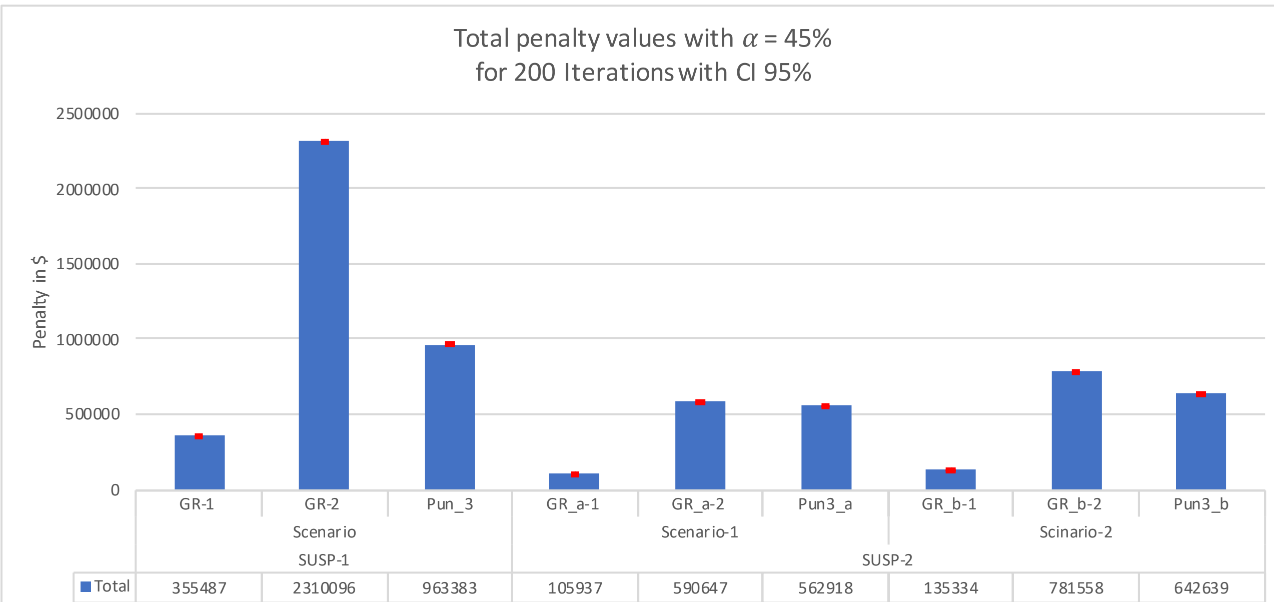


Figure 26: Total penalty values against Two SUSPs using two Graduated Responses Penalty approaches (GR-1 and GR-2) and natural exponential punitive penalty approach (Pun_3).

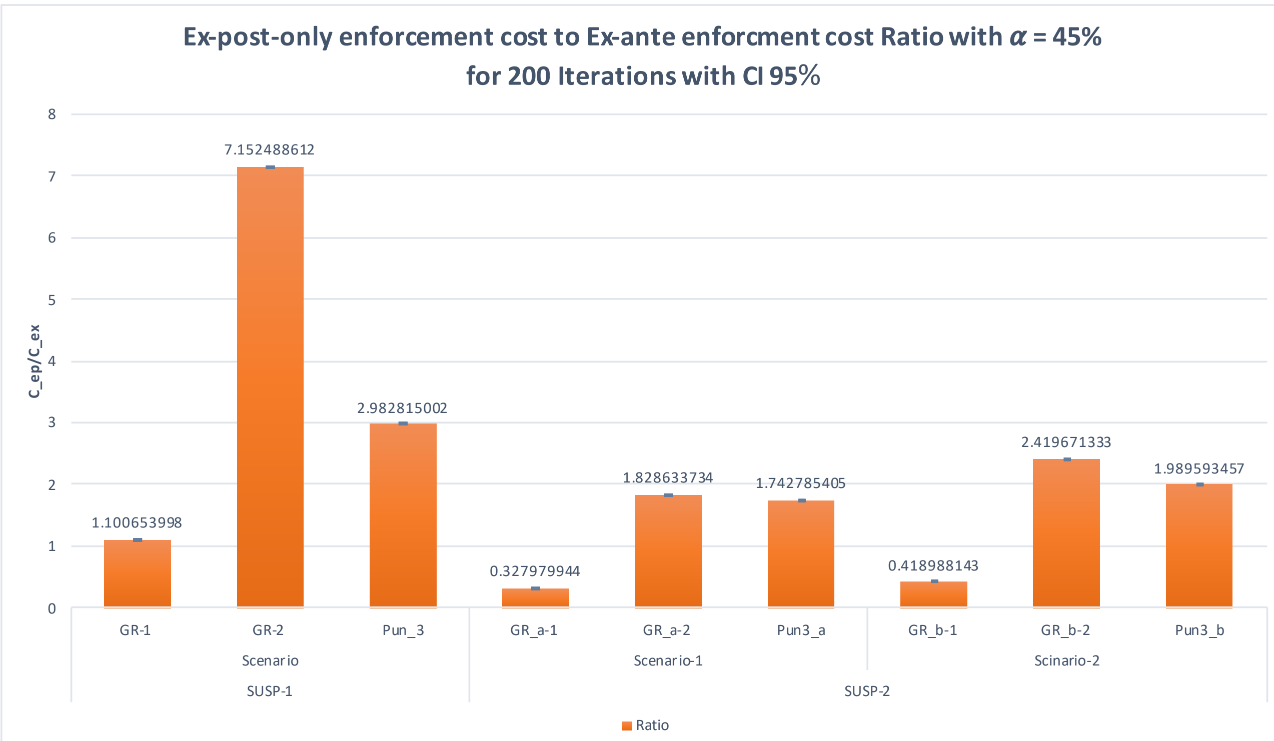


Figure 27: Ex-post-only enforcement cost to ex-ante enforcement cost ratio.

10.0 ANALYSIS

This chapter will explain the significance of the simulation results to the research hypotheses and questions.

10.1 STATISTICAL VALIDATION AND HYPOTHESES TESTING

In this part of the dissertation, we will test our proposed hypotheses significant to Stage 5 and stage 6 because they are directly related to the proposed hypotheses. To do that, we will perform T-test (paired and unpaired) on the data that we got from the simulation to reject/accept the null hypothesis. We run our test on the aggregated data from the experimental simulation with 95% confidence interval (CI) on the variance among the features linked to the hypotheses.

In order to reject or accept the null hypothesis of **H1**, we will use the ratio between the ex-post-only enforcement cost over the ex-ante enforcement cost results. The null hypothesis is that the SU will risk a higher interference penalty as the value of the SU transmissions increase when the dynamic response system is in place. The SU will risk a higher interference penalty when the ratio of the ex-post-only enforcement cost over the ex-ante enforcement cost is less than one.

Table 11: Outcomes analysis and T-test for H1.

Economic Penalty Approach		T-test Result	P-value	Conclusion
SUSP-1: Scenario				
GR-1 where the penalty is graduated every 2 minutes	Pun_3 where the penalty is applied every 2 minutes	$-5.3984 \times 10^{15} \pm 1.8771$	$p < 0.001$	The results are highly significant that the average Pun_3 ratio is higher than the average GR-1 ratio.
GR-2 where the penalty is graduated every 1, 2, and 3 minutes	Pun_3 where the penalty is applied every 2 minutes	$4.4007 \times 10^{15} \pm 4.1584$	$p < 0.001$	The results are highly significant that the average GR-2 ratio is higher than the average Pun_3 ratio.
SUSP-2: Scenario-1				
GR-1 where the penalty is graduated every 2 minutes	Pun_3 where the penalty is applied every 2 minutes	$-6.4035 \times 10^{15} \pm 1.4147$	$p < 0.001$	The results are highly significant that the average Pun_3 ratio is higher than the average GR-1 ratio.
GR-2 where the penalty is graduated every 1, 2, and 3 minutes	Pun_3 where the penalty is applied every 2 minutes	$1.4832 \times 10^{14} \pm 0.0858$	$p < 0.001$	The results are highly significant that the average GR-2 ratio is higher than the average Pun_3 ratio.
SUSP-2: Scenario-2				
GR-1 where the penalty is graduated every 2 minutes	Pun_3 where the penalty is applied every 2 minutes	$-3.2642 \times 10^{15} \pm 1.5719$	$p < 0.001$	The results are highly significant that the average Pun_3 ratio is higher than the average GR-1 ratio.
GR-2 where the penalty is graduated every 1, 2, and 3 minutes	Pun_3 where the penalty is applied every 2 minutes	$5.7701 \times 10^{14} \pm 0.4397$	$p < 0.001$	The results are highly significant that the average GR-2 ratio is higher than the average Pun_3 ratio.

Table (11) shows the T-test analysis for **H1**. In stage-6, we compared between two SUSPs. SUSP-1 does not care about the consequences of getting penalized and keep providing the service to any SU-device. And SUSP-2 cares about the consequences when getting penalized and tried to reduce the SU-devices every time it got penalized in two scenarios.

The results show that when there is a dynamic system using graduated economic penalties with fixed time limits (the sanctions is graduated every 2 minutes) and low probability of detection, the ratio of the ex-post-only enforcement cost over the ratio of the ex-ante enforcement cost is less than one, for some cases. This allows us to accept the null hypothesis for GR-1 when the SUSP risks a higher interference penalty by reducing the number of SU-devices by half every time it gets penalized.

Further, the results show when there is a dynamic system using graduated economic penalties that depend on different time limits, such as GR-2. The ratio of the ex-post-only enforcement cost over the ratio of the ex-ante enforcement cost is more than one. This allows us to reject the null hypothesis and accept the alternative hypothesis with the use of different time limits or additional sanctions that have the capability to stop the SU from interfering with PU's signal at the third graduated response.

On the other hand, we will use the ratio between the ex-post-only enforcement cost over the ex-ante enforcement cost results to reject or accept the null hypothesis of **H2**. **H2** hypothesized that including the detection technique will lead to a better quality of service (QoS) for PU, lower the probability of SU violations, and lower the cost of the ex-post enforcement. The Quality of Service (QoS) is defined as the ability of a network to guarantee a certain level of network performance (link availability, certain bit error rate, or a certain level of network delay) [86]. In this work, the QoS for PU parameters are the link availability and lowering the probability of SU from violating the spectrum sharing rights and these conditions are assured with the third response by adding the license suspension condition as shown in Table (10).

Table 12: Outcomes analysis and T-test for H2 outcomes.

Economic Penalty Approach		T-test Result	P-value	Conclusion
Pun_3 where the penalty is graduated every 2 minutes with probability of detection $\alpha = 45\%$	Pun_3 where the penalty is graduated every 2 minutes with probability of detection $\alpha = 60\%$	$6.6835 \times 10^{16} \pm 2.63$	$p < 0.001$	The results are highly significant that the average Pun_3 ratio with $\alpha = 45\%$ is higher than the average Pun_3 ratio with $\alpha = 60\%$.
GR-1 where the penalty is graduated every 2 minutes with probability of detection $\alpha = 45\%$	GR-1 where the penalty is graduated every 2 minutes with probability of detection $\alpha = 60\%$	$2.5633 \times 10^{15} \pm 0.9070$	$p < 0.001$	The results are highly significant that the average GR-1 ratio with $\alpha = 45\%$ is higher than the average GR-2 ratio with $\alpha = 60\%$.
GR-2 where the penalty is graduated every 1, 2, and 3 minutes with probability of detection $\alpha = 45\%$	GR-2 where the penalty is graduated every 1, 2, and 3 minutes with probability of detection $\alpha = 60\%$	$7.1561 \times 10^{15} \pm 6.7698$	$p < 0.001$	The results are highly significant that the average GR-2 ratio with $\alpha = 45\%$ is higher than the average GR-2 ratio with $\alpha = 60\%$.

Additionally, the rate of the probability of detection relies on the quality of the sensor antenna that the enforcer used to detect the harmful interference. We also know that if the detector sensitivity goes down to lower the cost of the ex-post-only enforcement, the probability of detection (α) goes down. Though we will use the ratio results between the ex-post-only enforcement cost over the ex-ante enforcement cost results of stage-5 when the probability of detection varies from 60% to 45% to accept or reject the null hypothesis for **H2**. The outcome analysis and T-test for **H2** is presented in Table (12).

Table (12) shows the T-test accepted the alternative hypothesis that the data of column A and column B comes from populations with unequal means at the default 5% significance level. This indicates us to reject the null hypothesis for **H2** (i.e., increasing the cost of the ex-post enforcement will lower the probability of SU violations which will lead to a better quality of service for PU). Further, this means that lowering the cost of the ex-post enforcement cost by lowering the probability of detection will most likely reflect on increasing the imposed penalty value.

10.2 SENSITIVITY ANALYSIS

This part of the dissertation will study the effect of changes in the assumptions that we used in our model. This section is divided into two parts. In the first part, we will study the changes our assumptions impact our model. In the second part, we will study the effect of using two different Path Loss models and compare them with the results that we got.

10.2.1 Assumptions Impacts

We will study the changes of the Signal Interference-to-Nose Ratio (SINR), the penalty zone, the penalty fluctuation on three important parameters: Secondary Users (SU) distance from the PU, desired received signal power, and interference received power. The first parameter showed that no matter how many SUs when the distances of the SU become less than 10 km, the SINR decrement rapidly the closer the SU is to the PU receiver. For the desired received signal power parameter, SU was better at transmitting at lower power when transmitting closer the PU. SINR limit played an important role in assigning the ex-post-only enforcement cost. The last parameter showed how the penalty zone fluctuated when the SU density changed around the PU.

Figure (28-a) shows the exclusion/protection zone with the radius of 90km with 100,000 SU uniformly distributed outside the exclusion/protection zone. Figures (28-b and 28-c) show how the SINR decline with distance; the closer SU the lower the SINR. Figure (28-b) shows that the minimum SINR is around 28 dB when the SU are uniformaly distributed outside the exclusion/protection zone. And Figure (28-c) shows the SINR drop when the 100,000 SU are uniformly distributed inside in an area of (90 $\times 90km$).

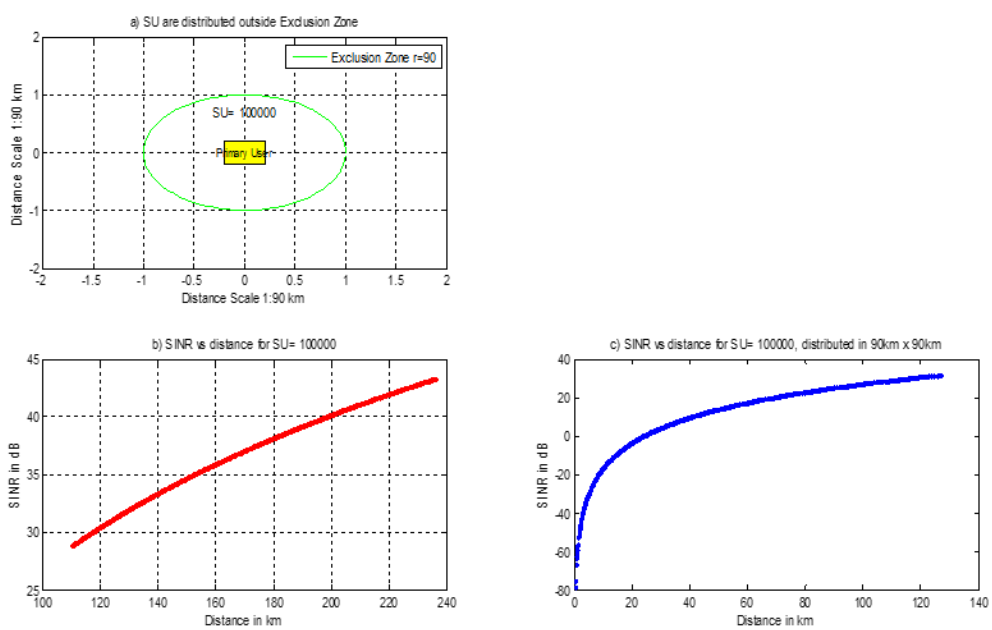


Figure 28: SINR when SUs' are distributed outside/inside the exclusion/protection zone

10.2.1.1 SU Density

There are many variables that may affect the decision of the SU to transmit using the ex-post-only enforcement or decide not to share the spectrum and prefer ex-ante enforcement. One of these variables is the SUs density within the exclusion zone. It can be predicted that the denser the SU around the PU, the more the SU would be penalized. Numerical results showed that the number of the penalized SUs goes down when the SUs were distributed in lower density.

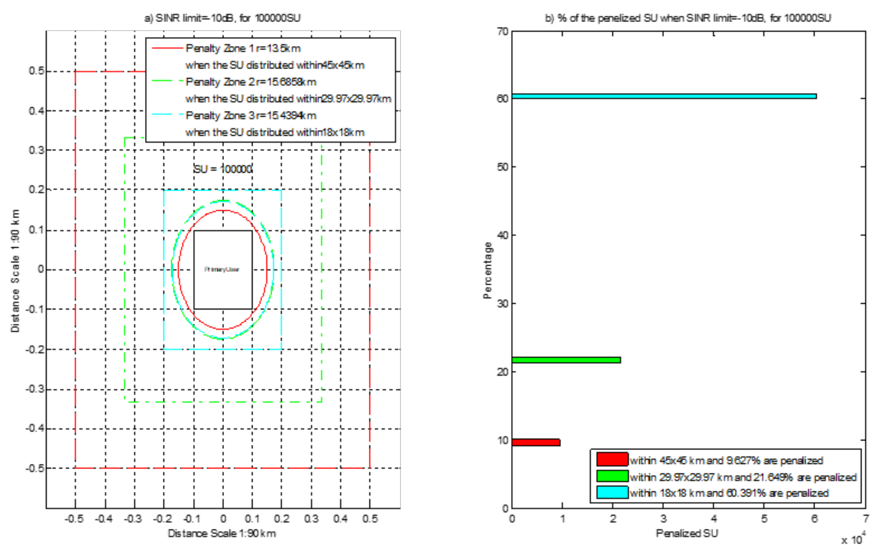


Figure 29: Penalty zone versus SU density

Figure (29) shows the variation of the SU density around the PU versus the number of the penalized SUs. It shows the number of penalized SU when the SUs are dense in three different areas (18km×18km, 29.7km×29.7km, and 45km×45km). The PU is simulated as the middle point of these areas. The transmitted power for the PU and the SU with the number of the SUs are fixed. The SINR is limited to -10 dB, so if the SU signal transmission power exceeds that limit the SU will be penalized.

Figure (29) shows that the more dens the SU around the PU the more SUs would be penalized. For example, only 9.661% of the SUs will be penalized when the SUs are distributed in (45km×45km), while more than 60% of the SU will be penalized if they are distributed in an area of (18km×18km).

10.2.1.2 SINR Limits

Figure (30) shows that when 100,000 SUs are uniformly distributed in the area of (90km×90km) around the PU, PU EIRP is 8.1dB, SU transmitted power is 23dBm, and SINR limits of (-10, -5, -1, 20) dB.

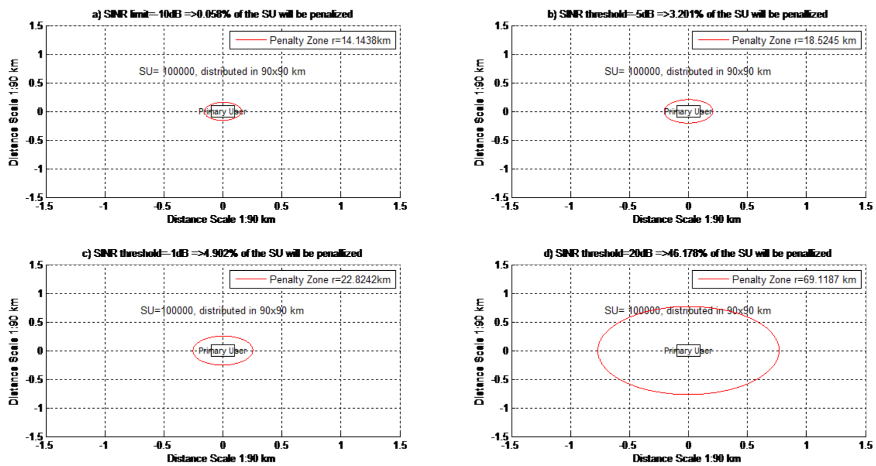
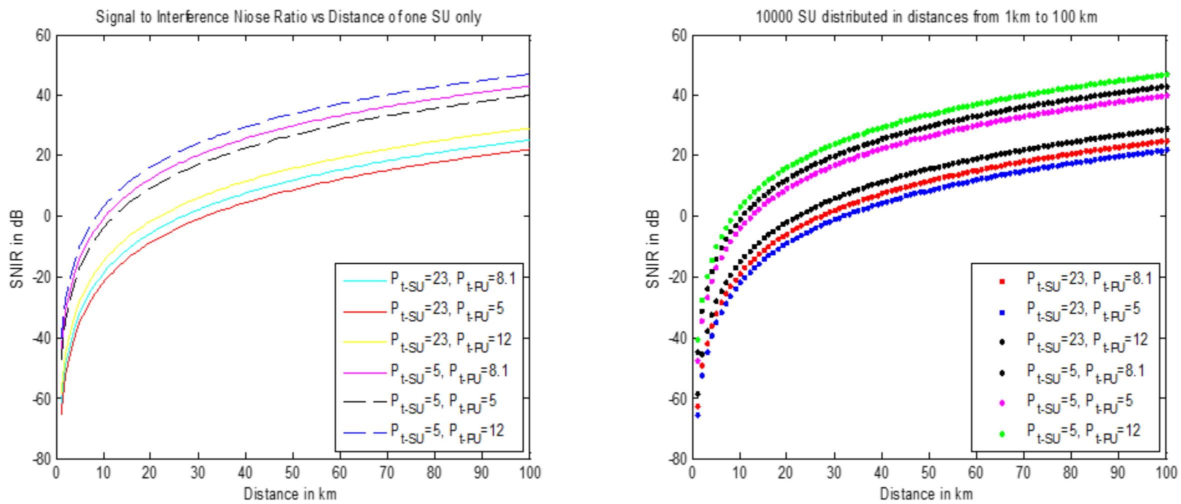


Figure 30: SINR vs penalty zone radius

Figure (30) shows the results of the effect changing the SINR limit on the radius of the penalty zone. Further, the spectrum sharing idea becomes inefficient for the SU, if the SINR limit is higher than -1dB because the radius of the penalty zone will be more than $65km^2$.

10.2.1.3 Equivalent Isotropically Radiated Power (EIRP)

Figure (31) shows the interference effect on the PU when varying the number of SU [1, 100000], PU EIRP is [8.1, 5, 12] dB, and SU transmitted power is [23, 5] dBm. The results



(a) One SU

(b) 100,000 SU

Figure 31: SINR variations whith three different EIRP values and two transmitted power values.

show not many differences in the SINR curve with changing the number of the SU. It shows also when the SU transmit at lower power the SINR becomes better. Finally, these results show that no matter the number of the SU when the distance of the SU is less than 10 km, the SINR decreases rapidly the closer the SU comes to the PU receiver.

10.2.1.4 Other Parameters fluctuation analysis (Appendix B)

Appendix (B) provides more sensitivity analysis of other parameters that will have an impact on the SU wither to share the spectrum or not.

10.2.2 Path Loss (PL) Model

As mentioned, to get the received power the path loss power must be found first. There are different models to get the path loss power (such as Okumura Model, Hata Model, and COST-231 Model). Each one of these models applicable to a certain range of frequencies. In this section, we will use Okumura-Hata Model and COST-231 model (C=0 that is used for cities with medium-sizes and suburban areas) to compare the outcome results with our results that were generated using COST-231 (C=3 that is used for metropolitan areas).

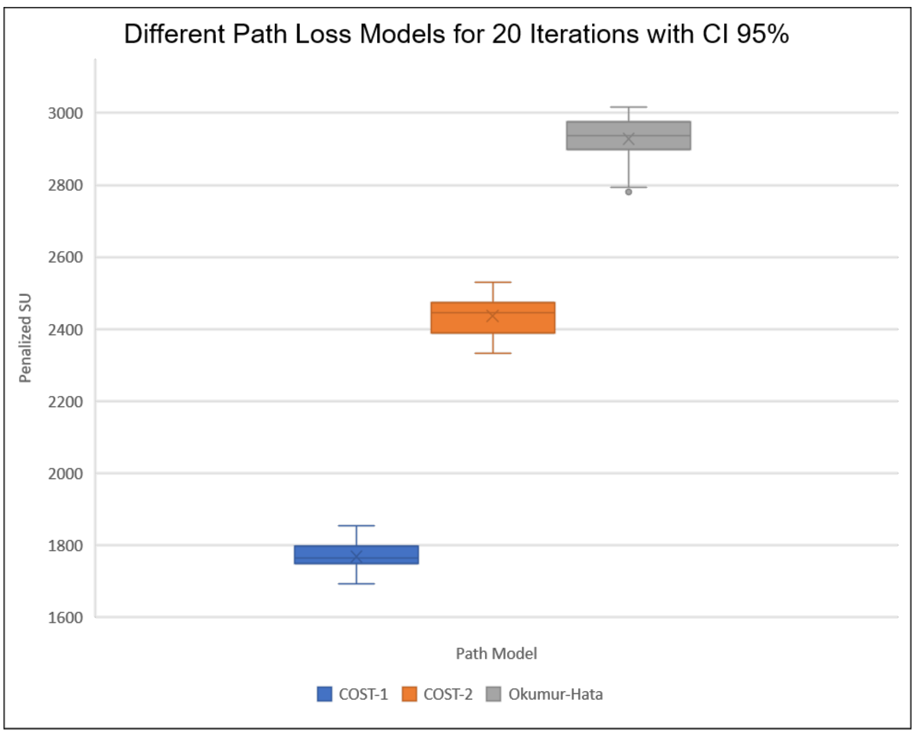


Figure 32: Number of Penalized SU using different path models

Figure (32) shows the average number of penalized SU when using three different techniques to get the path loss values. The three path loss models are 1) COST-231 with C=3 (COST-1) is the path loss model that we used in our model, 2) COST-231 with C=0 (COST-2), 3) and Okumura-Hata path loss model. Figure (32) results show the differences in the average number of SU whose signal power exceeds the SINR limits. The differences are significantly high when using different path loss models. The policymakers have to put into consideration when calculating the SINR appropriate PL model based on the environment (suburban or rural) and frequency range.

11.0 CONCLUSION, LIMITATIONS, AND FUTURE WORK

11.1 CONCLUSION

Determining the role of ex-post enforcement in a cooperative spectrum sharing scheme is of significant importance since spectrum sharing will, without a doubt, result in interference events. This dissertation evaluated the role of the ex-post enforcement approach. It did so by using a hypothetical scenario of the recommended exclusion/protection zones and the entities involved to analyze the current enforcement timing measures and evaluating the usage of ex-post-only enforcement measures.

The issue with the recommended ex-post enforcement measures by the CSMAC-enforcement subcommittee is that they are suitable for a static spectrum allocation policy but are not applicable for cooperative spectrum sharing. In fact, they might reduce the incentives for the SU to share the spectrum. Two main points of view were provided, which were regulatory and technical.

The CSMAC-enforcement subcommittee recommended that the PU and SU enter into a specific MOU or individual agreement to cover all specific interference enforcement issues. While this recommendation would fall under the umbrella of the Communication Act of 1934 and the Forfeiture Proceeding guidelines, it would not be ideal because the Forfeiture Proceeding guidelines did not consider the period of conducting the harmful interference.

The specific time period of the harmful interference is needed when imposing the penalty in order to calculate the expense of lost data.

Three alternative scenarios were given using ex-post-only enforcement to show the regulator how an ex-post-only enforcement scheme might work. In the first scenario, the remunerative penalty approach demonstrates an adjudication system that penalizes the SU when the interference level reaches a certain limit received at the PU's antenna with a fine amount equal to the value of the lost data. This approach imposes a fine on the SU that is proportional to the value of the lost data by the PU in addition to the enforcement costs incurred by it. The remunerative penalty is imposed for each SU-mobile device conducting harmful interference to the PU's received signal. The penalty also takes into account the length of time of the interference.

The benefits of using ex-post-only with remunerative approach suggested in [87] for the PU are: (1) PU will get the value of the lost data and can recover it, (2) PU will gain income from sharing the spectrum within the excluded areas, (3) the cost of building the sensors around the PU's base station to detect harmful interference is less than the cost for protection zones because it would have smaller ranges. The ex-post-only enforcement using the remunerative penalty approach might not halt the SU from interfering with the PU's reception as long as 1) the probability of detection is less than 100%, 2) the value for SU transmission increases, which may lead to denial of service (DoS) for the PU. An alternative ex-post-only scenario was explained to overcome these disadvantages.

In the second ex-post-only enforcement scenario, an adjudication system penalizes each SU when the interference level reaches a certain limit received at the PU's antenna. In this situation, the penalty is a much higher amount than the value of the lost data and is referred to as the punitive penalty approach. This approach was given to overcome the disadvantages of the remunerative penalty approach. A comparison between the remunerative and different punitive penalty functions was given and it showed how a punitive penalty approach has significantly higher enforcement costs than the remunerative economic-penalty approach.

As per our analysis, the ex-post-only enforcement using the punitive penalty approach might not be the most efficient solution to stop the SU from repeatedly interfering with the PU's receiving signals. This is because the SU may decrease the number of SU-mobile devices that interfere with the PU's receiving signals until it makes its transmission value profitable. Since the penalty is not escalated to more intrusive sanctions, the SU will repeat the violation act.

Further, the idea of a broader framework for evaluating the role of the ex-post-only enforcement to stop the SU from conducting harmful interference that was put forth. This example hypothesized an adjudication system by an enforcer that applied different enforcement sanctions on the SU. The enforcement sanctions would be upgraded gradually in responding to SU's interfering behavior. The ways of implementing the Graduated Response (GR) idea in cooperative spectrum sharing were explained depending on the agreement between the PU and SU.

A hypothetical scenario on applying the GR approach was explained, simulated, evaluated, and compared with the punitive economic-penalty approaches. In our hypothetical GR scenario, we considered three different interference event levels received at the PU's antenna. In the first interference level, the first economic-penalty would be a linear punitive penalty for the time limit of τ_0. In the second interference level, when the SU did not optimize the transmission and decided to continue transmitting closer to the PU's antenna, the response was upgraded to an exponential punitive penalty for time limit τ_1. If the SU then optimized transmissions, the net value of a sequence of transmissions would be positive. In the third interference level, if the SU continued transmitting closer to the PU's antenna, the response was upgraded to the natural exponential punitive penalty for time limit τ_2.

Further, we tested this GR hypothetical approach in three different ways (different time limits, different probabilities of detection, different SU behaviors) to test its significance to stop the SU from conducting harmful interference. The results showed that varying the time limit and lowering the probability of detection will provide the most aggressive economic penalty approach even more than the natural exponential punitive economic penalty approach.

On the other hand, the results showed that there should be an additional ex-post enforcement measure in the third response when using a sensor network that provides a high probability of detection (60% and more). This additional ex-post measure should have the capability to stop the SU from conducting harmful interference, such as license suspension or the Forfeiture penalty.

11.2 LIMITATIONS

The problem with the ex-post-only of using the economic penalty approach is that it may require policy changes if the SU does not agree with these steps because they are not covered by the statute. It was also recommended that either the policymaker of the CSMAC-enforcement subcommittee propose an update to the Communications Act of 1934 or adjust the procedures of adjudication to overcome these concerns.

Further, several propositions can be drawn from the assumption that we used to build our hypothetical model besides the remarks that had been recapped from the simulation results and the conclusion:

- We used one PL model which is the COST-231 with C= 0 that is used for cities with medium-sizes and suburban areas. And we built our model for an area of $90km \times 90km$. However, an area of $90km \times 90km$ could include both suburban and rural areas.
- The interference criteria could vary because the PU might not use the dedicated band all the time. However, we did assume that the PU is using the spectrum all the time in our hypothetical model.
- The value of the transmission per SU in equation (7.1) could vary from per transmission. However, we used the value of $1 for neutrality.
- The adjustment factor in equation (7.5) could be calculated in different ways (for example, the linear adjustment factor could be quadratic or some other functional form). However, we did use the simplest linear form to show the reader the implications of the punitive economic penalty function.
- The value of the lost data in section (8.5.4) could vary from one organization to another. However, we used the available numerical values related to the satellite.
- In chapter (9), we assumed the detection cost-less (time). But the sensor network could take a certain time to detect the violation act (e.g. 2 minutes or 3 minutes). This detection time will reflect on the penalty unction and the enforcer will have to put it in consideration.

11.3 RECOMMENDATION

Recomm. : SAS-like database system as an ex-ante enforcement mechanism will speed up part of the ex-post enforcement process which will lower the cost of ex-post enforcement.

$$R1 \rightarrow Ex-post|Ex-ante \rightarrow Cost_{ex-post} \sim f(\,Prevention + Detection),$$

The process to assign the responsibility of a violation against the interferer is lengthy because the policymakers are depending on the prevention-only measures as ex-ante enforcement. For example, the United States Coast Guard (USCG) filed a complaint about interference events to their operation on 1-17-2013. After two days of investigations by an agent from the Enforcement Bureau's Los Angeles Office, the agents located the interfering signal which was coming from Acumen Communication. On 1-30-2013, the FCC issued a Note-Of-Violation against Acumen Communication [58]. It took 13 days just to assign the responsibility of the interference against the violator, which may be acceptable with static spectrum allocation. The report indicates that Acumen was unaware that its device is transmitting its signal that caused interference to USCG. If a prevention-and-detection technique is in use as an ex-ante measure to monitor the harm, this time would be reduced. Further, prevention-and-detection techniques should take place in the spectrum sharing regime with more dynamic spectrum access to avoid hit-and-run from the violator and to guarantee sharing rights among the sharing parties.

In the motivation section, we showed the tradeoff between ex-ante and ex-post enforcement and we explained that if policymakers want to lower the cost (economic and time) of the ex-post enforcement, they need to add additional ex-ante enforcement measures to ease the process of ex-post enforcement. For example, If a database and a sensor network are in place as ex-ante measures to register and detect any SUs that intend to access the spectrum, the process of ex-post enforcement, such detection of interference signal and assigning responsibilities against the violator will be lowered and that will have a direct effect on the cost of the ex-post enforcement.

Further, we cannot rely on one type of ex-post enforcement measures (such as remunerative economic penalties) and apply it to all spectrum bands because each spectrum band will have a potentially unique telecommunication technology in use and each technology has its own properties. The policymakers understood these differences of the technologies' properties for each band, so they suggested different ex-ante mechanisms on different bands but not different ex-post enforcement mechanisms.

For example, for the suggested 3550-3650 MHz band, the suggested ex-ante measures are 1) Power and SINR limitations, 2) Dynamic exclusion zones, 3) Sensor network around the coastlines to sense if PU is present, 4) Spectrum Access System (SAS). SAS will have the ability to: 1) allocate the spectrum dynamically, 2) detect and resolve any spectrum sharing policy violation. One of the SAS functionalities is warning the SU with the appearance of the PU to evacuate the band.

SAS system will provide functionalities to help ease the process of ex-post enforcement mechanisms by detecting violation events with the assistant of a sensor network which will reflect on lowering the ex-post enforcement cost. Also, if SAS-like database system is used as an ex-ante measure for the 1695-1710 MHz band, it might: 1) lower the cost of the ex-post enforcement in comparison to the coordination between the PU and SU as an ex-ante mechanism, 2) and provide the opportunity to use alternative ex-post enforcement measures, such remunerative and punitive economic penalties. If time delay to sort out violations is reduced, which results in increased productivity for the SU and PU. For the PU, the faster the detection process will mean less damage and faster recovery times. For the SU, the SAS-like database will provide the opportunity to use different ex-post enforcement measures instead of using the maximal ex-post liability, which will lower the cost of the ex-post enforcement. This can be shown using a hypothetical model to measure the delay with the use of the SAS-like database system and compare that with the delay of using the coordination between the PU and SU.

11.4 FUTURE WORK

A comprehensive enforcement framework would include protecting the rights of the SU as well as having an ex-post component that can efficiently and effectively adjudicate claims of interference.

APPENDIX A

Table 13: The FCC Enforcement Bureau (EB) Notice of Apparent Liability (NAL) from 2018 to 2011 for the conducted harmful interference cases.

Begin of Table 13				
Year	Case name	Fine description	Case Summery	Violation
2018	JJerry W., Materne, Lake Charles, Louisiana [49]	\$7,000 forfeiture for interference, a \$1,000 forfeiture for failure to provide station identification, and an upward adjustment of \$10,000.	EB proposes an \$18,000 monetary forfeiture against Jerry Materne by causing intentional interference to licensed radio operations and by failing to transmit his designated-call-sign that is used for the Amateur Radio Service.	Communication-Act of 1934, section 333 , as amended (Act), and sections (97.101(d) and 97.101(d)) of the communication's rules.

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	Full Spectrum,,Inc [50]	The base forfeiture amount for operations without an instrument of authorization for the service is $10,000, the base forfeiture amount for harmful interference to radio communications is $7,000, and the base forfeiture for using unauthorized equipment is $5,000.	Full Spectrum for apparently willfully and repeatedly operated equipment without a license and without FCC equipment authorization that caused harmful interference to two hundreds Verizon Wireless sites in CA.	Section 301 and Sections 1.903(a), 2.805(a), and 27.51(a) of the Commission's rules.
2017	Ravi's Import Warehouse, Inc. [51]	The base forfeiture amount for operations without an instrument of authorization for the service is $10,000, the base forfeiture amount for harmful interference to radio communications is $7,000, and the base forfeiture for using unauthorized equipment is $5,000.	The Enforcement Bureau proposes a monetary forfeiture of $22,000 against Ravi's Import Warehouse, Inc., for operating a jammer in apparent. Signal jamming devices typically operate by transmitting powerful radio signals that overpower, jam, or interfere with authorized communications.	Sections 301, 302(b), and 333 of the Communications Act of 1934, and Sections 2.805(a) and 15.1(c) of the Commission's rules.

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
2014	CMARR, Inc., San Juan, PR [52]	The base forfeiture amount for operations without an instrument of authorization for the service is $10,000, $7,000 as the base forfeiture amount for conducting harmful interference to radio-communications, in addition to $8,000 as the base forefeiture fine for using equipment without authorization.	CMARR, Inc. operated radio transmitters without a license that caused interference to with a Federal Aviation Administration (FAA) weather radar in San Juan.	Sections 301 and 333 of the Communications Act of 1934.

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	Drew Buckley [53]	The base forfeiture amount for operations without an instrument of authorization for the service is $10,000, $7,000 as the base forfeiture amount for conducting harmful interference to radio-communications. An additional upward $8000 was granted by the EB to the combined $17,000.	Drew Buckley of Bay Shore, New York, operated radio-transmitter unlicensed and conduct interference with another licensed radio-communications system of the Melville Fire District of New York (Melville).	violated Communications-Act of 1934 sections 333 and 301, as amended (Act).

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	Jason R. Humphreys [54]	EB proposed the per violation statutory maximum of $16,000 per each of the offenses which are: 1)unauthorized operation, 2)use of an illegal device, 3) and causing intentional interference.	Jason R. Humphreys operated an illegal cell phone signal jammer (cell phone jammers operate by transmitting radio signals that overpower, block, or interfere with authorized cell phone communications). Mr. Humphreys admitted that he owned and had operated a cell phone jammer from his car for the past 16 to 24 months.	Sections 301, 302(b), and 333, and section 503(b) of the Communications Act of 1934, and Sections 2.805(a) and 15.1(c) of the Commission's Rules by operating a cell phone jammer.

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	R&N, Manufacturing, Ltd (RNM) [55]	For the unauthorized operation and illegal equipment violations, we will impose a forfeiture of $16,000 per violation, the maximum per violation forfeiture authorized by statute. For the companion interference violation, we will impose a $7,000 forfeiture. This would result in a total forfeiture of $39,00. Because RNM's surrender of the illegal device to Commission agents.,The Commission reduced the proposed forfeiture by 25%.	RNM actually, intentionally, and frequently activated a cell phone jammer in its manufacturing facility in Houston, Texas. This illegal operation caused actual interference to cellular and Personal Communications Service (PCS) communications in the surrounding area, creating potential public safety risks.	Sections 301, 302(b), and 333 of the Communications Act of 1934, as amended (Act), and Sections 2.805(a) and 15.1(c) of the Commission's rules.

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	Orloff Haines [56]	The base forfeiture amount for interference to radio communications is $7,000, and upward adjustment in the forfeiture amount of $5,000	Haines operated a Citizens Band (CB) radio transmitter to maliciously and intentionally to interfere with the communications of other CBs. Mr. Haines admitted that he was "keyed on" Channel 19 to prevent other CB operators in the area from harassing his wife.	Section 333 of the Communications Act of 1934, as amended (Act), and Section 95.413(a)(3) of the Commission's rules.
	James R., Winstead [57]	The base forfeiture amount for interference to radio communications is $7,000	James R. Winstead operated radio-transmitter on assigned frequency (7.195MHz) to a licensed operator.	Communication-Act of 1934 section 333, as amended (Act), in addition to the communication rules-section 97.101(d).

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
2013	Acumen, Communications [58]	The base forfeiture amount for operation on an unauthorized frequency, or unauthorized emissions is $4,000; and the base forfeiture amount for interference is $7,000.	Acumen Communications (licensee of Station WQJF635, in Los Angeles, California) operated the station on an unauthorized frequency and caused interference.	Section 301 of the Communications Act of 1934, as amended (Act), and in addition to communication's rules-sections (1.903(a) and 1.903(e)).

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation
	Gary P. Bojczak[59]	$16,000 for unlawful operation, $16,000 fine for using illigal equipment, $7000 fine of interfering with authorized communication, in addition EB applied 50 percent as adjustment to the base forfeiture amount for interference. The total become to $42,500 as forfeiture fine. Then, EB reduced the proposed forfeiture to $31,875 (of $42,500 by 25%) to provide appropriate incentives.	Gary P. Bojczak operated a Global Positioning System (GPS) jamming device. This illegal action caused harmful interference to a ground-based augmentation system operated by the Port Authority of New York and New Jersey and designed to increase the precision of GPS-based navigation at Newark Liberty International Airport, one of the busiest airports in the country.	Communication-Act of 1934 sections (301, 302(b), 333), and communication's rules sections (2.803(g), and 15.1(c).
2011	Estevan J.,Gutierrez [60]		Mr. Gutierrez operated on frequency 159.150 MHz without authorization (a frequency licensed to the Las Vegas, New Mexico, Police Department (LVPD)) that caused interference with LVPD.	Sections 301 and 333 of the Communications Act of 1934, as amended (Act).

Continuation of Table 13

Year	Case name	Fine description	Case Summery	Violation

End of Table

APPENDIX B

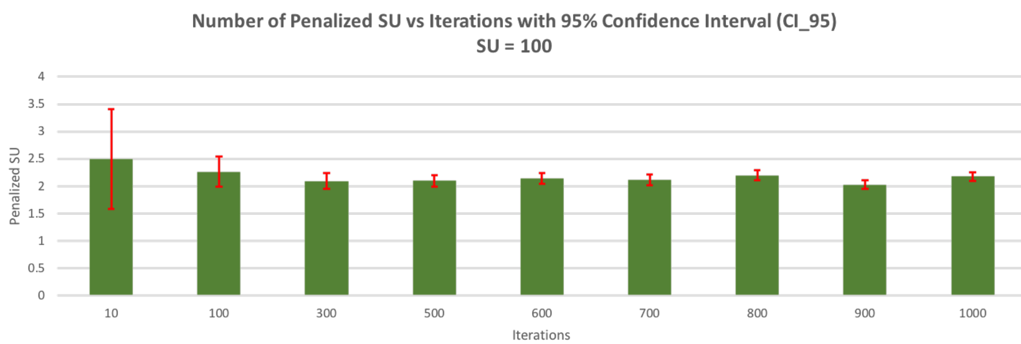
B.1 TRANSMIT POWER AND DISTANCE OF THE SU IMPACTS

Table (14) shows impact on the SINR when the SUs' distance from the PU base station and SU's transmitted power are varying. The SU transmit power are (5, 10, and 23) and the SUs' distances are (1, 2, and 9)km. The number of the SU and EIRP are fixed, where SU are 100,000 users and EIRP is 8.1. Table (14) shows that when the minimum distance of SU 9 km and the transmit power for the SU-devices is 5dBm, the received SINR by the PU antenna is 0 dB. The results also shows that the higher the transmit power and closer the SU to the PU antenna, the higher the SINR.

Table 14: SINR with the variation in distance and SU transmit power.

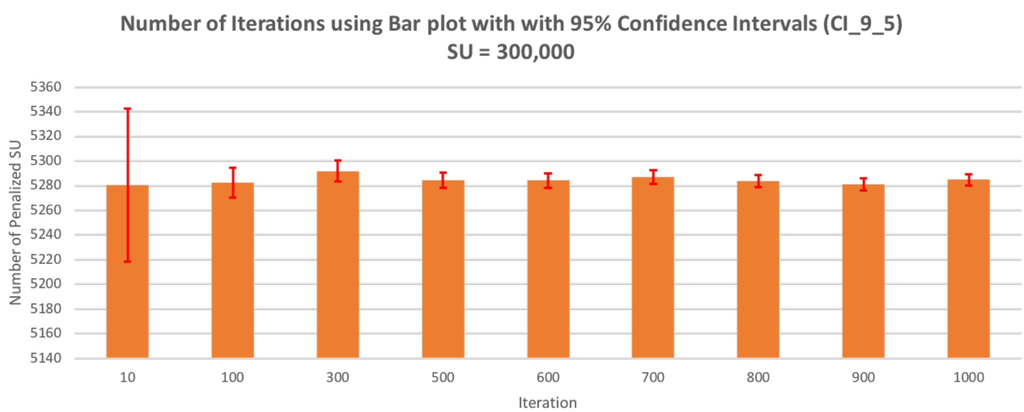
$P_{tr_{SU}}$ (dBm)	Distance (SU from PU) (km)	SINR (dB)
23	1	-60
5	1	-42
10	1	-45
23	2	-45
5	2	-28
10	2	-32
23	9	-18
5	9	0
10	9	-4

APPENDIX C



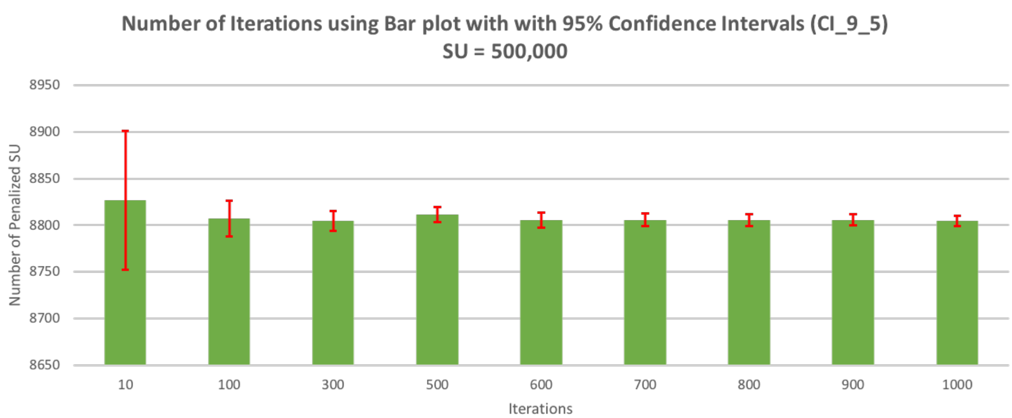
Matlab Results									
SU = 100									
Iterations	10	100	300	500	600	700	800	900	1000
Avg	2.5	2.26744186	2.09465021	2.1	2.14056225	2.1208981	2.19968553	2.02748691	2.17908654
Std	1.26929552	1.29636976	1.15855254	1.07676702	1.09706086	1.18492341	1.19159784	1.09234365	1.14439781
CI	0.90799931	0.27794225	0.14639899	0.10327649	0.09658797	0.09671848	0.09278501	0.07758007	0.07787471

Figure 33: Fraction of penalized SU when we have 100 SU uniformaly distributed in an area of $90km \times 90km$ for different number of iterations with Confidence Interval of 95%.



Matlab Results									
SU = 300000									
Iterations	10	100	300	500	600	700	800	900	1000
Avg	5280.2	5282.16	5291.79	5284.424	5284.04833	5286.90714	5283.39625	5280.92667	5284.704
Std	86.662564	61.8175419	76.74864	72.3903651	71.1742389	73.9954467	71.722377	71.5925093	71.1040799
CI95	61.9946637	12.2659415	8.72006324	6.36060618	5.70655107	5.49106653	4.97755588	4.68359692	4.41234132

Figure 34: Fraction of penalized SU when we have 300,000 SU uniformaly distributed in an area of $90km \times 90km$ for different number of iterations with Confidence Interval of 95%.



Matlab Results									
SU = 500000									
Iterations	10	100	300	500	600	700	800	900	1000
Avg	8826.5	8806.86	8804.48333	8811.144	8805.485	8805.89286	8805.7675	8805.86556	8804.554
Std	103.934007	96.2610109	93.3638711	92.0054633	98.616116	92.1375547	92.9757175	93.5794603	93.2686234
CI	74.3499096	19.100273	10.6078604	8.08409403	7.90676389	6.83735913	6.4525445	6.12198785	5.78775511

Figure 35: Fraction of penalized SU when we have 500,000 SU uniformaly distributed in an area of $90km \times 90km$ for different number of iterations with Confidence Interval of 95%.

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